



**UHASSELT**

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**LUND**  
UNIVERSITY

Doctoral dissertation submitted to obtain the degrees of  
- Doctor of Transportation Sciences | UHasselt  
- Doctor of Philosophy in Engineering | Lund University

**Tim De Ceunynck**

DOCTORAL DISSERTATION

Defining and applying  
surrogate safety measures and  
behavioural indicators through  
site-based observations

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D/2017/2451/39  
ISBN 9789089130587  
ISSN 1653-1930

CODEN:LUTVDG/(TVTT-3240)1-185/2017  
Bulletin: 304

# Defining and applying surrogate safety measures and behavioural indicators through site-based observations

Tim De Ceunynck



**LUND**  
UNIVERSITY

## DOCTORAL DISSERTATION

by due permission of the School of Transportation Sciences, Hasselt University,  
Belgium,  
and the Faculty of Engineering, Lund University, Sweden.

To be defended at Hasselt University, campus Diepenbeek, Agoralaan –  
building D, in auditorium H3, Diepenbeek, Belgium. 29<sup>th</sup> of September at 16:00.

*Faculty opponent*

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	<p>Date of issue: 23<sup>rd</sup> of August, 2017</p>	
	<p>Sponsoring organisations Hasselt University, European Union, Flemish Government, Research Foundation Flanders, Rijkswaterstaat</p>	
<p>Title and subtitle: Defining and applying surrogate safety measures and behavioural indicators through site-based observations</p>		
<p>Abstract This dissertation looks into surrogate safety measures and behavioural indicators that are collected through site-based observations. Surrogate safety measures are defined as measurements that are used to describe the relationship between two road users in a traffic event for the purpose of quantifying the crash probability and/or the potential crash severity in a meaningful way. The main goal of this dissertation is to contribute to filling methodological knowledge gaps in site-based observations of surrogate safety measures and road users' behaviour, and to investigate how such observations can be used to study road safety issues for which crash data appear to be less suitable. The dissertation includes a scoping review that investigates in a comprehensive and quantitative way how surrogate safety measures have been applied so far. The theoretical framework and first implementation of a new indicator, Extended Delta-V, are presented. Three case studies have been conducted that aim to further investigate how site-based observations of road users' behaviour and interactions could supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed. The case studies relate to: 1) the safety of bicyclists on bus lanes shared with bicyclists, 2) drivers' behavioural adaptations caused by wind turbines alongside the roadway, and 3) differences in drivers' interactions at right-hand priority intersections and priority-controlled intersections. The case studies provide some safety-relevant insights into topics that have rarely been addressed in scientific literature before. Policy and design implications are discussed.</p>		
<p>Key words: Surrogate safety measures, behavioural indicators, traffic safety, site-based observations, traffic conflicts, traffic conflict techniques, road user interactions</p>		
<p>Classification system and/or index terms (if any): NUR code 976 – Transport studies</p>		
<p>Supplementary bibliographical information CODEN:LUTVDG/(TVTT-3240)1-185/2017 D/2017/2451/39</p>	<p>Language English</p>	
<p>ISSN 1653-1930 Bulletin – Lund University, Faculty of Engineering, Department of Technology and Society, 304</p>	<p>ISBN 9789089130587</p>	
<p>Recipient's notes</p>	<p>Number of pages</p>	<p>Price</p>
	<p>Security classification</p>	

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Date 23<sup>rd</sup> of August 2017

*Sophiae via nemini soli ambulanda*

*(One cannot walk the path towards wisdom alone)*

*Dedicated to my wife Sofie,  
who was always by my side during this challenging journey*



## Acknowledgement

This dissertation presents the final result of a challenging journey that took seven years in total. To quote Thomas Edison, it is the result of “one percent of inspiration and ninety-nine percent perspiration”. It has been a difficult and scary journey at times, and I have felt like the proverbial donkey chasing a carrot on a stick more than once. However, it was exciting and enlightening as well, and I feel that it has allowed me to grow a lot on a professional level as well as on a personal level. I would never have managed to complete this major challenge without the help of many wonderful people who have contributed to this work, and without those who were there to lift my spirits when I needed a boost and to share in my happiness after each accomplishment. This chapter is a modest attempt to express my sincere gratitude to these people.

First of all, I would like to thank my promoters, Tom Brijs and Åse Svensson. Tom, thank you for your feedback and your help in taking some important strategic decisions during the process of this PhD. Thank you for your endless patience and your help in overcoming all administrative pitfalls that unexpectedly showed up in relation to the complexity of a double PhD agreement. And thank you for the pleasant cooperation in various projects and courses.

Åse, initially I only knew you as one of the most famous researchers in the field of traffic conflict studies. During my stay in Lund, however, I also got to know you as a warm and friendly person with a great sense of humour. Thank you for all the efforts you have gone through to make a double PhD agreement possible, for your continuous encouragements to persist and improve, and for your helpful feedback to my work.

Meeting inspiring people is a true blessing that can change your life and career forever. I have been fortunate enough to have two of the most inspiring people I have ever met as my co-promoters. I would therefore like to express my sincere gratitude to my co-promoters, Stijn Daniels and Aliaksei Lareshyn. Aliaksei, thank you for all your help during my PhD. The possibility to work together with you has been one of my main motivations to spend a long research stay at Lund University, and it has made my stay at Lund University the most productive and vital period of this entire process. It has been truly inspiring to cooperate with you. Thank you for always being ready to help me out by answering literally hundreds of e-mails that I have fired at you over the years, and thank you for being one of the nicest people that I have ever encountered. I hope that in the future we can continue to cooperate on many joint projects.

Stijn, I am genuinely convinced that without your help, this PhD would have taken twice as long to become only half as good. You have spent so many hours helping me set up and fine-tune my studies, and you have been such a great support during the years. You always made the time to help me out, no matter how busy you were or how stupid my question was. Over the years, you have entrusted me with a tremendous variety of tasks, and some of them seemed so important and challenging that they literally scared the hell out of me at first. Nevertheless, your belief in me always seemed endless, which gave me the confidence and the enthusiasm I needed to bring them to a successful conclusion. Many of these

occasions turned out to be interesting opportunities that have allowed me to learn new things and meet new people. I want to thank you for all these great opportunities and for the trust that you put in me. You have helped me grow as a researcher and as a transportation professional more than anyone else. I have also enjoyed our many hours of interesting discussions about many different topics during our regular jogging trips and during long travels and commutes. It has always been, and still is, a privilege and a true pleasure to work with you on a daily basis.

Furthermore, I would like to thank my committee members Elke Hermans and Geert Wets. Thank you for your input during committee meetings, for the opportunity to pursue a PhD and for the trust and the freedom to pursue it my way. I would also like to thank my opponent and jury members; Lars Ekman, Haneen Farah, Risto Kulmala, and Ali Pirdavani; for agreeing to be part of my jury and for your positive words and helpful feedback to the draft version of my dissertation.

I want to thank Evelien Polders and Wouter van Haperen for being my main “partners-in-crime” in building a research line in surrogate safety measures. I feel that we were a great team, and that we have managed to overcome many challenges together. It has been great to work together with you, and to share great as well as difficult moments. I would also like to thank Ellen De Pauw for the collaboration in one of the studies, and for bringing a positive vibe to our office during your years at IMOB. In addition, I wish to thank all colleagues from the InDeV consortium who contributed to the scoping review about surrogate safety measures, with Carl Johnsson deserving particular mention.

I would also like to thank all colleagues from the Transport and Roads department at Lund University for their hospitality during my stay in Sweden. I would especially like to thank Jean Ryan and David Lindelöw, who were great friends to me during my stay in Sweden. “Ett stort tack” for the many laughs, lunches and beers that we shared, and for making sure that I never felt out of place!

It is well known that researchers can be quite helpless when it comes to practical matters and administration. It was a great luxury not having to worry too much about that thanks to the help of the amazing people of the IMOB secretariat: Kristel Hertogs, Nadine Smeyers, Edith Donders, Tamara Dewalque and André Jacobs.

I would also like to express my gratitude to a number of (former) Master’s students, who have contributed to some of my studies within the frame of their Master theses. Thank you Bert Dorleman, Matthias De Smet, Michèle Baets, Bert Vanderspikken, Annelies Geussens, Beau Gardeniers, Brecht Cams, Joram Langbroek and (again) Evelien Polders. It has been a pleasure to guide you in this process, and your work and dedication have been very helpful for many of my studies.

Furthermore, I would like to thank the numerous colleagues who I have had the pleasure to cooperate with on various studies, projects and courses. I would also like to thank my new colleagues at the Belgian Road Safety Institute for their support and for the great cooperation during the last year. Also, I am still greatly

indebted to Els Hannes and Diana Kusumastuti for their guidance during my Master thesis; their genuine dedication and their believe in me have stimulated my interest in research, convinced me to start a PhD, and allowed me to publish my first publications.

Time away from work has been just as important for bringing this PhD to a good end. I would never have been able to succeed in obtaining this PhD without the support of my friends and my family. First of all, thank you to all my friends from the tennis team, high school and university for the great times. Thank you for many conversations about important matters in life as well as utter nonsense, for great support during tennis matches (despite my excessive swearing), for lots of fun and laughs, for nice game nights, great parties and experiences, and for accepting this PhD as the ever-returning cause of missing out on too many of those occasions.

Also my warm gratitude to my entire family. I want to thank my parents-in-law and my two brothers-in-law, who have supported and contributed each in their own way. Most importantly, I would like to thank my parents and my sister for their support and for encouraging me to dream big and never give up. Katrien, thank you for putting up with a major geek for a brother. I know that it has not always been easy! Mum and Dad, thank you for your great support and for always being genuinely proud of me. It means the world to me. Thank you for raising me to become an ambitious, hardworking and curious person. I know it took a lot of patience to keep encouraging the characteristics that I needed to become a researcher. Some examples: Mum who patiently answered me – probably a thousand times – when I asked what time it was while I was trying to teach myself to tell the time as a toddler. Dad who took me to a local pond to catch tadpoles to see how they evolve into frogs, the countless children's encyclopaedias you provided me with... I will never forget everything you did for me!

Finally, I owe much, if not everything to my beautiful wife Sofie. Sofie, thank you for being my lovely companion throughout this entire journey. Thank you for being my greatest comfort during difficult moments, and my biggest enthusiast during the good ones. Thank you for granting me all the freedom to pursue my PhD in my own way, and for encouraging me to persevere under all circumstances. Thank you for taking my frequent travels and my many working hours during weekends and during odd hours of the day (and night) with great patience. My long research stay abroad was a difficult time for us, but it has been of invaluable importance to my PhD, so I cannot tell you enough how much it means to me that you encouraged me to do this from the very beginning. During these busy years I have not always been the most enjoyable version of myself, and I have not always been able to be the prince that a princess like you deserves. I hope I will be able to make up for that now. Thank you for your endless support, for always making me happy, and for making me a better person!

Tim De Ceunynck,  
August 2017, Diepenbeek, Belgium



## Summary

The transport system plays an important role in our society. However, crashes are a major concern. There is a strong need for improvements in road safety. Traditionally, road safety has mostly been studied through analyses of crash data, which are, however, susceptible to some important limitations. As a result, road safety can strongly benefit from analysis methods that make use of observable data of non-crash events in traffic.

Therefore, this dissertation looks into surrogate safety measures and behavioural indicators that are collected through site-based observations. Surrogate safety measures are defined as measurements that are used to describe the relationship between two road users in a traffic event for the purpose of quantifying the crash probability and/or the potential crash severity in a meaningful way. The main goal of this dissertation is to contribute to filling methodological knowledge gaps in site-based observations of surrogate safety measures and road users' behaviour, and to investigate how such observations can be used to study road safety issues for which crash data appear to be less suitable.

A scoping review has investigated in a comprehensive and quantitative way how surrogate safety measures have been applied in scientific literature so far, and what their main limitations are. Major methodological challenges in the field of surrogate safety measures remain, including the need for further validation and a better inclusion of the potential outcome severity should a crash have occurred. In addition, it seems that the field lacks unified methodologies and a generally accepted "best practice" framework, which could help to improve the quality of future studies that make use of surrogate safety measures. The scoping review study in this dissertation might serve as a useful starting point for developing such a framework by providing an inventory of how surrogate safety measures have been applied to date. It is also shown that observations of surrogate safety measures can benefit from being supplemented by behavioural observations and/or data from other fields such as driving simulator studies.

The dissertation also presents the theoretical framework and first implementation of a new surrogate safety measure, Extended Delta-V, which aims to overcome some of the limitations of existing surrogate safety measures. Most importantly, the Extended Delta-V indicator aims not only to reflect the proximity of a traffic encounter to a crash (in terms of time or space), but also the potential outcome severity should a crash have taken place. While this is a promising first step, additional research is needed to further develop and validate the indicator.

Three case studies have been conducted that aim to further investigate how site-based observations of road users' behaviour and interactions could supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed. The case studies relate to: 1) the safety of bicyclists on bus lanes shared with bicyclists, 2) drivers' behavioural adaptations caused by wind turbines alongside the roadway, and 3) differences in drivers' interactions at right-hand priority intersections and priority-controlled intersections. The case studies provide some safety-relevant insights into topics that have rarely been addressed in scientific literature before. Policy and design implications are discussed.

The studies performed within the frame of this dissertation have led to a deeper insight into current practices as well as future challenges and opportunities within site-based observation studies of surrogate safety measures and behavioural indicators. It is concluded that such studies can be especially beneficial to road safety policy when crash data, for various reasons, cannot provide a sufficient insight into a specific topic or measure.

When selecting behavioural indicators to assess road safety, the choice of the specific behavioural indicators strongly defines the extent(s) to which inferences on road safety can be drawn from them since behavioural indicators are an even more indirect indicator of road safety than surrogate safety measures. From the conducted case studies it appears that a stronger emphasis on surrogate safety measures still leads to stronger evidence of the expected safety effects. But generally it seems that observations of behavioural indicators, when well selected and measured, could provide an indication of the direction of effect on safety in exploratory studies.

## Samenvatting

Het mobiliteitssysteem speelt een cruciale rol in onze maatschappij, maar verkeersongevallen zijn een belangrijk probleem. Er is een sterke behoefte aan verbeteringen op vlak van verkeersveiligheid. Traditioneel wordt de verkeersveiligheid hoofdzakelijk bestudeerd door analyses van verkeersongevallendata. Deze data zijn echter onderhevig aan een aantal belangrijke beperkingen. Daardoor kunnen analysemethoden die gebruikmaken van geobserveerde data van niet-ongevallen een waardevolle bijdrage leveren aan de verkeersveiligheid.

In dit proefschrift wordt daarom onderzoek gevoerd naar indirecte verkeersveiligheidsindicatoren (ook "surrogaatindicatoren voor verkeersveiligheid" genoemd) en gedragsindicatoren die verzameld worden aan de hand van locatiegebaseerde observaties. Surrogaatindicatoren worden gedefinieerd als metingen die bedoeld zijn om de relatie te beschrijven tussen twee weggebruikers die betrokken zijn in een interactie in het verkeer, met de bedoeling om op die manier de kans op een ongeval en/of de potentiële ernst van een ongeval op een betekenisvolle manier te kwantificeren. Het hoofddoel van dit proefschrift is om bij te dragen aan het wegwerken van methodologische kennishiaten met betrekking tot surrogaat- en gedragsindicatoren in locatiegebaseerde observaties, en om te onderzoeken hoe dergelijke observaties gebruikt kunnen worden om verkeersveiligheidsproblemen te onderzoeken waarvoor ongevallendata minder geschikt zijn.

Een scoping review literatuurstudie onderzocht op een extensieve en kwantitatieve manier hoe surrogaatindicatoren tot nu toe werden toegepast in de wetenschappelijke literatuur en wat hun voornaamste beperkingen zijn. Er zijn nog steeds belangrijke methodologische uitdagingen in dit domein, waaronder de nood aan verdere validatie en het beter incorporeren van de potentiële ernst indien een ongeval zou hebben plaatsgevonden. Ook mist het domein geïntegreerde methodologieën en een best practice framework. Deze zouden sterk kunnen bijdragen aan de kwaliteit van toekomstige studies die gebruikmaken van surrogaatindicatoren. De scoping review literatuurstudie kan dienen als een vertrekpunt voor de ontwikkeling van een dergelijk framework door een overzicht te bieden van hoe surrogaatindicatoren tot op heden zijn toegepast. Er wordt ook aangetoond dat observaties van surrogaatindicatoren baat hebben bij aanvullende observaties van het gedrag van weggebruikers en/of data vanuit andere disciplines zoals rijnsimulatorstudies.

Dit proefschrift presenteert ook het theoretische kader en de eerste toepassing van een nieuwe surrogaatindicator, Extended Delta-V, die bedoeld is om aan een aantal van de beperkingen van bestaande indicatoren tegemoet te komen. De voornaamste doelstelling van de Extended Delta-V indicator is om niet enkel de nabijheid tot een ongeval (in termen van tijd en ruimte) in rekening te brengen, maar ook de potentiële ernst van de gevolgen indien een ongeval had plaatsgevonden. Hoewel dit een veelbelovende eerste stap is, is verder onderzoek nodig om de indicator verder te ontwikkelen en te valideren.

Drie case studies werden uitgevoerd die verder onderzochten hoe locatiegebaseerde observaties van het gedrag en interacties van weggebruikers surrogaatindicatoren kunnen aanvullen of zelfs vervangen, vooral wanneer ernstige situaties relatief weinig en/of ruimtelijk verspreid plaatsvinden. De case studies gaan over de volgende onderwerpen: 1) de veiligheid van fietsers op busbanen met medegebruik door fietsers, 2) gedragsaanpassingen van bestuurders veroorzaakt door windturbines langs de weg, en 3) verschillen in interacties tussen bestuurders op kruispunten met voorrang van rechts en voorrangskruispunten. Deze case studies bieden eveneens nieuwe verkeersveiligheidsinzichten in onderwerpen die tot op heden nauwelijks aan bod kwamen in wetenschappelijk onderzoek. De implicaties voor beleid en ontwerp worden besproken.

De studies die werden uitgevoerd in het kader van dit proefschrift hebben geleid tot een diepgaander inzicht in de huidige toepassingen en de toekomstige uitdagingen en opportuniteiten van locatiegebaseerde studies die gebruik maken van surrogaat- en gedragsindicatoren. Er wordt geconcludeerd dat dergelijke studies in het bijzonder kunnen bijdragen aan de verkeersveiligheid wanneer verkeersongevallendata, omwille van verschillende redenen, onvoldoende inzicht kunnen bieden in een specifiek onderwerp of met betrekking tot een maatregel.

Bij het selecteren van gedragsindicatoren om de verkeersveiligheid te beoordelen bepaalt de keuze van de specifieke gedragsindicatoren sterk in welke mate hieruit conclusies over verkeersveiligheid kunnen getrokken worden aangezien gedragsindicatoren een nog indirectere indicator van verkeersveiligheid zijn dan surrogaatindicatoren. Uit de case studies blijkt dat een sterkere nadruk op surrogaatindicatoren nog steeds leidt tot sterkere conclusies met betrekking tot de verwachte veiligheidseffecten. Maar over het algemeen lijkt het er op dat observaties van gedragsindicatoren, wanneer deze goed geselecteerd en gemeten worden, een indicatie kunnen geven van de verwachte richting van het effect op verkeersveiligheid in verkennende studies.

## Sammanfattning

Transportsystemet spelar en viktig roll i vårt samhälle. Olyckor är dock ett stort problem. Det finns ett stort behov av förbättringar av trafiksäkerheten. Traditionellt sett, så har trafiksäkerheten oftast studerats genom analyser av olycksdata, som dock är mottagliga för vissa betydande begränsningar. Till följd av detta kan trafiksäkerheten dra fördel av analysmetoder som utnyttjar observerbara data ifrån händelser i trafiken som inte nödvändigtvis resulterar i en olycka.

Därför undersöker denna avhandling säkerhetsåtgärder och beteendeindikatorer som uppsamlas genom platsbaserade observationer. Indirekta säkerhetsindikatorer (eller surrogatmått) definieras som mätningar som används för att beskriva förhållandet mellan två trafikanter i en trafikhändelse för att kvantifiera sannolikheten för en olycka och/eller kvantifiera konsekvensen av en potentiell olycka. Huvudmålet med denna avhandling är att bidra till att fylla metodologiska kunskapsbrister i platsbaserade observationer av säkerhetsåtgärder för vägar och trafikanters beteende och att undersöka hur sådana observationer kan undersöka trafiksäkerhetsfrågor för vilka olycksdata tycks vara mindre lämpliga.

En litteraturstudie har på ett omfattande och kvantitativt sätt undersökt hur indirekta säkerhetsindikatorer har tillämpats i vetenskaplig litteratur och vad deras huvudbegränsningar är. Viktiga metodologiska utmaningar på området för hur indirekta säkerhetsindikatorer kvarstår, inklusive behovet av ytterligare validering och ett bättre införlivande av konsekvensen av en potentiell olycka. Dessutom verkar det som om fältet saknar enhetliga metoder och ett allmänt accepterat ramverk för bästa praxis som kan bidra till att förbättra kvaliteten på framtida studier som använder sig hur indirekta säkerhetsindikatorer. Litteraturstudien i denna avhandling kan vara en användbar utgångspunkt för att utveckla en sådan ram genom att ge en inventering av hur indirekta säkerhetsindikatorer har tillämpats hittills. Det framgår också att observationer av indirekta säkerhetsindikatorer kan dra nytta av att kompletteras med beteendeobservationer och/eller data från andra områden som simulerade trafik studier.

Avhandlingen presenterar också ett teoretiskt ramverk och ett första genomförande av en ny indirekt säkerhetsindikator, Extended Delta-V, som syftar till att övervinna några av begränsningarna i befintliga indirekta säkerhetsindikatorer. Viktigast är att Extended Delta-V-indikatorn syftar inte bara till att återspegla närheten av en trafikinteraktion till en olycka (i form av tid eller rum), men även den potentiella konsekvensen, i form av allvarlighetsgrad om en olycka hade ägt rum. Även om detta är ett lovande första steg krävs ytterligare forskning för vidareutveckling och validering av indikatorn.

Tre fallstudier har gjorts som syftar till att ytterligare undersöka hur platsbaserade observationer av trafikanters beteende och interaktioner skulle kunna komplettera eller till och med ersätta indirekta säkerhetsindikatorer, särskilt när allvarliga händelser är sällsynta. Fallstudierna avser: 1) Säkerheten hos cyklister på bussbanor som delas med cyklister, 2) förarens beteendemässiga anpassningar orsakade av vindkraftverk vid sidan av vägen, och 3) skillnaden mellan förarens

interaktioner i korsningar med högerregeln respektive väjningsplikt. Fallstudierna ger några säkerhetsrelaterade insikter om ämnen som sällan har behandlats i vetenskaplig litteratur tidigare. Policy- och designimplikationer diskuteras.

De studier som utförs inom ramen för denna avhandling har lett till en djupare inblick i nuvarande praxis samt framtida utmaningar och möjligheter inom platsbaserade observationsstudier av indirekta säkerhetsindikatorer och beteendeindikatorer. Slutsatsen är att sådana studier kan vara särskilt fördelaktiga för trafiksäkerhetspolitiken när olycksdata av olika anledningar inte kan ge tillräcklig insikt i ett specifikt ämne eller en åtgärd.

Vid val av beteendeindikatorer för att bedöma trafiksäkerheten definierar urvalet av de specifika beteendeindikatorerna i stor utsträckning omfattningen av vilka slutsatser som kan nås kring trafiksäkerheten, eftersom de är en ännu mer sekundär indikator för trafiksäkerheten än mer traditionella indirekta säkerhetsindikatorer. Från de genomförda fallstudierna framgår det att en starkare tonvikt på indirekta säkerhetsindikatorer fortfarande leder till starkare bevis på de förväntade säkerhetseffekterna. Men i allmänhet verkar det som om observationer av beteendeindikatorer, när de är väl valda och uppmätta, skulle kunna ge en indikation på effektriktningen på säkerheten i utforskande studier.

# Table of contents

Acknowledgement.....	I
Summary .....	V
Samenvatting.....	VII
Sammanfattning .....	IX
Table of contents .....	XI
List of figures .....	XV
List of tables .....	XVI
Glossary of terms .....	XVII
List of abbreviations.....	XXI
Chapter 1. Introduction.....	1
1.1 The problem of road safety and crashes .....	1
1.2 The use of non-crash events in traffic to study road safety .....	3
1.3 Methods of data collection in surrogate safety studies.....	5
1.4 Justification and research questions of this dissertation.....	7
1.5 Dissertation outline .....	9
Chapter 2. Scoping review on the use of surrogate safety measures and behavioural indicators in site-based observations of road traffic.....	11
2.1 Introduction .....	11
2.2 Background .....	13
2.2.1 How to express the “severity” of a traffic event? .....	13
2.2.2 Validity.....	13
2.2.3 Reliability.....	15
2.2.4 Framing within existing literature.....	16
2.3 Methodology.....	17
2.3.1 Methodology of the review of surrogate safety measures .....	17
2.3.2 Methodology of the review of behavioural observation studies .....	20
2.4 Results of scoping review on surrogate safety measures .....	20
2.4.1 Overview of the literature over the years .....	21
2.4.2 Study focus.....	22
2.4.3 Surrogate safety indicators .....	23
2.4.4 Traffic conflict techniques .....	29
2.4.5 Study design .....	31
2.4.6 Data analysis .....	34
2.5 Results of scoping review on behavioural observations.....	36

2.6	Discussion .....	39
2.6.1	Validity of applied surrogate safety measures .....	39
2.6.2	Safety continuum and continuous indicators .....	41
2.6.3	Outcome severity in case of a crash .....	42
2.6.4	Strengths and limitations of this literature review .....	43
2.7	Conclusions .....	44
Chapter 3. In search of the severity dimension of traffic events: Extended Delta-V as a surrogate safety indicator .....		45
3.1	Introduction .....	45
3.2	Extended Delta-V as a measure of the severity of a traffic event .....	46
3.2.1	How to measure nearness-to-crash .....	46
3.2.2	How to measure consequences in the event a crash would have taken place? .....	48
3.2.3	Extended Delta-V – an attempt to weigh nearness and potential outcome severity .....	51
3.3	The dataset used to illustrate the concept .....	52
3.4	Results .....	53
3.5	Discussion .....	60
3.5.1	Strengths and applications .....	60
3.5.2	Challenges and future research .....	61
3.6	Conclusions .....	63
Chapter 4. Sharing is (s)caring? Interactions between buses and bicyclists on bus lanes shared with bicyclists .....		65
4.1	Introduction .....	65
4.2	Background .....	65
4.2.1	Bus lane safety and bus–bicycle crashes .....	65
4.2.2	Subjective safety of bus–bicycle interactions .....	66
4.2.3	Overtaking of bicyclists .....	66
4.2.4	Other influences that affect the overtaking distance .....	68
4.2.5	Official roadway design guidelines for bus lanes shared with bicyclists .....	68
4.3	Research questions .....	69
4.4	Methodology .....	70
4.4.1	Study locations .....	70
4.4.2	Video data collection and analysis .....	70
4.4.3	Collected variables about behaviour .....	72
4.4.4	Indicators to describe closeness of interactions .....	73

4.5	Results .....	73
4.5.1	Behavioural aspects of bus–bicycle interactions .....	74
4.5.2	Occurrence of close interactions .....	78
4.6	Discussion .....	81
4.6.1	Discussion of behavioural aspects and occurring close interactions .....	81
4.6.2	Strengths, limitations and further research .....	84
4.7	Conclusions .....	86
Chapter 5.	The effect of wind turbines alongside motorways on drivers' behaviour .....	87
5.1	Introduction .....	87
5.2	Background .....	88
5.2.1	The impact of roadside objects on drivers' behaviour.....	88
5.2.2	The impact of wind turbines near roads on passing drivers.....	89
5.3	Methodology.....	90
5.3.1	Research location .....	90
5.3.2	Analysis of drivers' speed.....	92
5.3.3	Analysis of observed lane position.....	93
5.3.4	Analysis of traffic conflicts.....	96
5.4	Results .....	96
5.4.1	Analyses of drivers' speed.....	96
5.4.2	Analyses of observed lateral position.....	98
5.4.3	Analyses of traffic conflicts.....	99
5.5	Discussion.....	100
5.5.1	Impact on driving speed .....	100
5.5.2	Impact on lateral position .....	101
5.5.3	Impact on traffic conflicts .....	102
5.5.4	Strengths, limitations and further research .....	103
5.5.5	Policy recommendations .....	104
5.6	Conclusions .....	104
Chapter 6.	Road Safety Differences Between Priority-Controlled Intersections and Right-Hand Priority Intersections: a Behavioural Analysis of Vehicle-Vehicle Interactions .....	105
6.1	Introduction .....	105
6.2	Background .....	106
6.2.1	Overall traffic safety at priority-controlled and right-hand priority intersections.....	106
6.2.2	Road user behaviour .....	106

6.2.3	Influence of driver age and gender .....	108
6.2.4	Status .....	109
6.3	Methodology.....	109
6.3.1	Study design .....	109
6.3.2	Ensuring and assessing the reliability of the data collection .....	110
6.3.3	Analysis of the collected behavioural data .....	111
6.4	Results and discussion .....	111
6.4.1	Intercoder reliability .....	111
6.4.2	Descriptive statistics .....	112
6.4.3	Priority violations models.....	115
6.4.4	Looking behaviour models .....	118
6.5	Study limitations and further research .....	120
6.6	Conclusions .....	121
Chapter 7.	Final discussion and conclusions.....	123
7.1	RQ1: How are surrogate safety measures applied in scientific literature, and how can measures be improved/defined to mitigate current limitations? ....	123
7.2	RQ2: How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed? .....	126
7.3	There is more than meets the eye – combining multiple techniques of road safety research.....	128
7.4	Conclusions and implications for research and practice .....	130
	List of references .....	131
	Attachment: Curriculum Vitae .....	149

## List of figures

Figure 1 – The ‘safety pyramid’ (adopted from Laureshyn (2010), based on Hydén (1987)).	3
Figure 2 – Visualisation of dissertation outline.	9
Figure 3 – Flow chart of scoping review surrogate safety measures.	19
Figure 4 – Number of studies using surrogate safety measures over the years.	21
Figure 5 – Study focus of surrogate safety studies.	23
Figure 6 – Frequency of use of surrogate safety indicators.	24
Figure 7 – $TTC_{min}$ threshold values.	26
Figure 8 – PET threshold values.	28
Figure 9 – Frequency of use of different traffic conflict techniques.	30
Figure 10 – Number of observed locations.	32
Figure 11 – Duration of observations.	32
Figure 12 – Type of location(s) observed.	33
Figure 13 – Types of road users involved.	33
Figure 14 – Data collection methods.	34
Figure 15 – Additional data collected in surrogate safety studies.	35
Figure 16 – Applied data analysis methods.	35
Figure 17 – Behavioural observation data collection methods.	36
Figure 18 – Applied behavioural indicators.	37
Figure 19 – Applied study designs in behavioural observation studies.	38
Figure 20 – Other methodologies that are combined with behavioural observations.	39
Figure 21 – Simplified illustration of the $T_2$ concept. Detailed calculations that take into account the dimensions of the road users can be found in Laureshyn et al. (2010).	47
Figure 22 – Illustration of relationship between Delta-V and probability of a severe injury (Gabauer & Gabler, 2006).	49
Figure 23 – Calculation of Delta-V based on momentum conservation principle (inelastic crash, i.e. two objects “stick together” after the first contact).	50
Figure 24 – Conceptual illustration of the main dimensions of conflict severity.	51
Figure 25 – Screenshot T-Analyst (only one camera view shown).	53
Figure 26 – Frequency of events by severity.	54
Figure 27 – Delta- $V_0$ values: a) histogram; b) scatterplot against $T_2^{min}$ .	55
Figure 28 – Extended Delta- $V_4$ values: a) histogram; b) marked on Delta- $V_0$ scatterplot.	56
Figure 29 – Extended Delta- $V_8$ values: a) histogram; b) marked on Delta- $V_0$ scatterplot.	57
Figure 30 – Observation sites: Kortrijk (left) (3.1 m wide – in line with guidelines) and Ghent (right) (4.2 m wide – not in line with guidelines).	70
Figure 31 – Lateral position of the bicyclists on the wider bus lane at each measurement point for the three conditions.	77
Figure 32 – Distribution of $TTC_{min}$ -values (left: narrower bus lane; right: wider bus lane).	79
Figure 33 – Overtaking proximity on both bus lanes.	80
Figure 34 – Distribution of observed time gaps of interactions without overtaking (left: narrower bus lane; right: wider bus lane).	81
Figure 35 – Research location. Positions of wind turbines, temporary cameras and loop detectors (study sites only) are indicated (image adopted from Google Earth).	91

Figure 36 – Research location. Street view near camera 1 after construction of wind turbines (image adopted from Google Street View).....	91
Figure 37 – View of the project site with wind turbines in perpendicular condition (top) and parallel condition (bottom).....	94

## List of tables

Table 1 – Search terms used for searching the online databases.....	18
Table 2 – Descriptive statistics of the dataset. ....	54
Table 3 – Comparison ranking of the 20 most severe Extended Delta-V8 situations. ....	59
Table 4 – Characteristics of both analysed bus lanes. ....	71
Table 5 – Number of observed situations. ....	74
Table 6 – Analysis of bicyclists’ lateral position and speed.....	76
Table 7 – SDLP of bicyclists.....	78
Table 8 – Overtaking speed of buses. ....	78
Table 9 – Differences in mean speed and SDDS between the before and after period. ....	97
Table 10 – Regression model lateral position. ....	99
Table 11 – Regression model standard deviation of lateral position. ....	100
Table 12 – Descriptive statistics.....	113
Table 13 – Factors influencing the probability of a right-of-way violation. ....	117
Table 14 – Factors influencing the likelihood that a driver looks to the sides on approach to the intersection.....	119

## Glossary of terms

Behavioural indicator	Objectified aspect of the behaviour of road users, aimed at drawing inferences on road safety
Collision course	A situation where the road users will collide if they continue with unchanged speeds and paths
Collision point	Location of the first physical contact (projected on a road plane) when two road users collide
Continuous (surrogate safety) indicator	A surrogate safety indicator that describes a traffic event as a time series of values
Crash	Refers to a traffic event in which two or more moving road users, or a moving road user and a static object, collide with one another as the direct result of transportation activity. Synonyms: accident; collision
Delta-V	An object's change of velocity, in the context of this dissertation as a result of an impact with another object
Driving simulator	A research tool in which participants are seated in a mock-up of a vehicle and navigate through a virtual road environment projected on a screen
Evasive action	A discontinuity in the driving (or cycling or walking) process that follows the occurrence of an unexpected or surprising event in traffic, and that is aimed at avoiding a crash
Extended Delta-V	A surrogate safety indicator, weighing closeness to a crash and severity of possible consequences
Interaction	A situation in which two road users arrive at a location with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other. Synonym: encounter
Intercoder reliability	The extent to which independent coders who evaluate a characteristic reach the same conclusion
Microsimulation model	A computerized analytic tool that simulates the behaviour of individual road users when they move through a predefined road network
Naturalistic driving	A research method in which road users drive instrumented vehicles that collect data about road users' behaviour and occurring traffic conflicts and sometimes even crashes in a natural road environment
Priority-controlled intersection	A type of intersection priority regulation where drivers on the subordinate (or secondary) road are required to yield to drivers driving on the main road. The priority is indicated by road signs and/or markings

Process validity	Describes to what extent the surrogate safety measure reflect or reveal the causational chains and crash factors that are linked to crash frequency and/or severity
Product validity	A form of validity that describes how well a surrogate safety measure is able to estimate the expected number of crashes
Relative validity	A form of validity that indicates the direction (and possibly order of magnitude) of effect
Reliability	The property of a surrogate safety measure to be measured accurately and consistently
Right-hand priority intersection	Lowest level of intersection priority regulation where each driver needs to yield to another driver coming from their right-hand side
Road safety	The absence of unintended harm to living creatures or inanimate objects in the traffic system. Synonym: traffic safety
Scoping review	A type of literature review technique that applies a systematic and transparent protocol for identifying relevant literature. The general aim is to rapidly map key concepts underpinning a research area and the main sources and types of evidence available
Severity of a traffic event	An operational parameter describing the “closeness” of a traffic event to a crash. Ideally, event severity should reflect both the risk of a crash and the severity of the possible consequences should a crash have taken place
Severity hierarchy	Distribution of elementary events in traffic rated according to some operational severity measure
Site-based observations	Observations that take place at one or more static observation sites
Standard deviation of driving speed	An index of the turbulence in a traffic flow in terms of the heterogeneity in driving speed of different passing road users
Standard deviation of lateral position	An index of “weaving” of a vehicle, derived from multiple consecutive measurements of the lateral position on the roadway of a vehicle
Surrogate safety indicator	A subcategory of surrogate safety measures; a measurement of the severity of a traffic event that makes use of one particular measurement or numeric

Surrogate safety measures	<p>Measurements that are used to describe the relationship between two road users in a traffic event for the purpose of quantifying the crash probability and/or crash severity in a meaningful way. It should be emphasized that the term 'surrogate safety measures' should <i>not</i> be confused with <i>actions or interventions</i> to increase road safety.</p> <p>The term includes both surrogate safety indicators and traffic conflict techniques. Unless otherwise indicated, the term will in this dissertation solely refer to surrogate safety measures collected through site-based observations, hence excluding surrogate safety measures collected through for instance micro-simulation or naturalistic driving.</p>
T <sub>2</sub>	A surrogate safety indicator describing the time for the second road user to arrive at the collision point
Threshold value	A boundary value to distinguish between different levels of severity of a traffic event (usually to distinguish "severe" from "non-severe" events in traffic)
Time Gap	A surrogate indicator that expresses the distance between two consecutive vehicles in terms of time units
Traffic conflict	An observable situation in which two or more road users approach each other in space and time to such an extent that a crash is imminent if their movements remain unchanged
Traffic conflict technique	A subcategory of surrogate safety measures; refers to a broader established framework of practice to assess and classify events in traffic, including methods of observation, instructions for how to use the technique as well as one or more indicators to distinguish severe events (serious conflicts) from non-severe events
Trajectory	A path of a road user on the road plane; in a video analysis system a trajectory is represented as a sequence of positions measured with high frequency
Time-to-Accident	The time remaining from the first evasive action taken by one of the road users up to the collision that might have taken place had they continued with unchanged speeds and paths
Time-to-Collision	In collision-course situations it describes at each instant the time required for two road users to crash if they continue at their present speeds and on the same paths
Validity	Validity refers to whether an indicator describes the quality that it is intended to represent (in this case: road safety) and to what extent

Vision Zero	A road safety policy, setting the long-term goal that nobody should be killed or seriously injured in the transport system
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## List of abbreviations

ANOVA	Analysis of variance
CI	Confidence interval
DOCTOR	Dutch Objective Conflict Technique for Operation and Research
HGV	Heavy goods vehicle
MANOVA	Multivariate analysis of variance
mv	Motor vehicle
PCE	Passenger car equivalent
prim	Primary
PET	Post Encroachment Time
rpm	Rotations per minute
RTOR	Right turn on red
SDDS	Standard deviation of driving speed
SDLP	Standard deviation of lane position
S.E.	Standard error
sec	Secondary
SRLC	Speed and red light camera
SSAM	Surrogate Safety Assessment Model
STCT	Swedish traffic conflict technique
TAdv	Time Advantage
TCT	Traffic conflict technique
TTC	Time-to-Collision
TA	Time-to-Accident
VNP	No-priority vehicle
VP	In-priority vehicle
VRU	Vulnerable road user



# Chapter 1. Introduction

## 1.1 The problem of road safety and crashes

The transport system plays an important role in our society. Travelling allows people to perform their day-to-day activities that take place at different physical locations. As a result, the true value of transportation is usually not in the trip itself, but rather in the activities that it makes possible. In economic terms, transportation is therefore seen as a derived demand (Button, 2010).

The transport system is, however, not without its flaws. An important issue regarding the transport system is its safety performance. Each year, around 1.25 million people are killed on the world's roads. Traffic fatalities are one of the leading causes of death around the world, and even the main cause of death among those aged 15-29 years. Many more get severely injured in traffic, resulting in long rehabilitation periods and sometimes permanent disabilities. Crashes are not only a major cause of grief to those who are involved in the crash and their families and friends, but crashes also constitute an important economic loss of approximately 3% of the Gross Domestic Product (World Health Organization, 2015).

Belgium has a road fatality rate of 64 deaths per million inhabitants, which is substantially worse than the EU average of 51 deaths per million inhabitants. Sweden, on the other hand is among the best performing countries with a road fatality rate of 'only' 29 deaths per million inhabitants. Still, this constitutes a significant societal problem. Moreover, Sweden is one of the few European countries where the number of road fatalities per million inhabitants has not decreased anymore in the period 2010-2014 (European Commission, 2015).

The EU has the ambition to reduce the number of road fatalities by 50% in the period 2010-2020 (European Commission, 2015). One of the strategic goals set by the Mobility Plan Flanders (the Dutch-speaking northern region of Belgium) has set the ambitious target of reducing the number of road fatalities to 133 in 2030 and to zero in 2050 (Flemish Government, 2013). Sweden has adopted Vision Zero since 1997, which states that "the long-term goal for Swedish road safety policy is that nobody should be killed or seriously injured in the transport system" (Johansson, 2009). In order to meet these ambitious targets, increased efforts to further improve road safety are highly needed.

A justification of investments in road safety is, however, needed since it is a field in which large investments could potentially bring little or no results, and on rare occasions may even lead to negative effects (Hasson et al., 2012). As a result, there is a strong need for evidence-based road safety policy making and a systematic evaluation of measures that are taken in order to ensure that implemented measures and policies are indeed contributing to the goal of reducing the number of severe crashes. Alternatively, if measures or policies are taken with an aim other than improving road safety, it should be ensured that at least they will not lead to negative effects on road safety. The stronger road safety policies

are science-based, the more efficient they are in reducing severe crashes and casualties (Schulze & Koßmann, 2010).

Because of the enormous losses to society that are caused by crashes, and the need for implementing evidence-based road safety policies and measures to reduce the number of crashes, researchers continuously aim to gain a deeper understanding of factors that affect the occurrence and severity of crashes (Lord & Mannering, 2010). While road safety is generally defined as “the absence of unintended harm to living creatures or inanimate objects” (Evans, 2004, p. 6), it is, somewhat ironically, usually measured and analysed by its opposite, i.e. the occurrence of crashes. Most studies on road safety have relied on crash data to address a range of safety concerns, such as the identification of hazardous locations, the analysis of patterns of occurring crashes to infer their contributing factors, and the evaluation of the effectiveness of road safety programs and interventions (Chin & Quek, 1997).

The use of crash data to analyse road safety does, however, have a number of well-known important limitations:

- Compared to other events in traffic, crashes are (fortunately) quite rare events. Therefore, crash data are characterised by the chance effects that are inherent to small numbers (Hauer, 1997). As a consequence, it is often difficult to draw solid conclusions from safety analyses, especially at individual locations.
- Not all crashes are reported and included in official crash databases. Moreover, the level of underreporting is not constant and depends among other things on the severity of the crash and the type of road users involved (Alsop & Langley, 2001; Amorós et al., 2006; De Ceunynck et al., 2015b; Elvik & Mysen, 1999; Hauer & Hakkert, 1988).
- Crashes are complex events in the sense that most crashes are in fact caused by an accumulation of multiple factors and failures (Reason et al., 2006). In crash databases, however, information about the behavioural and situational aspects preceding the crash is usually quite limited (Svensson & Hydén, 2006). This limits the possibilities for drawing inferences about the complex chains of events leading to the crashes and how they can be prevented in the future (Davis, 2004; Elvik, 2007; Hauer, 2010; Tarko, 2012).
- The use of crash data to investigate road safety is a reactive approach. This raises the ethical issue that one has to wait until a sufficient number of crashes has occurred before hazardous sites or situations can be identified and corrected (Chin & Quek, 1997; Lareshyn, 2010; Lord & Persaud, 2004). The use of more proactive approaches is therefore preferable.
- The number of crashes continues to reduce, while the quality of the crash data does not seem to improve substantially over the years, which makes the abovementioned limitations a continuously growing concern (Lareshyn et al., 2017b).

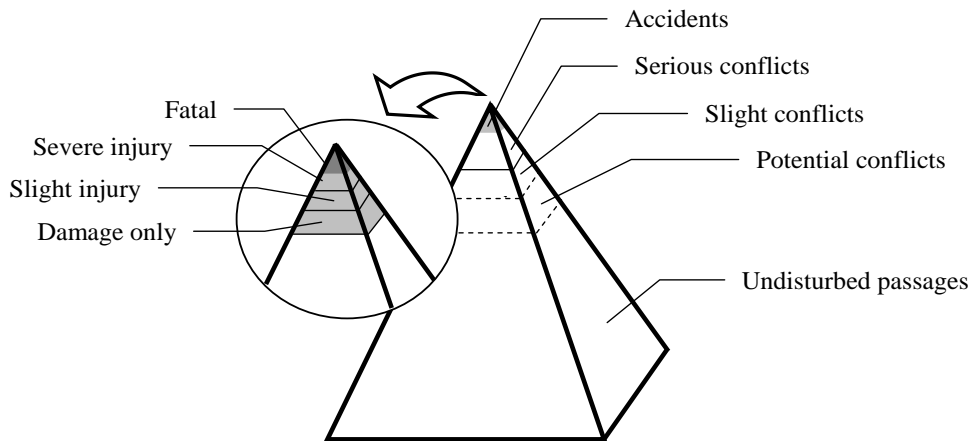
According to Ogden (1996), these limitations might partly explain why many concepts in road safety are still relatively weakly supported by thorough evaluation research, and why progress in the domain has often appeared to be

made by trial and error rather than through the principles of thorough evidence-based research.

## 1.2 The use of non-crash events in traffic to study road safety

Because of the limitations of crash data, road safety analysis can strongly benefit from reliable analysis methods that utilize observable non-crash traffic events (Laureshyn et al., 2010; Tarko et al., 2009). The basic theory behind the use of non-crash events to study road safety is the assumption that a relation exists between the severity and the frequency of different events in traffic (Svensson & Hydén, 2006). If there is a sufficient understanding of the relations between these types of events, one can study road safety by analysing the non-crash events to complement or even replace analyses of crash data.

This relation between the severity and frequency of traffic events is often visualized in the form of a pyramid (Hydén, 1987), as shown in Figure 1. The top of the pyramid represents crashes, which are the most severe but also the most rare events in traffic. This implies that, traditionally, road safety is studied using only a tiny fraction of the traffic events that take place. Immediately below the crashes in the pyramid come traffic conflicts. These can be further classified as serious, slight or potential conflicts according to their severity. Below the conflicts come the majority of events that characterise the normal traffic process (Laureshyn, 2010).



*Figure 1 – The 'safety pyramid' (adopted from Laureshyn (2010), based on Hydén (1987)).*

Each encounter between two road users has some potential to end up in a crash. Each crash can be explained by a number of factors that led to it (including road and vehicle conditions, drivers' emotional and physical state, the traffic situation, etc.) (Reason et al., 2006). The crash is therefore to some extent a stochastic event, since in case not all these factors happened to be present at the same time, the crash might not have taken place. Put in a different way, however, this also implies that each successful interaction between two road users might have led to a crash if a number of factors had been different. However, a near-miss has less

of a safety margin to endure additional unfavourable factors than a well-controlled passage; the severity of a near-miss is therefore higher than that of a well-controlled passage (Laureshyn, 2010).

The model therefore suggests that all elementary events in traffic have a common severity dimension that can, in general terms, be defined as their closeness to a crash and the severity of its consequences (Laureshyn, 2010). Over the years, this severity dimension of traffic events has been operationalized and measured in a great variety of ways. The term 'surrogate safety measures' is used in this dissertation to refer to such measurements that are used to describe the relationship between two road users in a traffic event for the purpose of quantifying the crash probability and/or crash severity in some meaningful way (St-Aubin, 2016). It should be emphasized that the term 'surrogate safety measures' should *not* be confused with *actions or interventions* to increase road safety.

By expressing the severity of traffic events in a meaningful quantified way, all encounters between road users can be arranged in some distribution as a function of their severity (Laureshyn, 2010). Such distributions are called 'severity hierarchies' by Svensson (1998). It should be mentioned that the way that the concept of 'severity' is defined will strongly affect the shape of the hierarchy (Svensson, 1998). For example, Svensson & Hydén (2006) show that in some operationalisations of the severity hierarchy, a diamond shape can be more appropriate than a pyramid shape. Additionally, there is evidence that the shape of the distribution may vary depending on factors such as regulatory form, road design, frequency of interactions, type of manoeuvre and involved road users, etc. (Svensson, 1998). The 'safety pyramid' that has been presented should therefore merely be seen as an illustration of the associations between events of different severity in traffic.

Most often, critical events that are severe but in which a crash was narrowly avoided (serious traffic conflicts) are used as surrogate safety measures (Tarko et al., 2009). Evidence suggests that these events are so close to the real crashes that the process of their development is highly similar and can therefore be used to understand how crashes develop; it is stated that conflicts and crashes belong to the same process, just with a different degree of outcome severity (Hydén, 1987). On a severity scale, or safety continuum, crashes therefore represent a logical continuation of serious conflicts. Some research findings suggest that even normal traffic events contain information that can be applied to make road safety assessments (Saunier & Sayed, 2007; Songchitruksa & Tarko, 2006; Svensson, 1998).

While surrogate safety measures aim to quantify the dangerousness of traffic events in a meaningful way, the observation of behavioural aspects of non-crash events can, in itself, contain a lot of useful information to investigate underlying processes of road safety as well (van Haperen, 2016). Behavioural observations can stand on their own as a road safety study method, or they can be combined with other research methods such as surrogate safety measures.

It should be mentioned that the usefulness of analysing more common yet less severe events in road traffic as a surrogate for the most severe but rare events is

not a unique approach. In fact, it is a long standing practice in very safe transport systems such as aviation (Kontogiannis & Malakis, 2009), maritime transport (Zhang et al., 2015), metro (Zhang et al., 2016) and railway (Elvik & Voll, 2014). In such transport systems, the previously mentioned issues play an even stronger role, since there are even fewer or no serious crashes in a country within a year. Surrogate safety measures are also applied in safety studies and monitoring in other fields, including for example medical science (Kessels-Habraken et al., 2010) and offshore oil platforms (Skogdalen et al., 2011).

### 1.3 Methods of data collection in surrogate safety studies

Multiple methodologies have been proposed and applied in scientific literature to collect surrogate safety measures and information about road users' behaviour. These include:

- Microsimulation modelling studies
- Driving simulator studies
- Naturalistic driving studies
- Site-based observation studies

The former two methodologies can be considered as a controlled form of data collection in which researchers have the ability to manipulate and control traffic events, while the latter two reflect road users' behaviour in a real road environment (van Haperen, 2016).

Microsimulation models are computerized analytic tools that simulate the behaviour of individual road users when they move through a predefined virtual road network (Archer, 2005). Each unit of the model is treated as an individual entity whose behaviour and interaction with other road users varies depending on stochastic parameters (Gettman & Head, 2003). These parameters are intended to represent individual preferences and tendencies, and aim at simulating a reasonable approximation of the real-world behaviour of road users in the modelled road network. While most of the microsimulation models are mainly used to study traffic flow characteristics, some of them contain a module for safety assessment. The Surrogate Safety Assessment Model (SSAM) is probably the best known tool to collect surrogate safety measures from microsimulation models. It is a post-processing module, compatible with multiple microsimulation packages, that can collect surrogate safety measures from the generated vehicle trajectories (Gettman et al., 2008). The main advantage of using microsimulation models is that they are a cheap and proactive tool to assess the safety of road infrastructure. An important limitation of most existing microsimulation models is that they deliberately prohibit vehicle crashes from occurring. Most existing microsimulation models by design target only normal driver behaviour in typical traffic conditions, which limits their usefulness for safety-related purposes (Xin et al., 2008). Another important limitation of the technique is the use of artificial data. There are limitations to the realism and level of detail of the simulated behaviour and infrastructure. Inevitably, some simplifications need to be made, even in the most advanced models. Therefore, it could be debated how valid the outcomes are as a representation of the real-world behaviour of road users.

In driving simulator studies, participants are seated in a mock-up of a vehicle interior and navigate through a virtual road environment projected on a screen. Low-level simulators have a fixed mock-up and use one or more computer screens

for scenario visualization, while high-level simulators are more advanced and use a moving base platform and virtual projection on large screens (e.g. 180° to 360°) (Fisher et al., 2011). The projected road environment can either be a virtually simulated road environment, or can partly or completely consist of real-life video footage (De Ceunynck et al., 2015a). Important advantages of driving simulator studies include the extremely high level of detail of the collected data, the fact that the experimenter is fully in control of the road infrastructure and situations the study participants encounter, the guaranteed safety of the participants and the proactive nature of the study method (Godley et al., 2002). An important issue is the extent to which behaviour in the simulated environment corresponds to the participants' actual driving behaviour in comparable real-life situations and environments (Fisher et al., 2011). Additionally, even in high-fidelity driving simulators, there are limits to the visual and tactile realism that can be offered (Bella, 2009). These are major drawbacks compared to field studies that make use of observed behaviour in the real world (De Ceunynck et al., 2015a).

Another type of surrogate safety studies makes use of instrumented vehicles to collect data about road users' behaviour and occurring traffic conflicts and sometimes even crashes. This way, the behaviour of road users is observed unobtrusively in a natural setting for a long period of time (Dingus et al., 2006). These studies are usually referred to as 'naturalistic driving studies' (alternatively, in the case of instrumented bicycles, motorcycles or mopeds, one could opt for the term 'naturalistic riding studies'). Due to the evolutions in data collection technologies, this type of data collection is a rather recent development in the domain of surrogate safety studies. An advantage of this type of study is the fact that the rich continuous real-world data provide a unique possibility to gain in-depth insights into the natural behaviour of drivers (van Nes et al., 2013). An important limitation of naturalistic driving studies is the usually very high set-up cost to equip the vehicles, and the difficulty of extracting and analysing the events of interest from the huge data warehouses (Zheng et al., 2014a). Another drawback is the possibility of selection bias because not all types of drivers are equally likely to participate in a study in which their driving behaviour is monitored in detail, and there is a risk of behavioural adaptations as a result of the drivers' awareness of being observed. Additionally, it provides a one-sided viewpoint of events, since an evasive action might be initiated by another road user, leaving the event undetected by the measuring devices. A related issue is that the available information about the 'other' road user involved in the event is much more limited.

In site-based observations, traffic is observed in a systematic way at one or more fixed study sites. This could be for example intersections, road sections or other observation points of interest. Data collection has traditionally been performed mostly by human observers, but has gradually been replaced by observations from video footage that can either be processed manually or with the help of (partly) automated video analysis systems. The aim is usually to collect surrogate safety measures or information about road users' behaviour (i.e., the lower levels of the safety hierarchy). For practical reasons, few site-based studies aim at observing actual crashes, exceptions being the studies by Pasanen (1993), van der Horst (2007b) and Saunier et al. (2011). The use of observed data has the advantage of providing very detailed information about behavioural and situational aspects that can help to gain a deeper insight into the causal

processes that lead to crashes. Furthermore, the data are generally collected in an unobtrusive way, limiting the risk of behavioural adaptation of the road users as a result of being observed. Another advantage is the more proactive nature of such studies, since one does not have to wait for a sufficient number of crashes to accumulate over a period of years before a safety assessment can be performed. The fact that the relationships between surrogate safety measures and road users' behaviour on the one hand and crashes on the other hand are still not fully understood is an important drawback of site-based observations. Additionally, data collection and analysis can be quite labour-intensive, although current advances in sensor techniques can to some extent mitigate this issue. Another disadvantage is that the area that can be covered by a single observation is fairly limited. As a result, the observation method is mostly suitable to observe events of interest that take place relatively concentrated in space. Events that take place more dispersed over the road network, such as single road user near-crashes and conflicts between road users travelling in the same direction (e.g. overtaking conflicts) are quite difficult to study.

## 1.4 Justification and research questions of this dissertation

An earlier project had been undertaken at the Transportation Research Institute of Hasselt University to experiment with the possibilities of surrogate safety measures (de Jong et al., 2007; Gysen et al., 2007). More specifically, traffic conflict data were collected by human observers by means of the Swedish Traffic Conflict Technique (STCT) in an exploratory study at two dangerous intersections in Belgium. The project confirmed the potential strengths of the study method, and mostly the improved insight into road users' behaviour was considered a major benefit to gain a deeper understanding into contributing factors of crashes. However, the time needed to collect the data and the challenge to assess the occurring situations sufficiently accurately initially hindered further implementation of the technique. However, by the start-up of this PhD project in 2010, significant advances in video processing techniques for detecting and analysing traffic events were being made that had the potential to partly overcome these barriers.

As indicated in the previous sections, there are a number of valid arguments favouring the use of surrogate safety measures as well as information about road users' behaviour. The interest and motivation for the work undertaken within the frame of this PhD project originated from the many emerging opportunities in this field to gain a deeper insight in road safety. Mostly because of a strong preference to make use of revealed road user behaviour in a real road environment, collected in an unobtrusive way, and for reasons of technical feasibility, it was decided to focus on site-based observations of surrogate safety measures and behavioural elements.

While site-based observations of surrogate safety measures and road users' behaviour offer major opportunities, a number of methodological challenges remain. The main goal of this dissertation is to contribute to filling methodological knowledge gaps in site-based observations of surrogate safety measures and road users' behaviour, and to investigate how such observations can be applied to study road safety issues for which crash data appear to be less suitable.

While it was found that numerous indicators and techniques have been applied over the years to quantitatively assess the severity of traffic events in site-based observations, a gap in scientific literature is that it is very difficult to gain an overview of which indicators and techniques have been applied, and how. It is often unclear what the main limitations of each indicator and technique are, and how these limitations could be addressed by altered or newly defined indicators and techniques.

As indicated in section 1.3, applying surrogate safety measures to study road safety may pose difficulties in case the expected number of severe non-crash events per time unit is low, unless very long observation periods would be applied (Laureshyn et al., 2017b). At least in theory, automation of the detection of serious events and automated measurement of surrogate safety indicators should allow for strongly extending observation periods, hence potentially overcoming this limitation. However, the currently operational automated video analysis tools are still relatively slow and not always sufficiently reliable, so very long observation periods are generally not feasible at present. As indicated, research questions that for instance relate to road sections where serious conflicts tend to occur quite dispersed pose difficulties. In such situations, it might be useful to supplement or even replace surrogate safety measures with systematic observations of road users' behaviour. A knowledge gap that remains is which behavioural elements can be analysed to address such topics, and how, in order to supplement or even replace surrogate safety measures to draw inferences on road safety.

Some behavioural aspects such as lateral position and following distances cannot reliably be estimated by human observers and should therefore be measured more precisely. If we want to supplement surrogate safety measures with some measurable behavioural aspects such as speed and distances, it would be useful to retrieve such data using the same video footage and the same video analysis tools that are used for surrogate safety measures to make maximum use of the data that are available. A knowledge gap that remains is how behavioural indicators can be defined and collected from video data.

Alternatively, in cases where severe non-crash events are expected to be too few to draw usable conclusions from, it would be useful to know whether the collection and analysis of video footage, which can be expensive, cumbersome and subject to some ethical and privacy limitations, could be skipped altogether, and systematic observations by human observers may suffice to assess road safety. To what extent behavioural data collected by human observers on-site can be used to draw inferences on road safety is a gap in current scientific literature.

The aims of this dissertation have been summarized in the following research questions:

- 1) How are surrogate safety measures applied in scientific literature, and how can measures be improved/defined to mitigate current limitations?
- 2) How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed?

## 1.5 Dissertation outline

The remainder of this dissertation includes five studies that emphasise on behavioural observations, surrogate safety measures, or a combination of both. The emphasis of the studies is visualised in Figure 2.

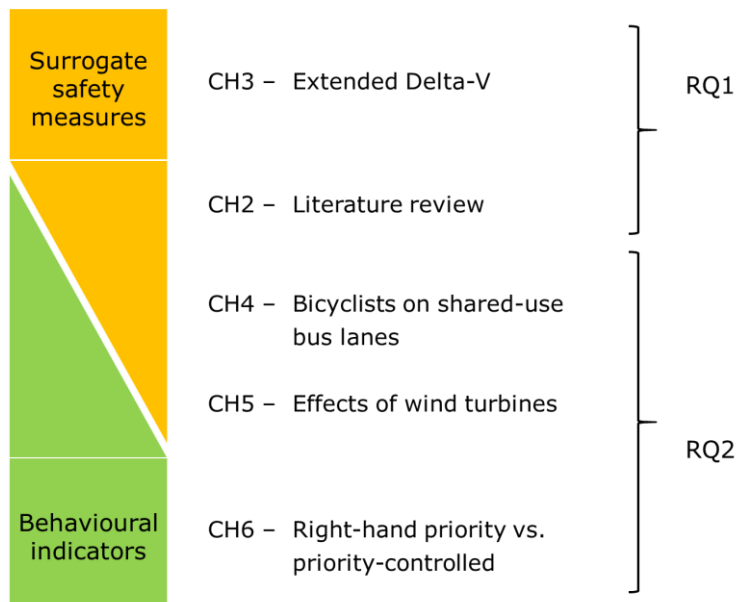


Figure 2 – Visualisation of dissertation outline.

In Chapter 2, a scoping review on surrogate safety measures in site-based observations is presented. This chapter will contribute to research question (1) by providing an extensive overview of how surrogate safety measures have been applied in scientific literature, and by identifying key challenges and opportunities in the field. The chapter also includes some relevant information from a scoping review about behavioural observations in road safety research by van Haperen (2016), which is a useful introduction to the use of behavioural indicators in some of the subsequent chapters.

In Chapter 3, the theoretical framework and first implementation of a new surrogate safety indicator, Extended Delta-V, are presented. This study contributes to research question (1) by developing an indicator that aims to address a number of limitations of existing indicators.

Chapters 4-6 relate to three case studies that apply observations of road users' behaviour and interactions and/or surrogate safety measures and will together address research question (2). At the same time, these case studies aim to address a number of policy-relevant road safety issues that have been scarcely researched to date. Chapter 4 uses a combination of surrogate safety measures and behavioural indicators to investigate the safety of bicyclists on bus lanes shared with bicyclists. Chapter 5 investigates the effects of wind turbines alongside

motorways on drivers. There is an emphasis on the use of behavioural indicators, although the study includes surrogate safety measures as well. This study partly replicates a driving simulator experiment, and will therefore also investigate how the results from both types of studies can supplement each other as well. Chapter 6 focuses on behavioural data collected by human observers to investigate road safety differences between right-hand priority intersections and priority-controlled intersections. A more elaborate justification of the chosen topics is included in the respective chapters.

The final chapter, Chapter 7, presents the general discussion and conclusions of this dissertation.

The content of the five studies in chapters 2-6 has been published or submitted for publication in five scientific journal articles:

- Chapter 2:  
De Ceunynck, T., Johnsson, C., Laureshyn, A., Svensson, Å., de Goede, M., van der Horst, R., Saunier, N., Włodarek, P., & Daniels, S. (in review). The use of surrogate safety measures in site-based observations of road traffic: a scoping review. *Submitted for publication to Accident Analysis & Prevention*.
- Chapter 3:  
Laureshyn, A., De Ceunynck, T., Karlsson, C., Svensson, Å., & Daniels, S. (2017a). In search of the severity dimension of traffic events: Extended Delta-V as a traffic conflict indicator. *Accident Analysis & Prevention*, 98, 46–56. <https://doi.org/10.1016/j.aap.2016.09.026>
- Chapter 4:  
De Ceunynck, T., Dorleman, B., Daniels, S., Laureshyn, A., Brijs, T., Hermans, E., & Wets, G. (2017b). Sharing is (s)caring? Interactions between buses and bicyclists on bus lanes shared with bicyclists. *Transportation Research Part F: Traffic Psychology and Behaviour*, 46, Part B, 301-315. <https://doi.org/10.1016/j.trf.2016.09.028>
- Chapter 5:  
De Ceunynck, T., De Pauw, E., Daniels, S., Polders, E., Brijs, T., Hermans, E., & Wets, G. (2017a). The effect of wind turbines alongside motorways on drivers' behaviour. *European Journal of Transport and Infrastructure Research*, 17(3), 477-494.
- Chapter 6:  
De Ceunynck, T., Polders, E., Daniels, S., Hermans, E., Brijs, T., & Wets, G. (2013b). Road Safety Differences Between Priority-Controlled Intersections and Right-Hand Priority Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2365, 39–48. <https://doi.org/10.3141/2365-06>

For a full list of my publications, the interested reader is referred to the CV in attachment.

## Chapter 2. Scoping review on the use of surrogate safety measures and behavioural indicators in site-based observations of road traffic

This chapter presents a literature review on the use of surrogate safety measures and behavioural indicators in site-based observations.

The emphasis in this chapter is on a scoping review about the use of surrogate safety measures in site-based observations. This review represents a joint research effort with important contributions from a number of researchers and is executed as part of the Horizon2020 project InDeV (In-Depth understanding of accident causation for Vulnerable road users) (InDeV, 2017). In this study, I set up the general study design, designed the code book, was one of the two coders of the retrieved publications, contributed to the quantitative analyses of the code book database and was the main person responsible for writing some sections of the report (such as the general sections about validity, the methodology section, the interpretation of the figures and the strengths and limitations) and contributed to many of the other parts as well. Parts of this chapter are submitted for publication to a peer-reviewed journal (De Ceunynck et al., in review). I had the primary responsibility in writing the paper.

In addition, some information in this chapter is adopted from a scoping review about behavioural observations that took place within the InDeV project as well (van Haperen, 2016). This information is considered to be a valuable introduction to the use of behavioural indicators in the next chapters, but a full overview of that study is beyond the scope of this dissertation. For more details, the interested reader is referred to the research report by van Haperen (2016).

This overview contributes to answering the first research question, “How are surrogate safety measures applied in scientific literature, and how can measures be improved/defined to mitigate current limitations?”.

### 2.1 Introduction

Surrogate safety measures are used to investigate traffic safety. The term “surrogate” describes that these measures do not rely on crash data and instead are meant to be an alternative or a complement to analyses based on crash records. “Traffic safety” is generally considered as “the absence of unintended harm to living creatures or inanimate objects” (Evans, 2004). Vision Zero set the highest priority in traffic safety work on reduction (and ultimately elimination) of the risk of fatal and serious injuries in the road transport system (Johansson, 2009).

Investigating traffic safety based on surrogate safety measures has advantages compared to crash-based analyses because it is more proactive (and thus more ethical as there is no need to wait for crashes to happen), and in some conditions more time-efficient, informative and even more accurate (Hydén, 1987; Svensson, 1992). Additionally, surrogate safety measures are less susceptible to some well-known issues related to crash data, such as underreporting of crashes

and lack of information regarding behavioural and situational aspects that may have contributed to the crash taking place (Laureshyn et al., 2010).

Surrogate safety measures have been applied for the first time half a century ago (Perkins & Harris, 1967), and their underlying theories and applications have evolved strongly over the years. Especially the last decade has been characterized by great improvements in sensor techniques and computer vision, that can be applied for the collection of traffic data in general and surrogate safety measures in particular (Laureshyn, 2010; Saunier et al., 2010; Tarko et al., 2017). This creates many new opportunities, but also poses new questions and challenges. There are still many unresolved issues when it comes to selection of the appropriate indicators, their validity, data collection and analysis procedures, etc.

After half a century of research towards and applying surrogate safety measures, it is time to make up a balance of the work that has been done over the years. The literature in the field of surrogate safety measures is vast and diverse, and recent evolutions seem to have raised a strongly increased interest in this field of road safety research. The amount and diversity of publications in the field, ranging from old but still relevant research reports that are not accessible in a digital format to very recent technical papers, makes it challenging for researchers new to the field to gain a clear overview of the scientific state-of-practice, while even for more experienced researchers there is a risk of losing track of the critical points of attention. The lack of a holistic overview seems to lead to “reinventing the wheel” and errors from the past being repeated.

The aim of this chapter is to provide the research community with a comprehensive overview of the state of practice in the field of surrogate safety measures. A scoping review is applied to systematically identify relevant literature, and the content of the publications is summarized by means of a structured code book. This chapter presents a quantitative summary of the available literature, including an overview of the surrogate safety indicators and traffic conflict techniques (TCTs) that are applied and the way data are collected and analysed. A number of critical challenges and opportunities that should be central in future research in the field are identified.

The study is limited to publications that make use of surrogate safety measures in line with its definition within this dissertation; i.e. measurements that are used to describe the relationship between two road users in a traffic event for the purpose of quantifying the crash probability and/or crash severity in a meaningful way. In other words, there must be some formalised assessment of the severity of the traffic event. Only studies that make use of site-based observations are included.

The observation of road users’ behavioural aspects in non-crash events can reveal useful information to investigate underlying processes of road safety as well. Behavioural observations can stand on their own as a road safety study method, or they can be combined with other research methods such as surrogate safety measures.

## 2.2 Background

The basic concept that surrogate safety measures are based on is that the traffic process can be seen as a number of elementary events. These events differ in their degree of severity (unsafety) and there exists some relation between the severity and frequency of events of that severity. For an elaborate description of this concept, I refer back to section 1.2.

This background section will first describe how the concept of “severity” of a traffic event should be expressed. Then, I would like to elaborate on two important features of surrogate safety measures: validity and reliability. Validity refers to whether an indicator describes the quality that it is intended to represent (in this case: road safety) and to what extent, while reliability refers to the methods used to measure the indicator and the accuracy of these measurements (Laureshyn, 2010). Finally, I will frame this review study in existing literature.

### 2.2.1 How to express the “severity” of a traffic event?

The concept of “severity” of an event also requires clarification. Most surrogate safety measures that have been developed over the last decades express the severity of an event as its proximity to a crash in terms of time or space (Zheng et al., 2014c). However, the proximity to a crash is only one dimension of “severity”. The potential consequences in case a crash had taken place is another dimension of “severity” that should be taken into account in some way as well (Laureshyn, 2010). Following the goals set by Vision Zero in road safety – “no one will be killed or seriously injured within the road transport system” (Johansson, 2009) – an appropriate definition for the severity can be “a nearness to a serious personal injury” (Laureshyn et al., 2017a). The potential consequences of an event are dependent on the type of road users involved and their vulnerability, speed, mass, type of crash, crash angle, etc. An attempt to combine the dimensions of nearness to a crash and potential consequences in case a crash had taken place into one indicator is presented in Chapter 3.

### 2.2.2 Validity

#### 2.2.2.1 The concept of validity

Validity is a crucial aspect of any study or measurement. Validity, in general, relates to the approximate truth of an inference, and it is informed by both correspondence and coherence conceptions of truth, as well as pragmatism (Shadish et al., 2002). It is important to note that validity is not a matter of ‘yes or no’, but it is a matter of degree (Carmines & Zeller, 1979). Therefore, validity is a concept designating an ideal state. This implies that validity is a concept that has to be ‘pursued’, but that cannot be completely ‘attained’ (Brinberg & McGrath, 1985). Whether a certain level of validity is considered ‘sufficient’ is therefore usually rather a matter of argumentation, debate and consent than a measurable aspect that should exceed a certain threshold. Validity has to be assessed relative to the purposes and circumstances (Brinberg & McGrath, 1985).

The validity of an indicator concerns the crucial relationship between concept and indicator. Validity relates to the use to which a specific measurement is put: does an indicator actually 'measure' the property that you want to measure (Carmines & Zeller, 1979)? Therefore, one validates not the measuring instrument itself, but rather the measuring instrument in relation to the purpose for which it is being used (Carmines & Zeller, 1979). Validity is evidenced by the degree that a particular indicator measures what it is supposed to measure rather than reflecting some other phenomenon that is not intended to be measured (Carmines & Zeller, 1979).

The main goal of applying surrogate safety measures is to measure traffic (un)safety. Therefore, the validity of an indicator means to what extent it describes (un)safety, which, from the perspective of Vision Zero, equals to expected serious injuries in traffic.

#### 2.2.2.2 Product validity

Product validity deals with how well a surrogate safety measure is able to estimate the expected number of crashes. Possibly the most fundamental definition about the validity of surrogate safety measures is the one proposed by Hauer & Gårder (1986). They argue that the performance of surrogate safety measures cannot and should not be judged by their success in predicting future crashes, because these are susceptible to random variation. Rather, the question is how well they can estimate the *expected* number of crashes. In this sense the surrogate safety measure should be compared to the performance of other methods, such as those that are based on crash data, and comparisons should be made between the variances of the estimates. Hauer & Gårder (1986) conclude that a technique for the estimation of safety is "valid" if it produces unbiased estimates, the variance of which is deemed to be satisfactory.

#### 2.2.2.3 Relative validity

In case a surrogate safety measure does not allow to produce unbiased estimates with a satisfactory variance, but allows to reliably indicate the direction (and possibly order of magnitude) of change, one could speak of 'relative validity'. If, as previously stated, validity is a matter of degree (Carmines & Zeller, 1979), then relative validity can be considered as a lower degree of validity than product validity.

#### 2.2.2.4 Process validity

Process validity indicates the extent to which safety indicators can be used for describing the process that leads to crashes (Svensson, 1998). Product (or relative) validity may allow to identify high-risk locations, to assess which road designs have a better safety performance than others, and which measures have a positive effect on the (expected) number of crashes that take place. But in themselves, however, relative nor product validity suffice to reveal causal chains underlying the crashes. In other words, such indicators cannot necessarily tell us *why* or *how* some locations perform better or worse than other locations.

The process is here understood as the chain of events preceding (and leading to) the crashes. To be able to reveal such causal chains, the factors linked to the frequency and/or severity of the measured non-crash events should be similar to those that are linked to crash frequency and/or severity. When these factors are highly similar, studying the causal factors that are linked to surrogate safety measures can be considered a valid alternative for analysing the causal factors that are linked to crashes.

### 2.2.3 Reliability

The concept of reliability refers to the accuracy and the consistency of measurements. In other words, the measured value very closely represents the 'true' value and the measurement error should remain within the same limits regardless of measurement locations, time of the day, traffic situation, etc., thus ensuring that measured differences reflect the actual difference in the studied phenomenon and not in the measurement's accuracy (Laureshyn, 2010).

From the perspective of surrogate safety measures, two main aspects should be considered:

- The accuracy of measurements for an individual traffic event (road users' position, speed, etc.) and the detection errors that are related to that.
- The observation time that is required to collect a sufficient number of individual events to be able to generalise their frequencies (e.g. estimate the "expected number of conflicts").

The original TCTs developed in 1970-80s relied heavily on human observer judgements both in the detection and the rating of safety-critical traffic events (Baguley, 1982; Hydén, 1987; Migletz et al., 1985; Muhlrad, 1982; van der Horst & Kraay, 1986). Human cognitive capacity puts serious limitations on the complexity of the analyses that are feasible to perform in field conditions and in real time. As a consequence, the techniques operated with very few severity categories and were often based on verbal rather than quantitative classifiers.

When it comes to human estimates of objective measures, several validation studies showed that with proper training it is possible to get quite adequate accuracy. In general, humans are not very good at estimating purely time-based measures (such as Time-to-Collision and Time-to-Lane-Crossing) and acceleration (Kiefer et al., 2006; van der Horst, 1991). Nevertheless, Hydén (1987) showed that it is possible to train observers to estimate speed and distance with sufficient accuracy (from which some single-value time-based indicators can be derived). Still, much critique was raised towards the reliability of the human observers as such. Also, it seems that human observers can have biases in their estimates based on their subjective perception of the dangerousness of the situation. For example, many situations that a human observer would judge as an event with two road users on a collision course do not in fact have a collision course when it is measured precisely (Laureshyn et al., 2017b).

On the contrary, automated data collection methods are by definition objective (i.e. not susceptible to subjective biases), but the performance of the technical tool might be influenced by the conditions in which it is used. When using automated video analysis tools, such factors are (beside the choice of the video processing algorithm itself) (Morse et al., 2016):

- Quality of the underlying calibration
- Characteristics of the camera (e.g. resolution) and characteristics of the installation (height and angle)
- The complexity of the traffic scene
- Environmental conditions (e.g. weather and lighting)

Performance measures of automated systems' reliability can relate to a number of aspects of the data collection, for instance how many of the relevant situations are missed by the system, how accurate the measurements of behavioural or surrogate safety measures are, how well the algorithms can deal with changing weather and light conditions, etc. Little research has been done into measuring and comparing the performance of automated video systems for traffic-related applications in varied circumstances. Exceptions are recent studies by Morse et al. (2016) in which a number of different conditions are formally tested and compared, and Laureshyn et al. (2013) who look into the accuracy of estimated camera calibration parameters and their effect on the final measurements from video. Saunier et al. (2014) suggested a standard procedure to objectively compare the performance of different video analysis systems based on the same input data and comparison of the output with manually produced ground truth.

Since the occurrence of safety-critical situations is, like the occurrence of crashes, partly a random process (though with much higher frequency compared to crashes), it is important that the observations are done during a sufficiently long time so that stable estimates of their frequency can be obtained. Very little research has looked into this subject in a systematic way, the only exception being a study by Hauer (1978). It was noted that the variation seemed to depend on conflict definition. Even though the TCTs have evolved a lot since the time this work was written and the suggested "rules of the thumb" are, most probably, no longer valid, the approach itself to the estimation of the observation period length appears to be very sound and can still be used for other surrogate safety measures and estimation of frequency of events based on these measures.

#### 2.2.4 Framing within existing literature

One existing literature review paper on the topic of surrogate safety measures was identified from literature (Zheng et al., 2014c). The paper has a relatively wide focus, and includes surrogate safety measures not only in site-based observations, but also in naturalistic driving.

Our review study aims to supplement the existing review by Zheng et al. (2014c). For a number of interesting aspects related to surrogate safety measures that are well-described in that paper, we would therefore like to refer the interested reader to that paper. These include the conceptual issues about how to define a "traffic conflict", and the different methods for data collection. A number of other publications include relatively elaborate and relevant background on surrogate safety measures as well (e.g. Chin & Quek, 1997; Laureshyn, 2010; Svensson, 1998). The review paper by Zheng et al (2014c) as well as the other publications are, however, narrative reviews of literature, which means that implicit processes to collect and provide evidence are used. Therefore, it cannot be verified whether the information presented is comprehensive and unbiased (Garg et al., 2008).

A unique feature and an added value to existing literature of the review presented in this chapter is the application of a systematic protocol to identify and code existing publications on surrogate safety measures. This has allowed us to generate a more comprehensive and objective overview of the work that has been done over the years. This work is beneficial because it can help researchers to gain a clear view on the current state-of-practice in the field, and it can help guide them towards addressing the challenges and opportunities that are of major importance to the field. This will help reducing duplication of research efforts, repetition of errors from the past and “reinventing the wheel”.

In addition, a related scoping review paper that emphasises on the use of surrogate safety measures to study the safety of vulnerable road users (VRU) in particular has recently been submitted for publication (Johnsson et al., in review). The review paper by Johnsson et al. (in review) that emphasises on VRU makes use of a subset of the data that are included and analysed within this chapter. It deepens the understanding of how surrogate safety studies are applied to study the safety of VRU, and provides specific points of attention and limitations related to such studies. The scoping review that is included in this chapter has a more general and holistic focus, and will therefore not go into detail about the specific issues related to applying surrogate safety measures to study the safety of VRU.

## 2.3 Methodology

### 2.3.1 Methodology of the review of surrogate safety measures

Many review studies have traditionally taken the form of a narrative review, which means that implicit processes to collect and provide evidence are used. A limitation of narrative reviews is, however, that the reader usually cannot be certain that the information presented is both comprehensive and unbiased (Garg et al., 2008). Therefore, this study applied a more systematic approach to identify and analyse the available literature. We used a scoping review to retrieve and structure the information that is available on the topic of surrogate safety measures, and to identify the critical gaps in existing knowledge and the required steps forward in the field. In general, the aim of scoping reviews is to rapidly map the key concepts underpinning a research area and the main sources and types of evidence available (Mays et al., 2001; Wilson et al., 2012). A major advantage of scoping reviews is that they can produce a broad map of evidence that can be used by many and for applications beyond the authors’ originally intended purpose (Armstrong et al., 2011). They are particularly useful where an area is complex and has not been reviewed comprehensively before (Mays et al., 2001; Wilson et al., 2012). Scoping reviews strongly contribute in reducing duplication of efforts and in guiding future research (Armstrong et al., 2011; van Wee & Banister, 2016), which are considered two critical points of attention in current research in the field of surrogate safety measures.

A systematic and transparent protocol was set up to find relevant studies and to extract knowledge from them. The main method of locating literature for this review was by searching the following databases available online: ScienceDirect, TRID, Web of Science, Engineering Village and Scopus. Applied search terms are shown in Table 1. Additionally, the library of the Transport and Roads Department of Lund University was manually searched, since this library contains a lot of old

reports and dissertations that are highly relevant to this review, but that are usually not available in online repositories. To a limited degree, we have allowed for snowballing when some references found in papers turned out to be missing and seemed to be of high importance, and in case personal knowledge of the involved experts identified critical papers that were missed by this systematic procedure. For practical reasons, the studies had to be written in English, Swedish or Dutch. Older studies are included without age restrictions as long as they could be retrieved. All publications up until the end of 2015 are included.

*Table 1 – Search terms used for searching the online databases.*

Keyword 1	Boolean operators	Keyword 2
Traffic conflict		
Conflict Technique		
Surrogate safety		
Safety critical event		
Indirect safety	AND	Traffic
Near-accident	AND	Traffic
Near-miss	AND	Traffic safety

All references were downloaded to EndNote reference management program, and duplicates were removed using the automatic procedure embedded in it. The screening of the papers to decide about inclusion or exclusion was performed by two researchers. In a first screening, the title and (if necessary) the abstract were used to judge whether a study should be included or not. In case this was insufficient to come to a conclusion, the full paper was checked.

The focus of this review is limited to surrogate safety measures that are observed from real traffic using on-site static cameras, sensors or observers. The following exclusion criteria were defined:

- Not about road surrogate safety measures (e.g. air traffic conflicts);
- Not about site-based observations (e.g. naturalistic driving studies, microsimulation studies);
- Surrogate safety measures are only supportive (e.g. observed traffic conflicts are validated against by driving simulator or microsimulation data, but are not analysed and reported on their own);
- Publications not fully written in English, Swedish or Dutch. Providing an abstract in one of these languages was not sufficient;
- Duplicate (e.g. two publications about one study or other duplicates not automatically removed by EndNote).

Methodological publications that included or discussed surrogate safety measures in a broader perspective (i.e. not exclusively focused on site-based observations) were included as well. These were four publications in total.

Figure 3 shows the review decision process. Full papers were extracted automatically through EndNote. Full papers that could not be automatically extracted were searched for manually through Google and Google Scholar search engines (e.g. full papers from ResearchGate, self-archiving databases of universities,...). Given enough time and resources, additional efforts to retrieve

the remaining papers could have been made, such as contacting the authors or buying access to additional databases or individual papers. Unfortunately, this was not feasible within the frame of this review. It seems, however, that the majority of studies that could not be retrieved are mostly small-scale studies, published as conference proceedings only and/or published in non-ISI ranked journals. While this is a limitation of the study, the added value of these papers to the review is considered limited. While this means that this dissertation cannot provide a complete representation of all available literature, we believe that the analysed dataset still provides an extensive and robust view of the field. Because of the limitations in available time and resources, a total of 177 references that, based on the title and abstract, might be relevant to the study could not be further analysed and included. It should be stressed that not all of these papers necessarily relate to the subject at hand, so the true number of appropriate papers that is missed because of this could be lower. A total of 239 publications were included in the review.

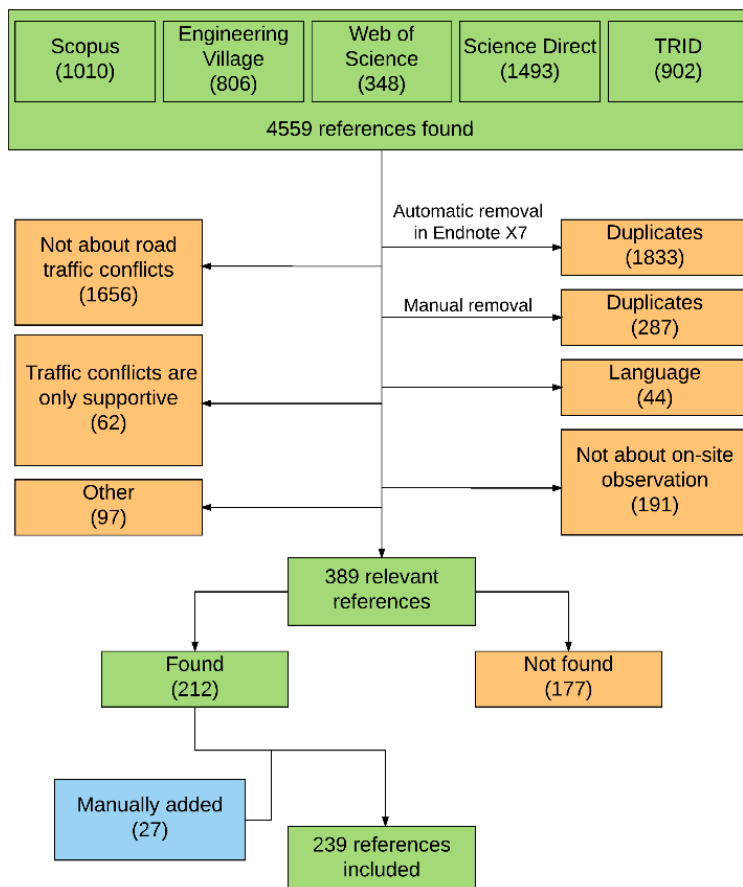


Figure 3 – Flow chart of scoping review surrogate safety measures.

Information about each publication was stored using a predefined codebook. The codebook included information about the aim of the study, the data collection, surrogate safety measures that were used, threshold values that were used to distinguish between serious and non-serious events, data analysis techniques, possible links to other types of data and methodological aspects that were dealt with in the paper. The coding work was distributed among the same two researchers who decided on the in- or exclusion of papers. They were also the ones who designed the codebook (with additional input from the rest of the research team) and therefore have a very good understanding of the exact meaning of each element. Additionally, a guideline book was designed that accompanied the codebook and that could serve as a lead in case of any doubts. The codebook was pre-tested on a small sample of the data and showed a good inter-coder agreement. Regular discussions and consistency checks between both researchers took place during the entire coding process.

### 2.3.2 Methodology of the review of behavioural observation studies

The literature review of behavioural observation studies by van Haperen (2016) applies a similar methodology. The study also applies a scoping review, in which a systematic search protocol is applied to identify the papers, papers are systematically screened for relevance, and the information of selected papers is stored through a predefined codebook.

This study was limited to peer-reviewed journal articles in English only. The initial search yielded 21.169 hits. After removal of duplicates and screening for relevance, 620 papers remained. Since 37 papers could not be retrieved, the final database included 583 papers.

## 2.4 Results of scoping review on surrogate safety measures

The following subsections present the analyses of the content of the 239 included publications in the scoping review on surrogate safety measures. First, an overview of the distribution of publications over time is presented. Then, the study focus of the publications will be presented. Next, the different surrogate safety indicators and traffic conflict techniques that have been used are presented. Finally, the study design and the data analyses are investigated.

The difference between surrogate safety indicators and traffic conflict techniques (TCTs) requires some clarification. Surrogate safety indicators and TCTs are both surrogate safety measures. A surrogate safety indicator should be seen as a measurement of the severity of an event, expressed in terms of proximity to a crash and/or consequences should a crash take place, using one particular parameter or numeric (usually objective). On the other hand, a TCT refers to a broader established framework of practice to assess and classify events in traffic, including methods of observation, instructions for how to use the technique as well as one or more indicators to distinguish severe events (serious conflicts) from non-severe events. Many TCTs depart from the idea that one single indicator is usually not sufficient to classify all events in traffic in a meaningful way. Therefore, they often combine different indicators and/or include a subjective component into their classification. Most TCTs originate from the 1970s-1980s and are mostly fit to suite data collection by human observers, while surrogate safety indicators

have been developed throughout history and can be adjusted to human data collection or some form of (partly) automated data collection.

#### 2.4.1 Overview of the literature over the years

Figure 4 presents the distribution of the found publications over the time. The graph shows both the publications that are actually included in the study and those identified as potentially relevant, but for which no full text could be retrieved. The first number describes the publications that have actually been read and analysed within the frame of this scoping review while the second gives a better idea about the “true” number of publications over time.

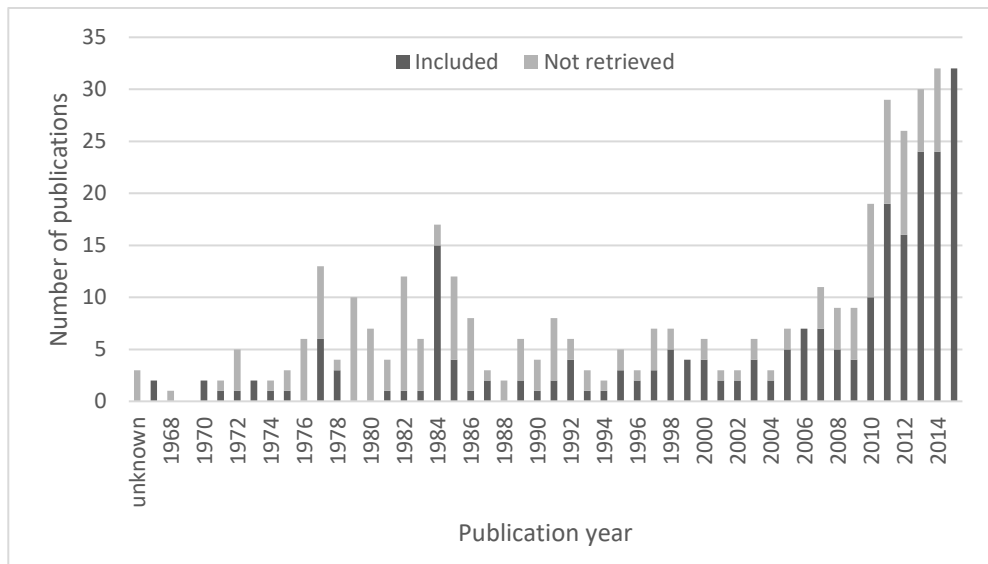


Figure 4 – Number of studies using surrogate safety measures over the years.

Although the first documented application of surrogate safety measures was performed by Perkins & Harris (1967), the usefulness of surrogate safety measures was first advocated by Forbes (1957) a decade earlier. After the successful first attempts, the approach rapidly gained popularity, leading to the development of numerous new conflict observation techniques in the 1970s. Countries that developed their own techniques included Sweden, the Netherlands, France, Germany, Finland, Canada, the United Kingdom, the United States, Austria, etc. (Asmussen, 1984).

Since all techniques used different indicators and protocols to select traffic conflicts, comparability of the findings as well as limited validation for each individual technique were identified as significant issues. Therefore, in the 1980s and early 1990s, research efforts emphasized on aspects such as validity (Hauer & Gårder, 1986; Williams, 1981), comparability (Grayson et al., 1984) and reliability of observations and assessments (Hydén, 1987; Krusysse, 1991; Lightburn & Howarth, 1979). The International Committee on Traffic Conflict Techniques (ICTCT) deserves mention in this context. Founded in 1977 by a group

of researchers working with traffic conflicts (ICTCT, 2016), this organisation organised a number of workshops and international calibration studies around TCTs, and developed solid theoretical grounds for the use of surrogate safety measures.

However, studies making use of surrogate safety measures were applied less frequently after the early 1990s. The most important reason for this languish was most likely the significant costs in time and efforts required to collect such data in the field through human observers.

A steep increase in the number of publications can be observed starting around 2010. It seems that the recent improvements in advanced video analysis techniques (Laureshyn, 2010; Saunier et al., 2010) and other sensor technologies (Tarko et al., 2017), which allow to collect surrogate safety measures in a more efficient and accurate way, have led to a renewed interest in this method of road safety research.

It can be observed that there is a relatively high number of publications that could not be accessed from the period up to the early 1990s. This is due to the fact that many of the publications in this period are reports and conference proceedings that are not available in an electronic format. Even in more recent years, a number of publications could not be accessed. These included a large number of conference proceedings as well, and a limited number of articles in some less-known journals that our institutes did not have access to.

#### 2.4.2 Study focus

Figure 5 shows the focus of the reviewed publications. Applied studies use surrogate safety indicators or TCTs to answer a particular question about road safety, while methodological ones study the indicators or techniques themselves (e.g. their validity or theoretical grounds). Papers from before 2005 and papers from the 2005-2015 period are shown separately to allow the identification of recent developments in the field. It can be observed that publications with an applied focus mostly date from the last decade, while methodological publications are more equally spread over time.

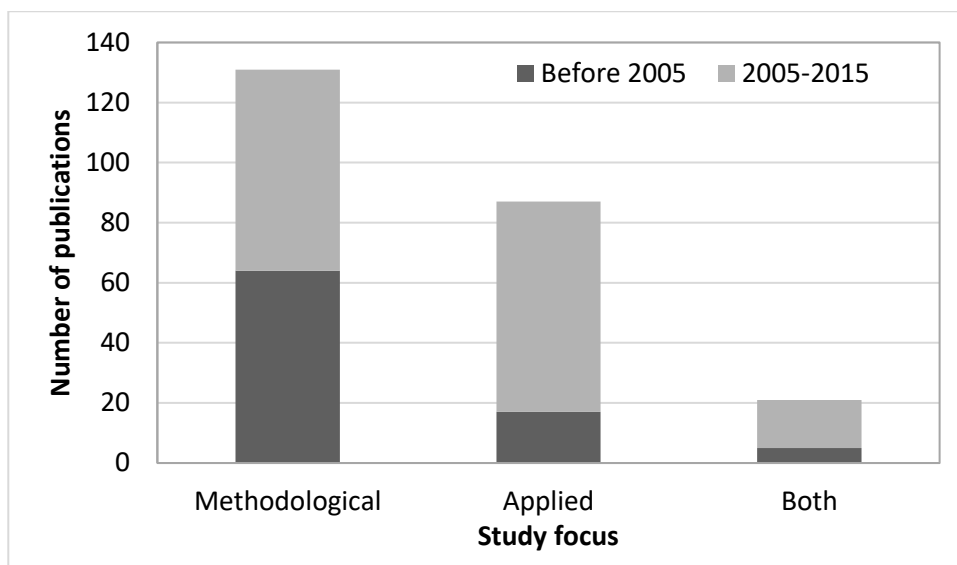


Figure 5 – Study focus of surrogate safety studies.

### 2.4.3 Surrogate safety indicators

Dozens of surrogate safety indicators have been developed over history. Laureshyn (2010) provides a non-exhaustive overview of existing indicators. Many indicators are derived from similar ideas or concepts and are therefore closely related to each other. Based on these underlying similarities, we have been able to group them into a limited number of “families”. Each family is described into more detail in the following subsections.

Figure 6 shows that the indicators from the Time-to-Collision (TTC) family have been applied most frequently, followed by the indicators from the Post-Encroachment Time (PET) family and the Deceleration family. A limited number of indicators do not fall within these families and are grouped in the category ‘other’. The category ‘unspecified’ relates to papers that provide insufficient details to identify the indicator(s) or technique(s) that have been applied. Most of these papers made use of some abstract, unspecified concept of ‘conflicts’ without explaining what parameters or thresholds were used to select them. This information is, however, crucial for the replicability of a study and to assess the validity of its results and interpretations.

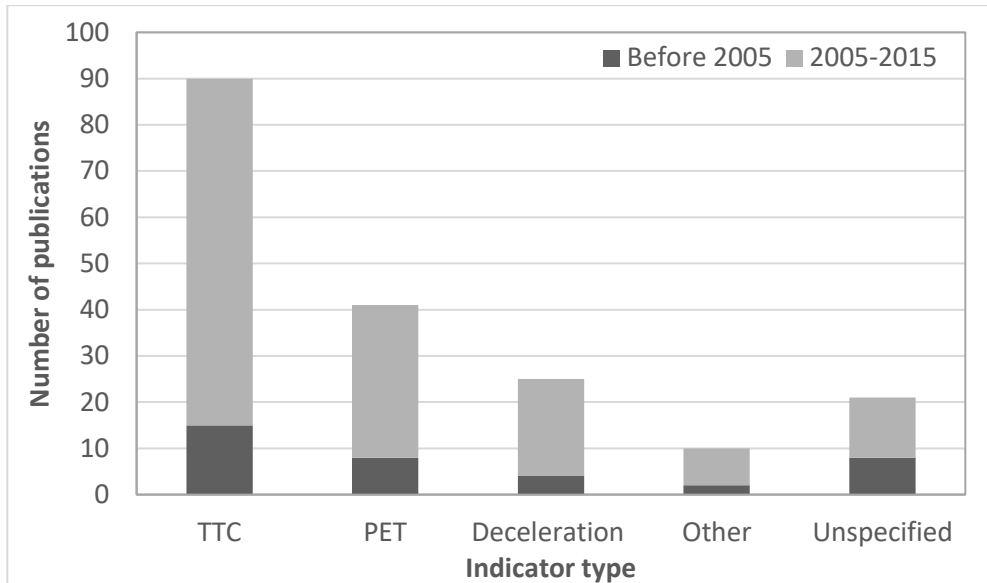


Figure 6 – Frequency of use of surrogate safety indicators.

#### 2.4.3.1 TTC-family

Figure 6 shows that 90 of the reviewed publications make use of an indicator from the TTC-family. The Time-to-Collision is one of the most common methods to describe the severity of a traffic event, and many indicators are derived from it. Hayward (1972) defined TTC (originally called “Time-Measured-to-Collision”) as “the time until a crash between the vehicles would occur if they continued on their present course at their present rates”. TTC therefore possesses a number of distinct properties:

- TTC cannot be measured directly but is calculated based on future motion prediction;
- It can be calculated only as long as road users are on a collision course;
- It is a continuous indicator that may be calculated for any instance during the collision course.

The concept of a collision course is therefore a key concept of many surrogate safety indicators, as well as most TCTs. A collision course is by definition a precondition for a crash – without a collision course at least at the very last phase of an interaction, a crash is not possible. The concept, however, requires some elaboration. As can partly be derived from the TTC definition, the basic idea behind the collision course concept is that the two road users will collide if they continue “as is”. This requires, however, more precise instructions on how the future motion is to be predicted.

The earlier definitions involved travelling on “present course and at present rates” (Hayward, 1972; Hydén, 1987; van der Horst, 1990). However, continuing with the exact same speed and direction is in practice a quite unlikely scenario to occur. A more general, but also more realistic interpretation could be the planned path

given that the road users would be unaware of each other's presence (fail to detect the danger in time). This also seems to be the practical interpretation that has been used by conflict observers in the field.

Different predictions could therefore be made for each road user about their future motions. Therefore, each road user can have multiple predicted trajectories, each with its own probability of actually taking place. One or more of such predictions might lead to a crash. A more generalized definition of a collision course could therefore be a situation in which there is at least one possible trajectory per road user that could lead to their crash at a future instant (Saunier & Sayed, 2008).

Since the TTC is a continuous indicator, the question is which moment describes the severity of the event in the most representative way. At least two individual points of the curve are in literature indicated as important moments in the interaction development:

- Time-to-Accident (TA), which is defined as the TTC-value at the moment the first evasive action is taken by one of the road user (Hydén, 1987).
- $TTC_{min}$ , which is the lowest value of TTC that takes place during the interaction (Hayward, 1972; van der Horst, 1990).

Time-to-Accident has rarely been used as a surrogate safety indicator by itself, but it is one of the key elements of the Swedish Traffic Conflict Technique (STCT).  $TTC_{min}$ , on the other hand, is the most commonly used individual surrogate safety indicator in the TTC-family, and the most commonly used individual surrogate safety indicator across all families as well. It has been applied in 55 of the analysed publications. This has allowed to do an analysis of the applied threshold values to distinguish between severe and non-severe traffic events (see Figure 7).

19 publications did not apply a threshold value to distinguish between severe and non-severe events, but analysed all events for which  $TTC_{min}$  could be calculated. Most of these studies have a methodological focus. In case a threshold value is applied, threshold values of 1.5s, 2s and 3s are most common (11, 7 and 9 publications, respectively). Unlike the papers that do not apply a threshold value, the majority of the papers that make use of a threshold value have an applied focus. The share of methodological papers is somewhat higher for papers with a threshold value of 1.5s than for the threshold values of 2s and 3s. It is, however, clear that there is very little consensus in literature on which threshold value should be applied to distinguish between severe and non-severe events in traffic by using  $TTC_{min}$ .

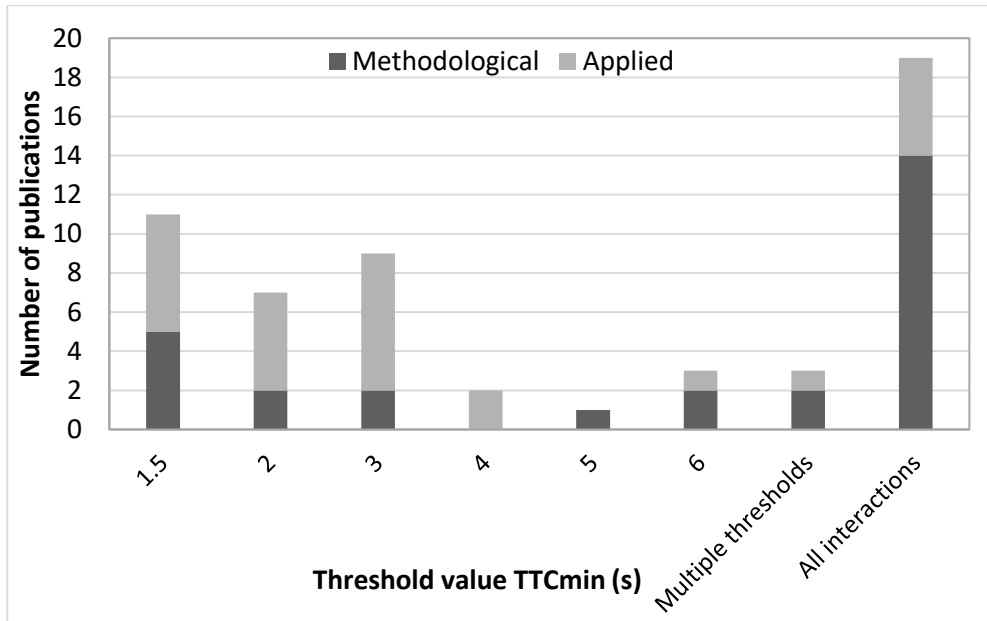


Figure 7 – TTC<sub>min</sub> threshold values.

Many other indicators have been derived from the TTC concept. These include, for instance, Time-to-Line crossing (van Winsum et al, 2000), Time-to-Zebra (Várhelyi, 1998), reciprocal of TTC (Chin et al., 1992), T<sub>2</sub> (Laureshyn et al., 2010), Time Exposed TTC and Time Integrated TTC (Minderhoud & Bovy, 2001). Most of them have rarely if ever been applied in practice.

Additionally, it should be mentioned that the use of momentarily values of TTC is not without its flaws. It has been shown that 'compressing' the TTC into single values can lead to quite diverse situations being classified as if they are very similar. For more details and illustrations, the interested reader is referred to Hydén (1987).

Despite the wide use of TTC as a surrogate safety measure, validation studies relating TTC to crash data are few. All of the available validation studies make use of TTC<sub>min</sub>. None of the other indicators of the TTC-family have been validated against crashes. Only one validation study was identified in which automated measurements of TTC<sub>min</sub> were made (Sacchi et al., 2013). All other validation studies using TTC<sub>min</sub> (Hydén, 1977; El-Basyouny & Sayed, 2013; Lord, 1996; Migletz et al., 1985) made use of estimations by human observers, which can deviate from the actual objective measurements. While the study using automated measurements of TTC applied a threshold value of 3s, all studies that made use of estimations by human observers applied a threshold value of 1.5s. It should be mentioned that some evidence about the validity of TTC indicators could also be derived from validation studies of TCTs that include the TTC-concept in their methodology, such as the Swedish Traffic Conflict Technique and the Dutch Objective Conflict Technique for Operation and Research (DOCTOR).

#### 2.4.3.2 PET-related indicators

PET is calculated as the time between the moment that the first road user leaves the path of the second road user, and the moment that the second road user reaches the path of the first (Allen et al., 1978). Put differently, PET measures by what time margin two road users miss each other. Allen et al. (1978) argued that TTC-based indicators are incomplete measures of traffic conflict severity because they become infinite in case there is no collision course, even if a crash is avoided only by a fraction of a second without any evasive action. Therefore, not all events that intuitively might be considered as close or dangerous events can be assessed by these indicators. Based on a sample of observed crashes, Allen et al. (1978) conclude that in a number of crashes an evasive action had not been present or could not be easily observed. Additionally, it was concluded that a crash is most of the time a result of several sequential events, requiring more than one surrogate safety measure to describe the process adequately.

While PET is the most commonly used indicator from the PET-family, a number of other indicators are quite related to it as well. These include Time Advantage (TAdv), which can be considered as an extension of the PET as it 'predicts' the PET value in case both involved road users would continue with the same speed and path (Hansson, 1975; Lareshyn et al., 2010), and Time Headway, which expresses the time elapsed between the front of the lead vehicle and the front of a following vehicle passing the same point moving in the same direction (Vogel, 2003). Time Gap is an indicator that is highly similar to Time Headway and is used to express the distance between two consecutive vehicles in terms of time units. Time Headway and Time Gap are mostly used as indicators of traffic flow, while their use as a surrogate safety measure is less common. Vogel (2003) states that TTC is a more suitable surrogate safety indicator than Time Headway, because Time Headways only indicate potentially dangerous situations, while low TTC values indicate the actual occurrence of dangerous situations.

The relatively high number of studies that make use of PET has allowed to conduct an analysis of the applied threshold values to distinguish between severe and non-severe events. It can be seen from Figure 8 that, when applying PET, the use of a predefined threshold value is – relatively speaking – less common than for studies applying  $TTC_{min}$ . Measuring the PET-value of all traffic interactions is by far the most common approach. Few publications make use of a predefined threshold value to distinguish between severe and non-severe events, which is a remarkable difference with  $TTC_{min}$ . This could be a result of the fact that PET can be measured relatively easily for all events that have a crossing course, while  $TTC_{min}$  can only be calculated for events that have a collision course.

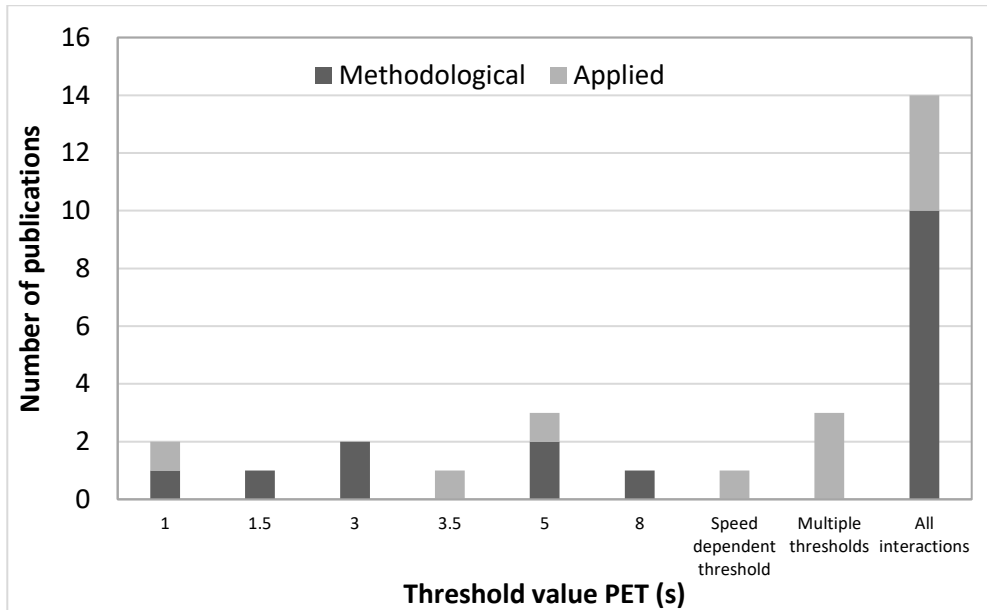


Figure 8 – PET threshold values.

PET has been validated to some extent through a number of studies with quite dissimilar methods (Cooper, 1984; Peesapati et al., 2013; Sonchitruksa & Tarko, 2006; Zheng et al, 2014a, 2014b). A study by Alhajyaseen (2014) validated a Conflict Index that was derived from a combination of crash probability (derived from PET) and severity (derived from speed, mass, and conflict angle). No validation studies for any of the other indicators of the PET-family have been found.

#### 2.4.3.3 Deceleration family

The deceleration family includes various indicators that are mostly applied in practice only once or a few times. Therefore, a more detailed analysis of the individual indicators is not possible. Indicators that are part of this family include Deceleration Rate (or Initial Deceleration Rate), which is the magnitude of the deceleration action when the road user starts its evasive braking manoeuvre; Maximum Deceleration, which is the maximum deceleration observed during a traffic event (Gettman & Head, 2003); Deceleration-to-Safety Time, which is the minimal necessary deceleration for a road user to avoid the crash (i.e., to turn a collision course situation into a non-collision course situation) (Hupfer, 1997); and Jerk, which is the derivative of acceleration and measures the suddenness and intensity of a braking manoeuvre (Bagdadi & Várhelyi, 2011; Zaki et al., 2014). No formal validation against crashes has been found for any of the indicators belonging to the deceleration-family.

#### 2.4.3.4 Integration of different indicators to a single index

The general idea of safety indices is to integrate different indicators describing a traffic event into one single value. The rationale behind this approach is that many indicators are not sufficiently universal and cannot be applied to every event in traffic at any time. It is thus plausible that various surrogate safety indicators represent partial images of the true severity of a traffic event (Ismail et al., 2011). It should be noted that many TCTs could also be considered part of this category. For example, the Swedish TCT is based on TA and Conflict Speed, the DOCTOR technique is partly based on  $TTC_{min}$  and PET, and some others integrate objective indicators and subjective observer judgments. Because of their context and history, TCTs are dealt with in more detail in section 2.4.4.

Some other examples of integrating multiple indicators into a single index can be found in Lu et al. (2012), in which non-complete braking time and TTC are combined to calculate the severity of a traffic event, and in Wang & Stamatiadis (2014) who used required braking rate, maximum available braking rate and TTC to create an Aggregate Crash Propensity Metric. A number of indicators that combine deceleration with other aspects such as radial acceleration (i.e. steering) or reaction time of the involved road users have also been suggested (Balasha et al., 1979; Li et al., 2013; Nasab et al., 2015; Oh et al., 2006; Uno et al., 2002).

#### 2.4.4 Traffic conflict techniques

This section presents an overview of existing TCTs. Various versions of TCTs were used in 75 of the 239 included publications.

Most of the techniques have been developed over a long period of time which implies that not all publications regarding a specific TCT use exactly the same methodology. Publications that use modified versions of an original technique are presented together with the original technique. A detailed description about each of the techniques is beyond the scope of this dissertation. The following references may be used to find more detailed descriptions of the techniques:

- US TCT: Parker & Zegeer (1989)
- Swedish TCT: Hydén (1987)
- DOCTOR: Kraay et al. (2013)
- British TCT: Baguley (1984)
- Canadian TCT: Sayed & Zein (1999)
- Finnish TCT: Kulmala (1984)
- French TCT: Muhlrads & Dupré (1984)
- Czech TCT: Kočárková (2012)
- Austrian TCT: Risser & Schutzenhofer (1984)

Figure 9 shows that the US TCT and the Swedish TCT have been most commonly applied in the publications included in our dataset. When only looking at the last decade, however, the US TCT has been used less frequently than the Swedish TCT. When comparing the proportion of the TCT studies that took place during the last decade with the surrogate safety indicator studies, it can be observed that the proportion of 'recent' studies is in general substantially higher for the surrogate safety indicator studies than for the TCT studies. It therefore seems that there is a shift away from the use of the traditional TCTs towards the use of

surrogate safety indicators. Regarding the US TCT, it is noteworthy that many publications applied slightly modified versions of the US TCT, but have not explicitly referred to it as such.

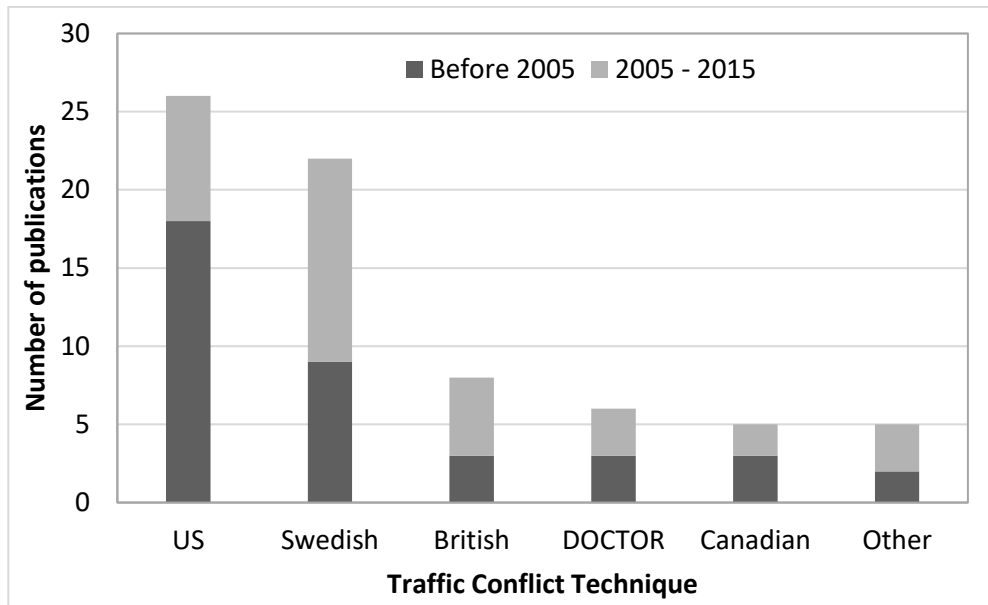


Figure 9 – Frequency of use of different traffic conflict techniques.

In general, at least some of the identified TCTs seem to have been validated more strongly than the individual surrogate safety indicators. However, most TCTs are quite closely related to some of the individual surrogate safety indicators. For example, the Swedish TCT includes the TTC at the start of the evasive action (the so-called Time-to-Accident), while the DOCTOR technique includes  $TTC_{min}$  and PET. As a result, some of the validation findings might be (partly) transferable between TCTs and indicators. It is, however, beyond the scope of this dissertation to judge to what extent findings might be transferred.

The US TCT has been validated in a number of large-scale validation studies at hundreds of intersections (Baker, 1972; Paddock & Spence, 1973; Pugh & Halpin, 1974). Additionally, two validation studies of the US TCT have been applied at a few dozens of intersections (Cooper, 1973; Migletz et al., 1985). Large-scale validation studies of the Swedish TCT have been conducted by Hydén (1987) and Svensson (1992) at more than 100 intersections each. As opposed to most of the other techniques and indicators, validation efforts of the Swedish TCT do not only relate to product validation (i.e., to what extent serious traffic conflicts can estimate the (expected) number of crashes), but also some process validation (i.e., to what extent serious traffic conflicts can be used for analysing the processes that lead to crashes). Additional validation studies regarding the Swedish TCT include those by Linderholm (1981) and Shbeeb (2000). Some validation efforts of the DOCTOR technique are published by van der Horst (2007a) and van der Horst et al. (2017). Regarding the British TCT, two small-scale validation studies were identified from literature (Spicer, 1973; TRRL, 1980).

For the Canadian TCT, one large-scale validation study with nearly 100 intersections (Sayed & Zein, 1999) and two small-scale validation studies were found (Brown, 1994; Brown et al., 1984). No formal validation studies have been identified for any of the other TCTs.

## 2.4.5 Study design

### 2.4.5.1 Number and types of locations and observation duration

Figure 10 shows the number of observation sites in the studies and Figure 11 the average duration of the observations per site. It can be observed that many studies (approximately one third) take place at only one observation site. On the other hand, one third of the studies make observations at 5 or more observation sites. Observations at only one site might be acceptable if the aim is to assess the impact of a specific measure at a specific site, to test the performance of a surrogate safety measure itself, or to test some technical data collection tools. However, if the study is focused on applying observations for practical road safety study purposes, making observations at only one site can strongly limit the possibilities to generalize results. It seems that very large studies that take place at many observation sites mostly took place some time ago, but have been quite rare during the most recent decade.

Relatively short observation periods per observation site are quite common as well. 45% of all studies observed less than 8h per site (25% even less than 4h), while only 22% of all studies observed more than 24h per observation site. Quite surprisingly, 23% of the included publications did not include any information about the duration of the observations at all. This is a remarkable result, since the duration of observations can have a strong effect on the robustness of findings. This information is therefore considered quite an essential part of the description of the study design.

One might expect that there is a trade-off between the number of observation sites and the duration of observations at each site (more locations equal shorter observations at each site and vice versa). However, such trade-off is hardly observed. For instance, when looking at studies that observed only one site, short observation times of less than 8h and less than 4h are almost equally common (45% and 28% of the single-site studies compared to 45% and 22% for all studies taken together, respectively). Only studies with a duration of more than 24h per site are somewhat more common in the subgroup of single-site studies (30% for single-site studies, compared to 22% for all studies taken together).

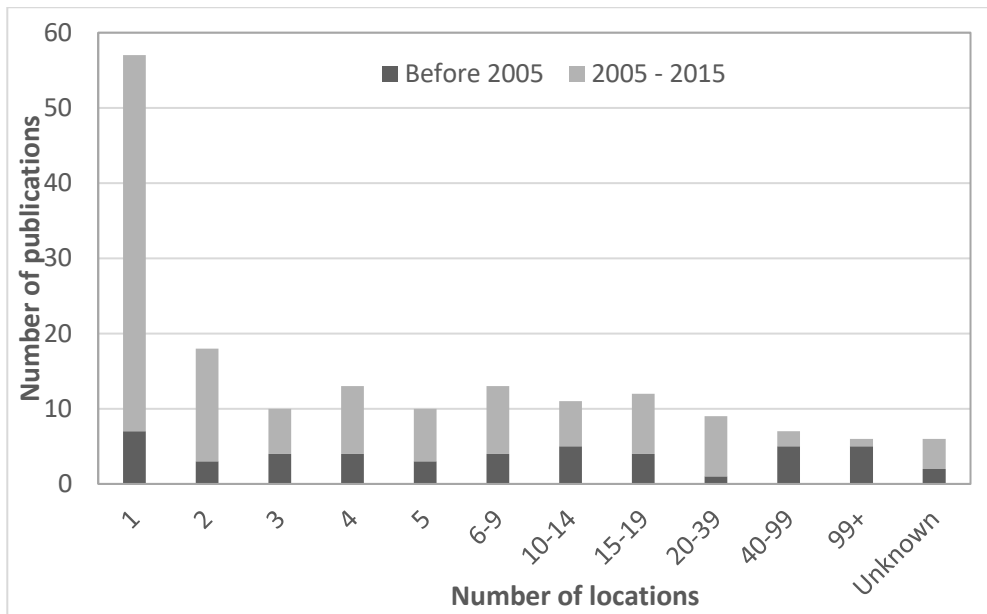


Figure 10 – Number of observed locations.

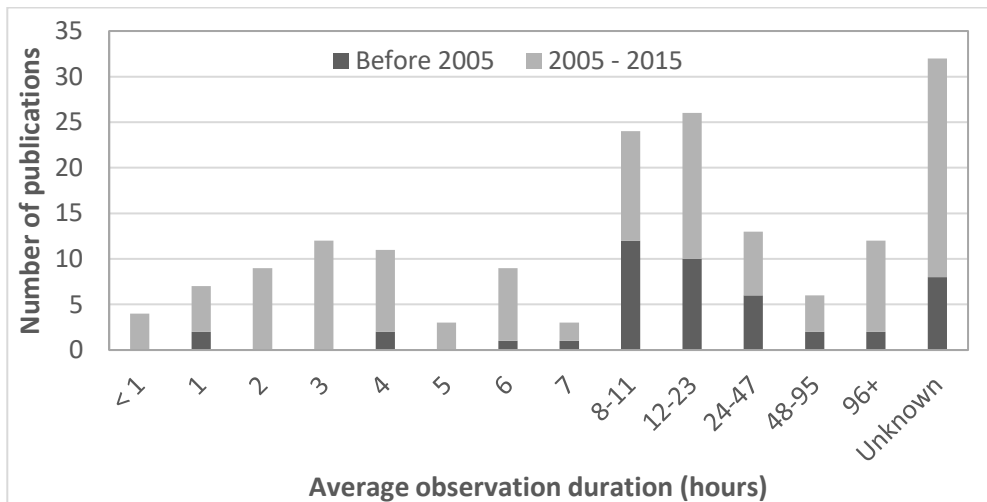


Figure 11 – Duration of observations.

Figure 12 shows where the observation sites are located. It can be concluded that site-based observation studies mostly take place in urban areas. It can also be seen that this information is missing or unclear in a large number of publications, which can have important implications for the interpretation and transferability of study findings. The “other” category includes publications that specifically focus on motorways, tunnels, work zones and toll stations.

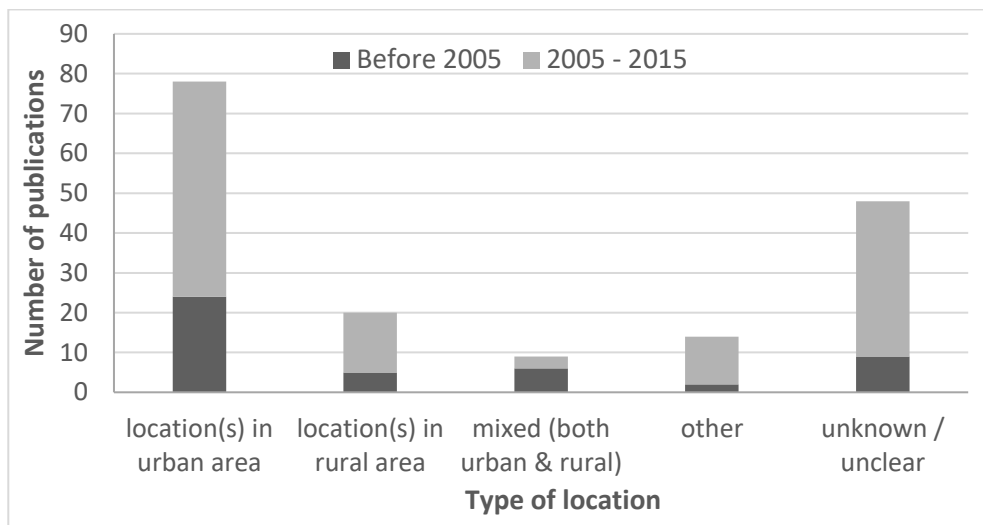


Figure 12 – Type of location(s) observed.

#### 2.4.5.2 Involved road users

Figure 13 shows the types of road users studied in the reviewed publications. The majority of studies includes motor vehicles only, but studies where VRU are included are not uncommon either. Note that publications might include multiple types of road users and are then counted more than once.

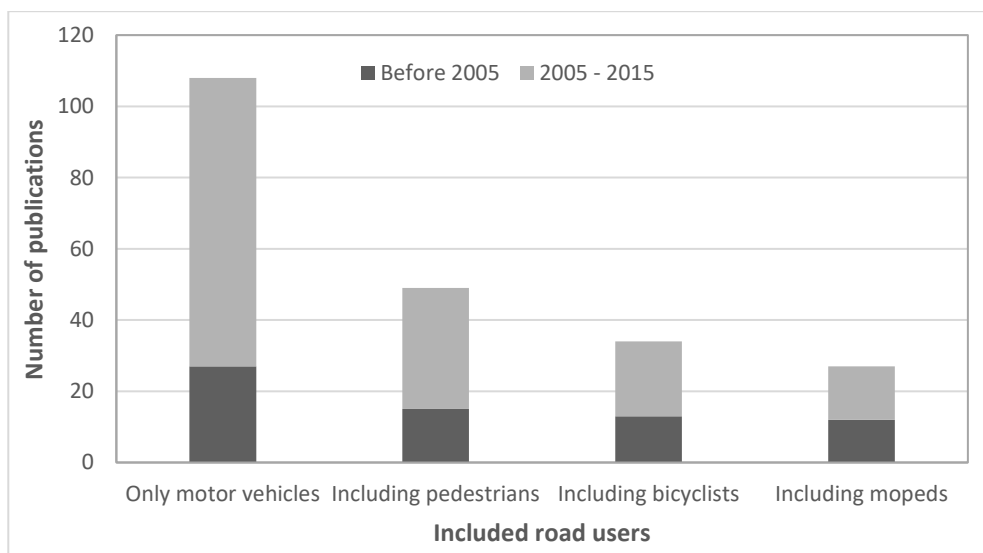


Figure 13 – Types of road users involved.

### 2.4.5.3 Data collection method

The applied methods to collect surrogate safety measures are presented in Figure 14. It can be seen that the different forms of manual observation (three left-most bars) have been most common over the years. However, the number of publications that apply video analysis software take up a substantial share as well, especially over the last 10 years. Fully manual observations (i.e. human observers on-site without video support) are a relatively large category for all publication years taken together, but have rarely been applied during the last decade. It is also noteworthy that manual observation from video (i.e. without a human observer on-site) is the largest individual category of data collection methods, and is very common during the last decade. On the contrary, fully automated video analyses and non-video sensors (including for example LiDAR and inductive loop data) are a relatively recent way of collecting surrogate safety measures and have rarely been applied before 2005.

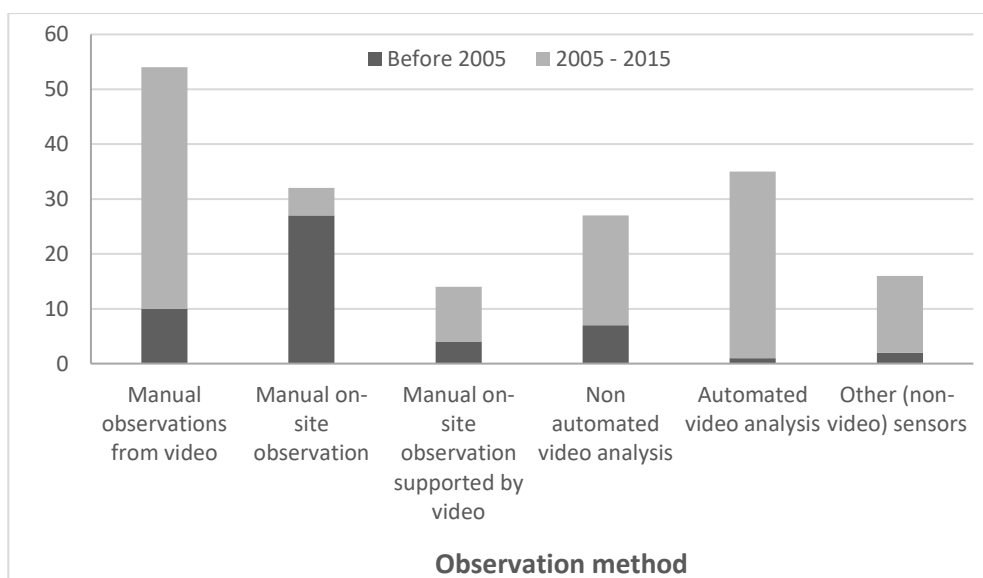


Figure 14 – Data collection methods.

### 2.4.6 Data analysis

Any additional data that are collected in conjunction with surrogate safety data are shown in Figure 15. It can be seen that only few studies do not include any additional data together with surrogate safety data. The most common additional data that are collected are exposure data (though defined in many different ways). Somewhat less commonly collected are crash data, information about the infrastructure and systematic behavioural observations. The category "Other" is quite large as well, including very diverse types of data such as results from microsimulation or driving simulator experiments, road user characteristics such as gender and age, and survey or interview data.

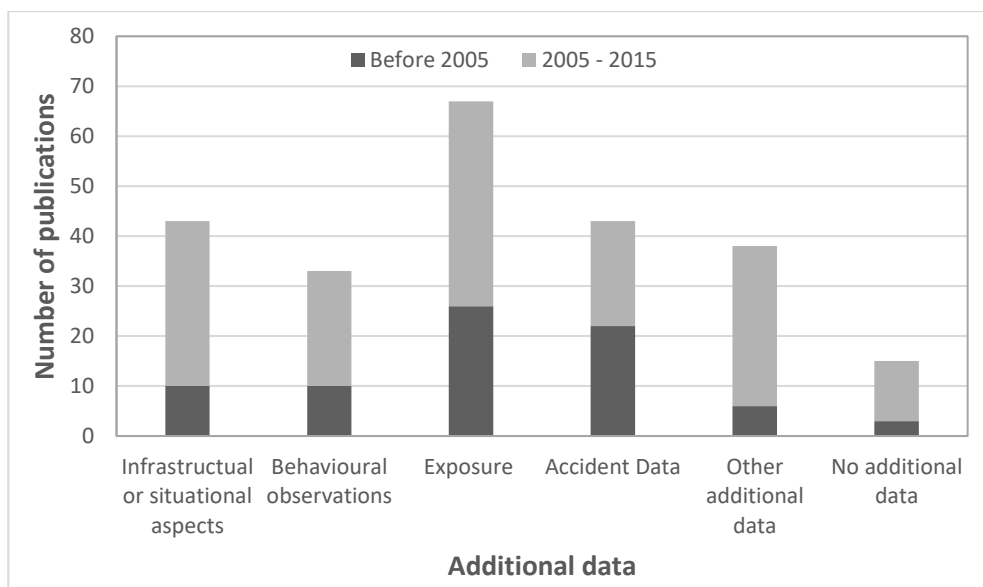


Figure 15 – Additional data collected in surrogate safety studies.

Figure 16 shows the techniques that are used to analyse surrogate safety data (note that each study can have multiple analysis techniques). Simple conflict counts are by far the most common type of analysis and are included in more than half of all studies that performed data collection and analysis (106 out of 169 studies in which data are collected and analysed). In approximately half of these studies, it was the only form of data analysis. Statistical models and tests, before-and-after comparisons and visualization of the observed events on a map or aerial photo of the study sites are less common.

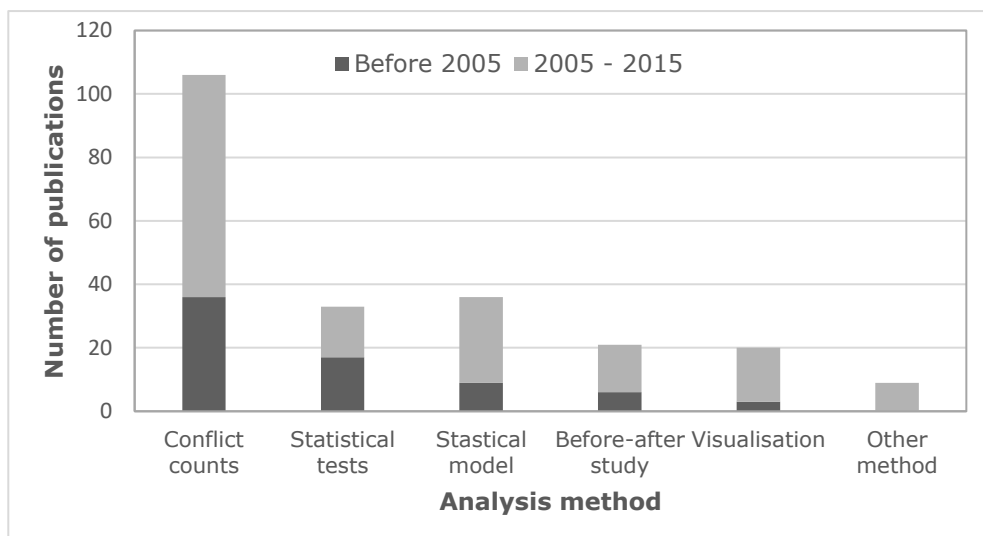


Figure 16 – Applied data analysis methods.

## 2.5 Results of scoping review on behavioural observations

This section provides a brief overview of how behavioural data in site-based observations are collected, how the studies are designed, what behavioural indicators have been collected and what other types of data collection are applied. The results from this section are adopted from van Haperen (2016). In most analyses, a distinction was made between VRU-papers (studies including at least one type of VRU) and driver-papers (studies including at least one non-VRU). 214 of the 583 papers were labelled as VRU-studies (37%), and 477 as driver-studies (82%).

Six data collection tools are identified that are used to collect behavioural data (see Figure 17). For both VRU- and driver-studies, cameras have been used most often to collect behavioural data, followed by human observers. Other data collection methods such as speed guns and sensors have been used less frequently.

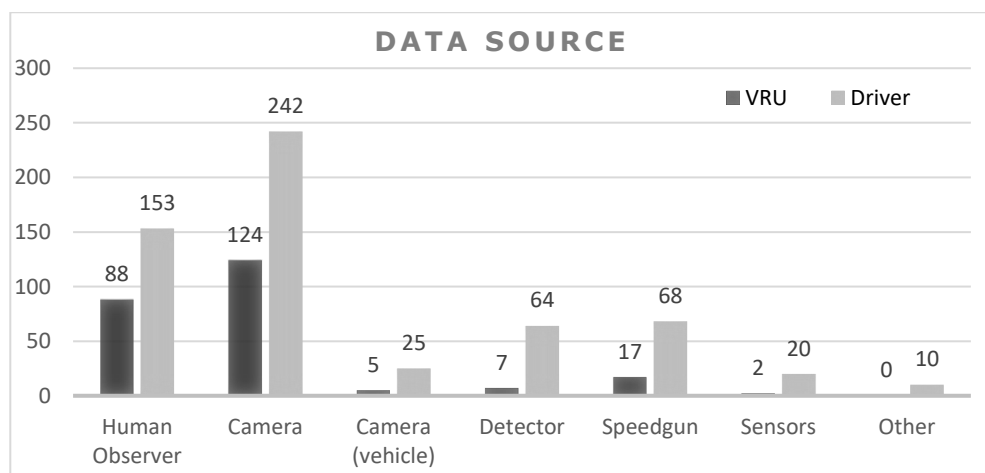


Figure 17 – Behavioural observation data collection methods.

A full list of observed behavioural indicators in VRU and driver studies can be found in Figure 18. The review identified 47 behavioural indicators that have been used in behavioural observation studies in road safety research. It appears that drivers' speed is by far the most commonly studied behavioural indicator, being used in more than half of the included publications. This is most likely due to the well-known quantified relationship between speed and crash risk and crash severity (Aarts & van Schagen, 2006; Elvik et al., 2004). Drivers' speed is analysed on road sections. Other behavioural indicators that are commonly studied at road sections include following distance (expressed in time or in space) and road users' lateral position. In observation studies that take place at intersections, yielding behaviour, red light violations and looking behaviour are most commonly studied.

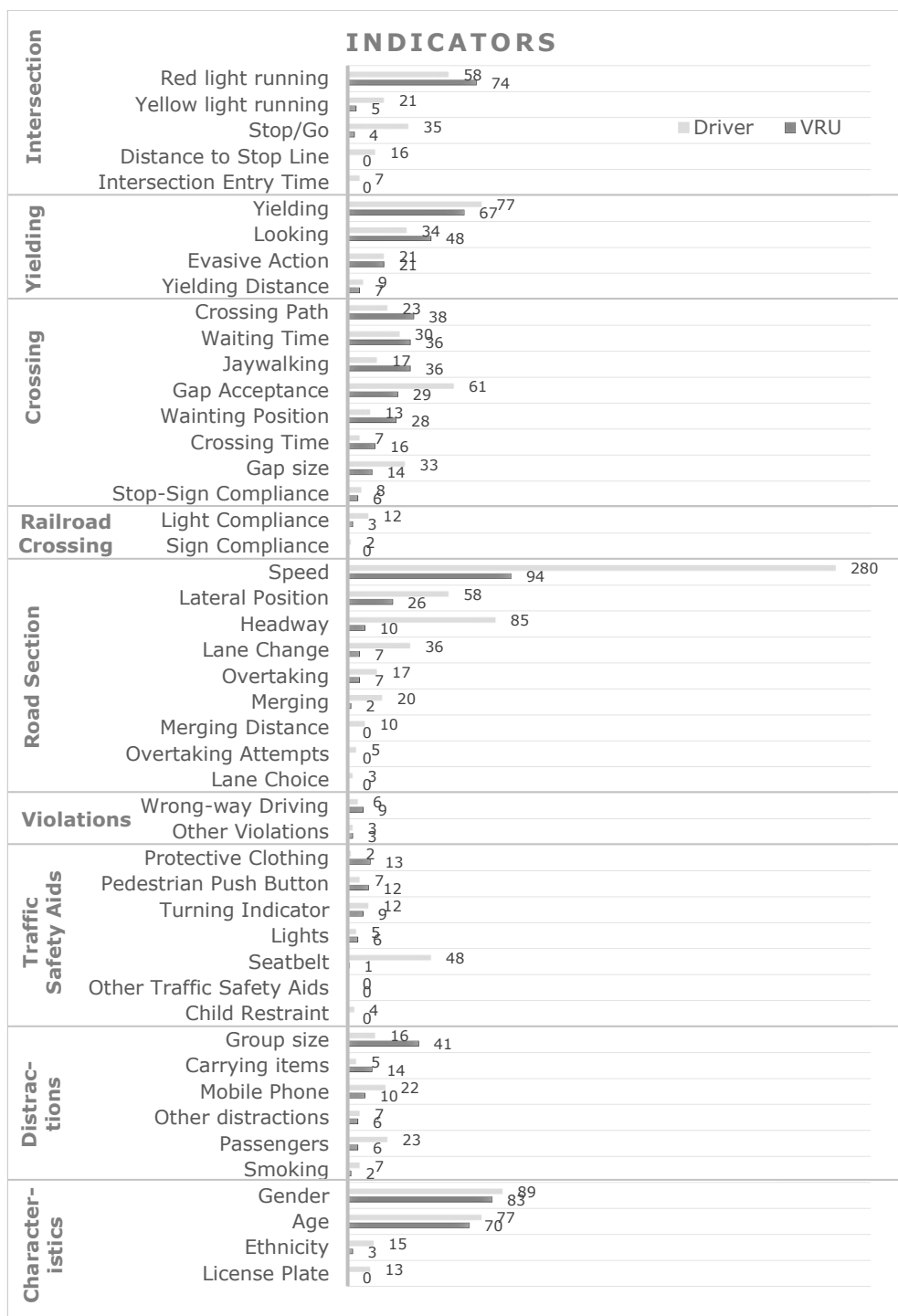


Figure 18 – Applied behavioural indicators.

Figure 19 shows the proportions of use of different research designs that are applied in behavioural observation studies. For both VRU and driver studies, a single observation design is most common (more than 50% of all studies). A before-after design is applied in approximately 20% of the studies. Cross-sectional designs and with-without designs are each applied in approximately 10% of the studies.

Similarly to the findings of the scoping review on surrogate safety measures, it was found that the majority of studies took place at only one or a few observation sites.

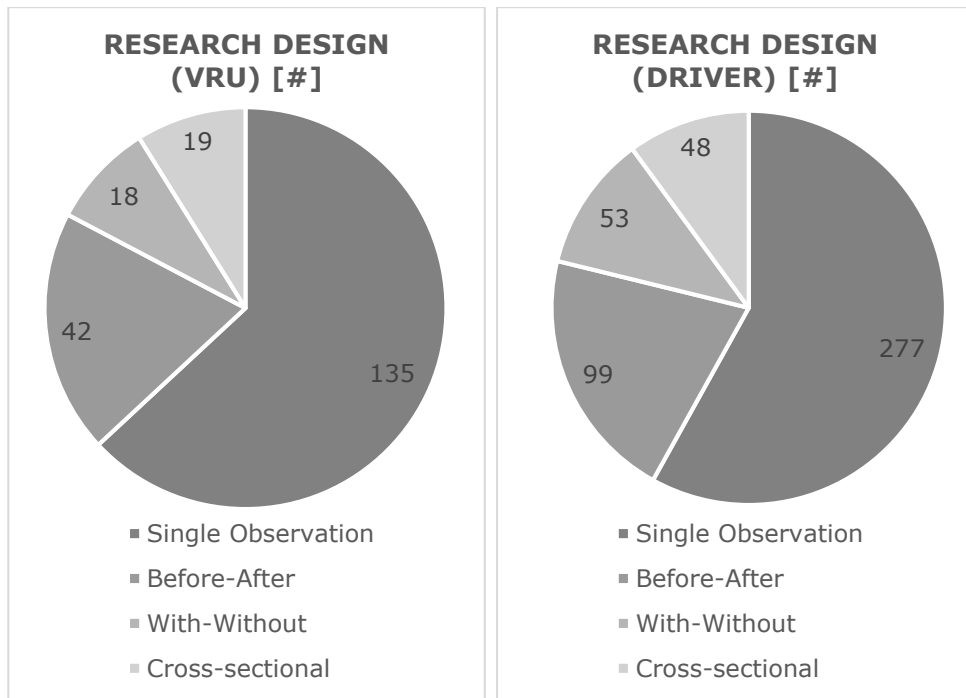
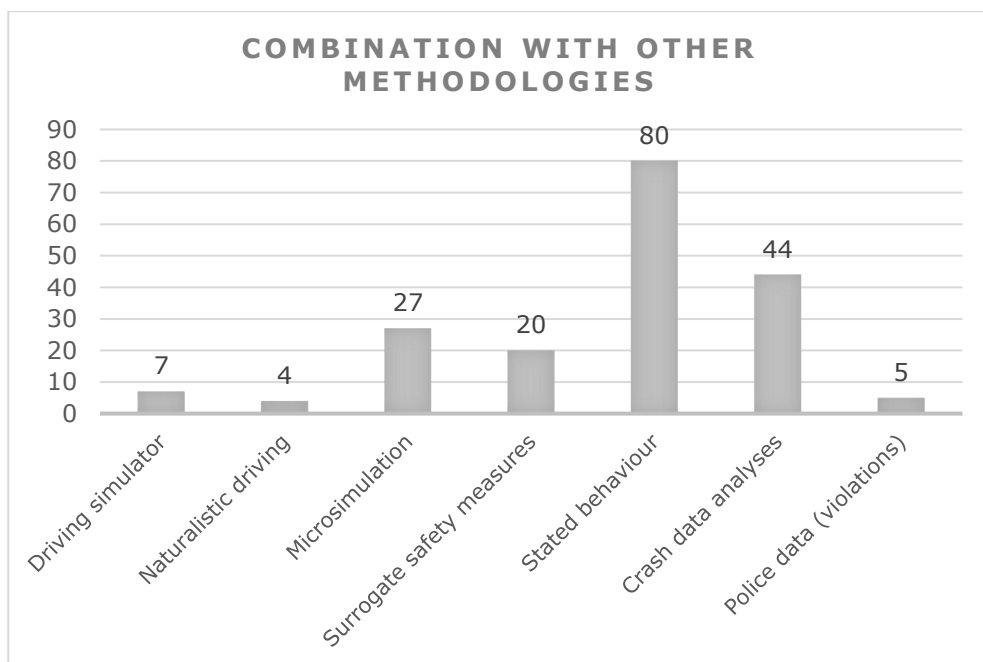


Figure 19 – Applied study designs in behavioural observation studies.

A substantial number of studies was found that combined the use of behavioural observations with another type of study methodology (see Figure 20). The combination with stated behaviour techniques (questionnaires, interviews and focus groups) is most common (13.7% of all studies). A link with crash data analyses was made in 7.5% of the studies. Particularly noteworthy within the frame of this dissertation is the fact that the combination with surrogate safety measures is relatively uncommon; only 3.4% of all behavioural observation studies collected data on surrogate safety measures as well.



*Figure 20 – Other methodologies that are combined with behavioural observations.*

## 2.6 Discussion

### 2.6.1 Validity of applied surrogate safety measures

As indicated in section 2.2.2, product validity can be considered as the most fundamental form, or the highest extent of validity. The usefulness of a surrogate safety measure does, however, not (only) depend on the extent to which expected crash numbers can be correctly estimated (Grayson et al., 1984). Its usefulness mainly depends on whether safety problems can be detected or not, and/or road safety countermeasures/treatments can be compared or evaluated (Chin & Quek, 1997; Grayson & Hakkert, 1987; Hauer, 1978). If we accept the premise that the ultimate goal of surrogate safety studies is not the estimation of expected crash numbers, we can see validity in different perspectives, i.e. the perspectives of relative validity and process validity.

Relative validity is easier to achieve than product validity, because it suffices to have sufficient evidence that a direction of effect on expected crashes can be inferred from a surrogate safety measure, instead of requiring a way to convert the non-crash events to an expected number of crashes. It is the determination of a practical way to convert the non-crash events to the (expected) number of crashes that seems to be the most problematic validity issue (Hauer & Gårder, 1986). However, this does not imply that attaining product validity is not useful or worthwhile since an indicator with a high product validity still provides the most accurate and detailed information about safety performance. If we consider

validity as a matter of degree, and not a “yes or no” concept, we can consider a high degree of relative validity a lower (yet for some purposes acceptable) degree of validity than product validity.

A parallel can be made here with other types of research, such as driving simulator research. The validity of driving simulator studies is fairly often questioned because one may doubt the extent to which behaviour in a simulated road environment corresponds to the participants’ actual driving behaviour in a real-life environment (De Ceunynck et al., 2015a; Fisher et al., 2011). While product validity of the driving simulator as a research tool is not always attained, there is however plenty of research showing that driving simulators generally reach high relative validity (Bella, 2009; Godley et al., 2002; Törnros, 1998; Yan et al., 2008). This implies that the driving simulator is considered a valid tool for controlled experiments to compare safety aspects between different experimental conditions. As an illustration, suppose we are interested in comparing drivers’ speed behaviour while approaching two different types of road design. If we observe a considerably lower approach speed for road design A compared to road design B, relative validity implies that we can be confident that we would also observe a lower speed at road design A than at road design B in the real world. However, it is unsure whether the driving speeds in absolute terms would be exactly the same in the real world. The exact driving speeds in the real world (and the order of magnitude of the difference between both designs) might differ substantially. This is (the uncertainty about) product validity.

Therefore, it is concluded that one should ultimately aim to attain product validity for a surrogate safety measure, but that one should be aware that a measure that has a sufficient relative validity can be useful for specific study designs as well.

Process validity indicates the extent to which conflicts can be used for describing the process that leads to crashes (Svensson, 1998). Product (or relative) validity in itself may be enough to identify high-risk locations, to assess which road designs have a better safety performance than others, and which measures have a positive effect on the (expected) number of crashes that take place. In itself, however, this validity does not suffice to reveal the chains of events underlying the crashes. In other words, such indicators cannot necessarily tell us *why* or *how* some locations perform better or worse than other locations. To be able to reveal such event chains, the factors and processes that lead to conflicts should be similar to those that lead to crashes. When the factors are highly similar, studying the factors that lead to traffic conflicts can be considered a valid alternative for analysing the factors that contribute to traffic crashes. Therefore, process validity is a highly relevant form of validity additional to product (respectively relative) validity.

Given the fact that validity as a concept has multiple dimensions and is a continuum, it is not an easy task to summarise the current status in the field. The literature shows mixed results. A number of publications indicate a poor relationship between the number of conflicts and crashes and have seriously questioned the usefulness of TCTs (Glennon et al., 1977; Tiwari et al., 1998; Williams, 1981). Researchers analysing reasons for the poor performance of the number of conflicts as a surrogate safety measure however came to the conclusion that at least part of these issues can be attributed to unreliable and underreported

crash data itself, and to operational and methodological issues to the studies themselves (such as ill-founded operations of the concept of “conflicts” and poor data collection methods) (Chin & Quek, 1997; Muhlrads, 1982; Oppe, 1977; Peesapati et al., 2013). On the other hand, there is a significant body of literature that has investigated the relationships between surrogate safety measures (operationalized in various ways) and crashes and came to favourable results (Brown, 1994; El-Basyouny & Sayed, 2013; Hydén, 1987; Lareshyn et al., 2017b; Lord, 1996; Peesapati et al., 2013; Sacchi et al., 2013; Sonchitruksa & Tarko, 2006; Zheng et al., 2014a, 2014b).

Therefore, it seems fair to conclude that the concept of surrogate safety measures in the broader sense has shown a reasonable degree of relative and process validity as a surrogate for crashes. Some indicators and techniques (e.g. the US and Swedish TCT) have been somewhat more elaborately validated than others, but no indicator or technique has been proven to outperform the others.

Additionally, it must be added that many of the validation studies are relatively old studies, and a critical reassessment needs to show which findings still apply to current practices in surrogate safety studies (using video analysis software) and current traffic conditions (much busier traffic, traffic calming designs, safer vehicles, driver assistance technologies, etc.). It also seems that human observers can have a bias towards “adjusting” TTC, speed, etc. based on their subjective perception of the dangerousness. For example, it has been shown that many situations that a human observer would judge as an event with two road users on a collision course do not in fact have a collision course when it is measured precisely (Lareshyn et al., 2017b). It therefore needs to be kept in mind that an automated tool replacing a human observer will likely not produce the same results even though formal definitions and thresholds are kept exactly the same. This can affect the transferability of results from (older) validation studies based on human observations to (newer) studies based on automated observations.

In conclusion, more research around the validity of surrogate safety measures is strongly recommended, but it should be kept in mind that high product validity does not always seem a prerequisite to use surrogate measures of safety as a useful and valid tool for road safety studies. A sufficiently high level of process and/or relative validity allows for a wide range of road safety evaluation and diagnosis activities.

## 2.6.2 Safety continuum and continuous indicators

There seems to be a blind spot in surrogate safety measures studies about the interpretation of continuous indicators like TTC, TAdv and speed-based indicators that result in time series for each traffic event. In traditional TCTs, this data is reduced to a single value per event to identify and count serious conflicts, for example by applying a threshold on TA or  $TTC_{min}$ . Other approaches have been tested to derive a single indicator value from its time series, such as 15<sup>th</sup> centile (St-Aubin et al., 2015). Although interpreting the number of serious conflicts (and less serious conflicts) over an observation period is the most common method to evaluate road safety at a site, the complete distribution of indicators such as  $TTC_{min}$  can also be analysed, although the conclusions may be more difficult to draw (St-Aubin et al., 2015). This is one of the ways of empirically investigating

the safety hierarchy or continuum by ranking the severity of all observed traffic events on the same dimension. Research is still necessary to interpret these distributions and how different parts of the safety hierarchy may relate in different ways to safety (Saunier et al., 2011, 2010; Svensson, 1998; Svensson & Hydén, 2006). Some evidence suggests that events further down the severity hierarchy may actually indicate proper and safe interactive behaviour between the road users, especially at unsignalised intersections (including roundabouts), where interactive behaviour and road user awareness of each other is the intended mode of safe operation (Svensson & Hydén, 2006). Further research is needed on the measures used to define the safety hierarchy, i.e. how to rank the interactions in a safety hierarchy, and on the interpretation and comparison of these hierarchies, for example to identify indicator distributions that are typical for safe and unsafe situations.

There has been some research in the analysis of the continuous time series of road user interactions, instead of deriving only a single value. This has been implemented in the form of the clustering of interactions, in the case of a video dataset of crashes and conflicts, based on various time series such as distance, speed differential and TTC (Saunier & Mohamed, 2014). Appropriate similarity measures based on the longest common subsequence are used to compare time series, including their rate of change. The resulting clusters show that some conflicts appear to bear no similarity to observed crashes and should therefore not be used to draw conclusions about safety. This is one of the only attempts to empirically define process validity, which can lead to better defining which traffic events should be used for safety evaluations. An important point is that such analysis is feasible only in an automated way.

### 2.6.3 Outcome severity in case of a crash

It was found that the vast majority of surrogate safety measures describe the severity of an event only in terms of nearness to a crash (i.e. the proximity of the involved road users in time and/or space to a crash). The potential outcome severity in case the event had led to a crash is usually not included. From a validity perspective, this can be considered an important limitation as the holistic reflection of risk is not attained.

It was stated earlier that validity has to be assessed relative to the purposes and circumstances of the study (Brinberg & McGrath, 1985). Current road safety policies acknowledge that it is mostly the severe crashes that need to be avoided. Most road safety policy documents set ambitious targets for reducing the number of fatalities in the traffic system and quite a few set targets for reducing the number of severely injured victims as well. It seems, however, that few of them set explicit targets for reducing the number of slightly injured victims. Additionally, Vision Zero suggests that policymakers and road designers should strive towards a traffic system without fatalities or serious injuries, but acknowledges the fact that a traffic system without any crashes may be difficult to accomplish (Johansson, 2009). In that way, the vision "accepts" that property damage only or slight injury crashes may still happen.

Therefore, in order to be "valid" to support policies such as Vision Zero, the applied surrogate safety measures need to better reflect the outcome severity. By using

surrogate safety measures that reflect the occurrence of any crashes instead of the most severe ones, there is a risk that conclusions cannot meet the demands of road safety policy. A strong recommendation is therefore to further develop and apply surrogate safety measures that take the severity of the potential outcome severity into account as well.

To this aim, a new indicator (Extended Delta-V) has been designed to better reflect the severity in case a crash would have resulted from the traffic event. The conceptual framework and a field test are presented in detail in Chapter 3.

#### 2.6.4 Strengths and limitations of this literature review

The strength of this study is that it provides a systematic overview of the scientific literature around surrogate safety studies. It provides broad information about the field that can be used for a wide variety of goals (Armstrong et al., 2011). It can help to reduce duplication of research efforts and can guide future research in the field (Armstrong et al., 2011; van Wee & Banister, 2016).

A limitation of the study is the relatively high number of found publications for which no full text could be accessed. Because of this high number of missing publications, it cannot be claimed that this scoping review provides a complete overview of the existing literature. This is partly the consequence of the decision to include all types of publications found from the databases, including not only journal papers, but also research reports, conference papers, doctoral dissertations, book chapters, etc. A solution that could have partly avoided this issue would have been to limit the review to journal papers only. Limiting the included publications in a scoping review to journal papers only is not uncommon and leads to much higher percentages of found full texts because journal papers (even older ones) are more easily accessible than other types of publications such as research reports and conference proceedings (Pham et al., 2014). However, we know from experience that many influential studies in this domain (especially older studies) have not been published as journal papers. It has therefore been decided not to limit the type of publication. While this may have come at the cost of having less of a non-biased sample of publications than when we would have focused on journal publications only, we believe that it has strongly improved the content of our review.

A limitation of the wide scope of a scoping review, is that it does not allow to go into a very high level of detail of the different aspects. The use of a predefined code book to systematically collect the content of the papers inevitably provides a strong simplification of the richness of existing literature. Future research could narrow the focus to specific subtopics of surrogate safety literature and deal with them into more detail. Additionally, it could be useful to conduct systematic reviews of related research fields (including naturalistic driving and microsimulation studies) with the specific focus of identifying aspects that might be of use in site-based surrogate safety studies (such as investigating the potential of new indicators, tests of threshold values, methods of data analysis, etc.).

## 2.7 Conclusions

In recent years, research and use of surrogate safety measures has increased significantly. While human observations were traditionally the most common way of collecting surrogate safety measures, (semi-)automated video analysis techniques have become the most common way of collecting and analysing surrogate safety measures. The applied surrogate safety indicators (such as TTC or PET) and traffic conflict techniques (such as the Swedish TCT and the US TCT), the threshold values applied to distinguish between severe and non-severe events, number of observation sites and duration of observations, data analysis techniques and supplementary data collected show an overwhelming variety and creativity. While this partly reflects the traffic safety research community's strong interest and need for surrogate safety measures and provides a variety of different insights into methodological aspects as well as policy-relevant questions, it also indicates that the field lacks unified methodologies and a generally accepted "best practice" framework. As a result, the quality of studies, and the reliability of their results, varies strongly.

Behavioural observation studies are usually conducted by means of camera footage or human observers on-site. Drivers' speed is by far the most commonly analysed behavioural aspect. Other commonly studied behavioural elements on road sections are the following distance and road users' lateral position. In studies that take place at intersections, yielding behaviour, red light violations and looking behaviour are the most commonly collected behavioural aspects.

The relation between surrogate safety measures and crashes is an important aspect regarding the usability of the surrogates. The conducted validation studies are few, most of them are relatively old and use data collected by human observers. The transferability of results from these earlier validation studies to the current context using automated sensor techniques in a changed traffic environment is therefore uncertain. Therefore, more research around the validity of surrogates is strongly recommended. It should be kept in mind though that high product validity does not have to be a prerequisite to use surrogate safety measures as a useful and valid tool for road safety studies. A sufficiently high level of relative validity allows for a wide range of road safety evaluation and diagnosis activities while process validity allows for a deeper understanding of the underlying factors leading to crashes.

It was also concluded that applied surrogate safety measures need to reflect outcome severity in a better way. Including the potential outcome severity in surrogate safety measures is very much in line with the philosophy of Vision Zero that sets the highest priority on elimination of fatalities and severe injuries rather than prevention of any kind of crashes.

## Chapter 3. In search of the severity dimension of traffic events: Extended Delta-V as a surrogate safety indicator

This chapter presents the theoretical framework and first implementation of a new surrogate safety indicator named Extended Delta-V. This indicator has been defined to meet some of the limitations of existing indicators that have been identified in Chapter 2. This study therefore addresses research question (1), "How are surrogate safety measures applied in scientific literature, and how can measures be improved/defined to mitigate current limitations?"

The content of this chapter is published in Laureshyn et al. (2017a). My main contributions to this study are performing the majority of the data processing and analyses of the case study as well as writing most of the paper. Defining and implementing the indicator itself was mainly the responsibility of the lead author.

### 3.1 Introduction

The literature review in Chapter 2 revealed that dozens of surrogate safety measures have been developed over the past decades (De Ceunynck et al., in review). Most of these measures express the severity of a traffic encounter as its proximity to a crash in terms of time or space (Zheng et al., 2014a). However, proximity to a crash is only one dimension of 'severity'. Intuitively, getting close to a crash that would likely have resulted in a slight touch should not be considered as severe as getting equally close to a crash that would likely have resulted in a severe injury. Therefore, the potential severity of the consequences in the event that a crash would have taken place needs to be taken into account in some way (Laureshyn et al., 2010). According to initiatives such as Vision Zero, policymakers and road designers should strive towards a traffic system without fatalities or serious injuries (Johansson, 2009). The primary goal of Vision Zero is, therefore, to avoid *severe* crashes, rather than *all* crashes. Thus, the event severity that is calculated from an indicator should express the proximity to a serious/fatal injury rather than the proximity to a crash alone. Very few of the existing surrogate safety measures take the outcome severity into account in some way. For example, the Swedish TCT (Hydén, 1987) uses both the proximity in time and the speed at which the conflict takes place, which indirectly reflects the possible consequences. The Dutch technique, DOCTOR (van der Horst & Kraay, 1986), and the Canadian TCT (Brown, 1994) use a subjective score for potential consequences that is added to the objective nearness-in-time indicator(s). However, these examples are exceptions and the ways they combine the probability of a crash and its consequences are not completely problem-free.

In order to develop a surrogate safety indicator that meets this suggested definition, three questions need to be addressed:

- 1) How can we measure the proximity of an encounter to a crash?
- 2) How can we measure the consequences in the event a crash would have taken place?
- 3) How can we weigh both elements together?

These three questions will be addressed in the following subsections.

## 3.2 Extended Delta-V as a measure of the severity of a traffic event

### 3.2.1 How to measure nearness-to-crash

As indicated, the nearness to a crash has been studied extensively, since most surrogate safety measures are exclusively based on some measure of proximity in time or space. From a methodological perspective, the time-based measures are preferred, since they are the result of a combination of road users' speeds and distances (Laureshyn et al., 2010). One of the most frequently used surrogate safety measures is TTC. TTC is defined as 'the time until a crash between the vehicles would occur if they continued on their present course at their present rates' (Hayward, 1972). In the Swedish TCT, the TTC value at the moment of the evasive action start (TA-value) together with the driving speed define the severity of a traffic event (Hydén, 1987), while the minimum value of the TTC ( $TTC_{min}$ ) during an encounter is used as a part of the DOCTOR technique (van der Horst & Kraay, 1986). In recent studies using automated video analyses,  $TTC_{min}$  has also been commonly used as a surrogate safety indicator (De Ceunynck et al., in review).

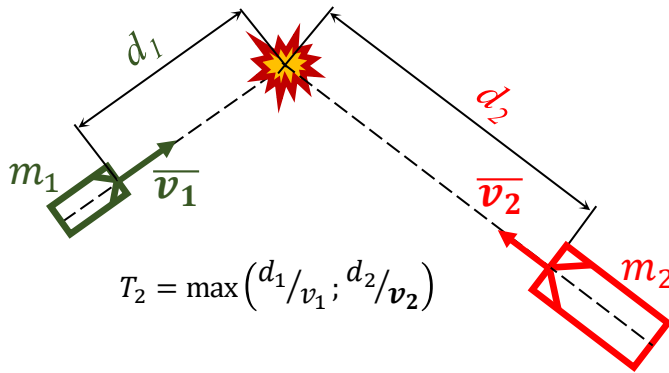
PET is applicable in situations where two road users pass the 'conflict zone' with a time margin (Allen et al., 1978). It is defined as the time between the first road user leaving the 'conflict zone' and the second one arriving at it. A PET value equal to zero indicates no margin, i.e. a crash.

In order for a crash to take place, a collision course of the two road users is a pre-condition; without it, a crash is not possible. However, encounters without a collision course might have crash potential as well, since even minor changes in the spatial or temporal relationships between the road users can lead to a collision course. This means that the use of TTC alone is not sufficient for detecting all potentially dangerous situations. This is also supported by the observations of actual conflicts in traffic (van der Horst, 1990). Svensson (1998) noticed that in situations where two vehicle drivers were about to miss each other by a very short time margin, their evasive behaviour was the same as if they were on a collision course. In other words, even though there was strictly speaking no collision course, the drivers perceived and acted as if they were on a collision course. Laureshyn et al. (2010), in an attempt of studying in detail the process of traffic conflicts, noted that an interaction between two road users could smoothly switch from being a collision course event to being a non-collision course event, and vice versa. Since this was a result of very minor (and reversible) speed changes, it appears counter-intuitive if the dangerousness of the situation would change dramatically from one time instance to the next. Also, it was noted that in fact the majority of the situations that a trained conflict observer would select as conflicts and having a collision course had in fact small time margins revealed if more accurate tools for speed and position measurements were used (Laureshyn et al., 2017b).

Therefore, measures used to describe the severity of any interaction should be flexible enough to include both the collision course and non-collision course state, and allow a smooth transfer between both. The indicator  $T_2$  suggested by

Laureshyn et al. (2010) is an attempt to fill this gap.  $T_2$  describes the expected time for the second (latest) road user to arrive at the conflict point, given unchanged speeds and 'planned' trajectories (see Figure 21). If the road users are on a collision course,  $T_2$  equals TTC. In the event that the two road users pass the conflict point with a time margin,  $T_2$  reflects the maximum time available to take evasive actions and alleviate the severity of the situation. It is not stated in the original paper explicitly, but the current practice of the application of  $T_2$  is that it is no longer calculated after the first road user has left the conflict zone (since the crash is no longer possible). This put a natural limit for how low a  $T_2$  value can be reached during an interaction – for situations with a large time margin  $T_2$  remains large, while when the margin is small  $T_2$  can also reach small values.

The  $T_2$  indicator extends the concept of TTC, since its calculation does not require a collision course, and therefore allows for a smooth transfer from collision-course and no-collision-course situations within the same interaction without a need to change indicators (unlike the traditional TTC versus PET dichotomy).



*Figure 21 – Simplified illustration of the  $T_2$  concept. Detailed calculations that take into account the dimensions of the road users can be found in Laureshyn et al. (2010).*

Similar to TTC,  $T_2$  is a continuous indicator and can be calculated for any time instance as long as both road users are heading towards the common 'conflict area'. This raises the question of which value (or what combination of values) is most relevant and should be used. The latest possible value of  $T_2$  during an interaction, i.e. the moment when the first road user leaves the 'conflict zone' and after which a crash is no longer possible without a change of trajectories, has practically the same meaning as the PET and reflects the moment when the two road users are closest in space to each other. Alternatively, the minimum value of  $T_2$  ( $T_2^{\min}$ ) during the encounter reflects the moment when they are closest in time. In most cases, these two values coincide (as  $T_2$  normally decreases as the road users approach each other), but in the case of substantial speed changes during an interaction, e.g. due to hard braking, they might represent different time instances.

Because of the more extensive scope of  $T_2$  compared TTC, the  $T_2$  indicator will be applied to express the nearness to a crash. More specifically, the minimum value of  $T_2$  ( $T_2^{\min}$ ) will be used, since this value represents the point where road users

have approached each other closest in time, which can therefore be considered the most critical instant of their interaction.

### 3.2.2 How to measure consequences in the event a crash would have taken place?

Delta-V ( $\Delta v$ ) is a notation often used in physics to denote an object's change of velocity (for example, because of an impact with another object). In the context of road crashes, Delta-V refers to the change of a velocity vector experienced by a road user during a crash. A rapid change in the magnitude and the direction of the speed implies extensive forces acting on the road user and can be expected to have a strong effect on personal injuries. Moreover, Delta-V is sensitive to the 'vulnerability' of the road user, since a light object colliding with a heavy one will 'bounce back', while the heavy object's speed will remain quite unchanged. This is a very important property in studies of crashes between, for instance, a car and a pedestrian or a heavy truck and a car.

Numerous examples in crash safety research support this assumption (Evans, 1994; Gabauer & Gabler, 2008; Johnson & Gabler, 2012). The relationship between Delta-V and the probability of a serious injury is visualised by a logistic regression curve in Figure 22. The example is adopted from Gabauer & Gabler (2006), but the relationship between Delta-V and the risk of serious injury is confirmed by various authors (Augenstein et al., 2003; Evans, 1994; Gabauer & Gabler, 2008; Jokschi, 1993; Ryb et al., 2007). Jokschi (1993) defined a rule of thumb, showing that the mean rate of percentage of two-vehicle crashes resulting in a fatality is approximately proportional to Delta-V to the fourth power. Studies by Evans (1994) and O'Day & Flora (1982) confirm that Jokschi's rule provides a good approximate fit.

Because of this strong evidence, various researchers consider Delta-V the best single predictor of crash severity (Evans, 1994; Shelby, 2011).

The estimation of Delta-V for crashes that have taken place is relatively straightforward. In these cases, there is a 'true' value of Delta-V that has taken place during the crash. Based on evidence about the post-crash trajectories of the involved road users and other information, such as vehicle specifications, experts can make a backward reconstruction of the pre-, during and post-crash phase. An estimation of the Delta-V values experienced by the vehicles in that particular crash can be calculated, for example, by using the momentum conservation principle (Burg & Moser, 2007).

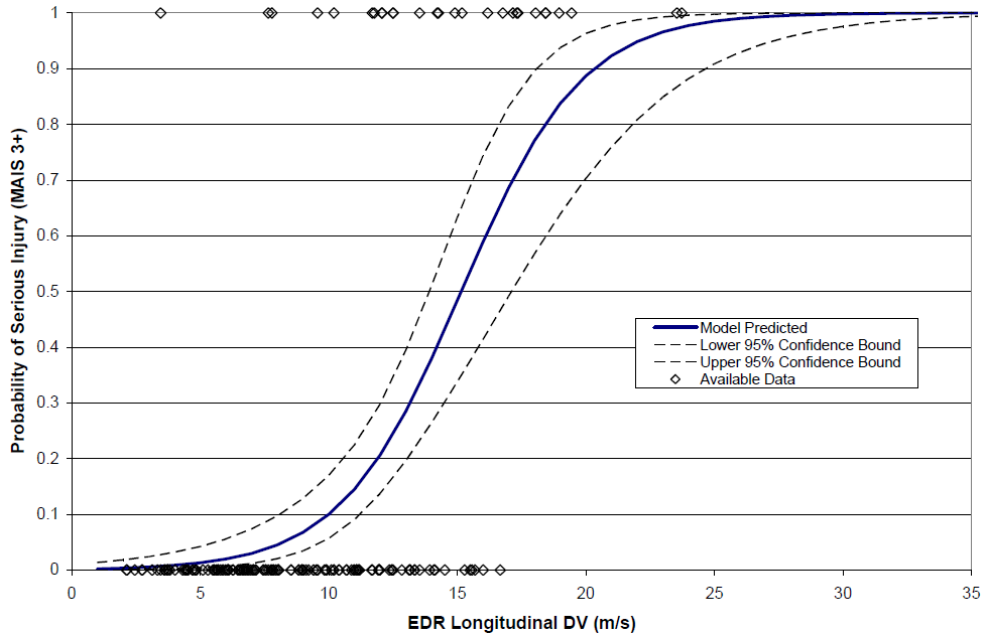


Figure 22 – Illustration of relationship between Delta-V and probability of a severe injury (Gabauer & Gabler, 2006).

It should be mentioned that an important characteristic of the crash which would affect the Delta-V values is how much energy is absorbed by the deformation of the colliding bodies, i.e. how 'elastic' the crash is. As a first simplified approach, we calculate Delta-V as if it was a completely inelastic crash, i.e. both objects stick together and move as one after the first contact. Delta-V (absolute values) for two road users involved in an inelastic crash can be calculated (see Figure 23):

$$\Delta v_1 = \frac{m_2}{m_1 + m_2} \cdot \sqrt{v_1^2 + v_2^2 - 2v_1v_2 \cos \alpha} \quad \text{and}$$

$$\Delta v_2 = \frac{m_1}{m_1 + m_2} \cdot \sqrt{v_1^2 + v_2^2 - 2v_1v_2 \cos \alpha} ,$$

where  $m_1, m_2$  – the masses of the road users 1 and 2 respectively,  
 $v_1, v_2$  – their speeds,  
 $\alpha$  – the approach angle.

Since each road user has its own Delta-V value, to describe the interaction severity the highest value can be used.

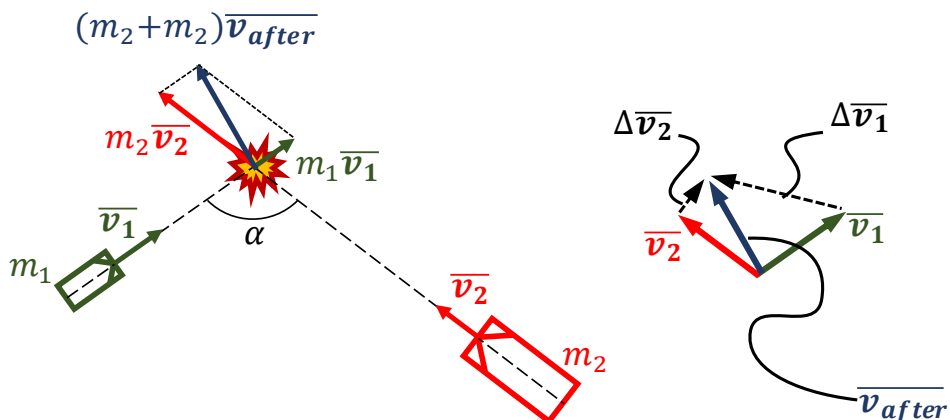


Figure 23 – Calculation of Delta-V based on momentum conservation principle (inelastic crash, i.e. two objects "stick together" after the first contact).

The problem in applying this concept of Delta-V for surrogate safety studies is that no 'true' Delta-V value has manifested itself. However, when assumptions are made about the road users' future movements, it is possible to calculate a hypothetical or 'expected' Delta-V value that would have emerged from a crash. For example, assuming that both vehicles will crash with the same speed as they have at a certain moment during an interaction, their respective 'expected' Delta-V values can be estimated. This, however, creates a number of issues to resolve: *i)* the 'expected Delta-V' becomes a continuous variable that can be calculated for each instant during the interaction; and *ii)* for every instant during the interaction, different values can be calculated based on the assumptions that are made about how the interaction will develop (primarily, if the planned paths and speed will stay the same or change).

Delta-V has not been applied as a surrogate safety indicator until recently when it was incorporated into the automated surrogate safety assessment algorithms of SSAM (Gattman et al., 2008; Shelby, 2011). It is measured by calculating the expected change in velocity between the pre- and post-crash phase of the road users involved in the conflict assuming a hypothetical crash of the two road users at the angle and velocity they have at the moment  $TTC_{min}$  takes place. However, this approach has a number of limitations, particularly when applied on trajectory data observed in field rather than generated by a microscopic model. Firstly, the use of  $TTC_{min}$  as the time at which Delta-V is estimated limits its application to interactions in which there is a collision course only. As mentioned in the previous section, experience from field observation studies learns that many (even close) encounters in traffic do not have an actual collision course (Laureshyn et al., 2017b; Svensson, 1998). Secondly, in this form, the indicator only represents the potential outcome severity in the event a crash would have taken place, but it does not include the nearness to a crash. An event with a large  $TTC_{min}$  value of several seconds can therefore have the same calculated value as a very close interaction with a  $TTC_{min}$  less than one second. Because of this, it is less suitable as a stand-alone indicator to distinguish severe from non-severe events in traffic. It has been acknowledged that the implementation of Delta-V in SSAM still needs substantial improvements (Shelby, 2011), and leads to some counter-intuitive results in experiments (Zha et al., 2014).

A framework that extends to non-collision course events is therefore to be preferred. The use of  $T_2^{\min}$  instead of  $TTC_{\min}$  as the basis for expressing the nearness to a crash in our indicator overcomes this limitation. To overcome the second limitation, the nearness to a crash and the estimated severity of the outcome in the event a crash would have taken place should be weighed together into a single indicator.

### 3.2.3 Extended Delta-V – an attempt to weigh nearness and potential outcome severity

Figure 24 conceptually plots the two main dimensions of traffic event severity that have been identified in the previous sections ( $T_2^{\min}$  and 'expected' Delta-V at the same time instant). Quite intuitively, the severity of an encounter increases as the  $T_2^{\min}$  value goes down (as the road users are closer to a crash) and as the 'expected' Delta-V value goes up (as the consequences can be more severe). Encounters that combine a low  $T_2^{\min}$  value and a high 'expected' Delta-V value can be considered very dangerous situations. The "severity level"-lines represent the events of "equal severity". How exactly the "severity" can be calculated requires clarifications.

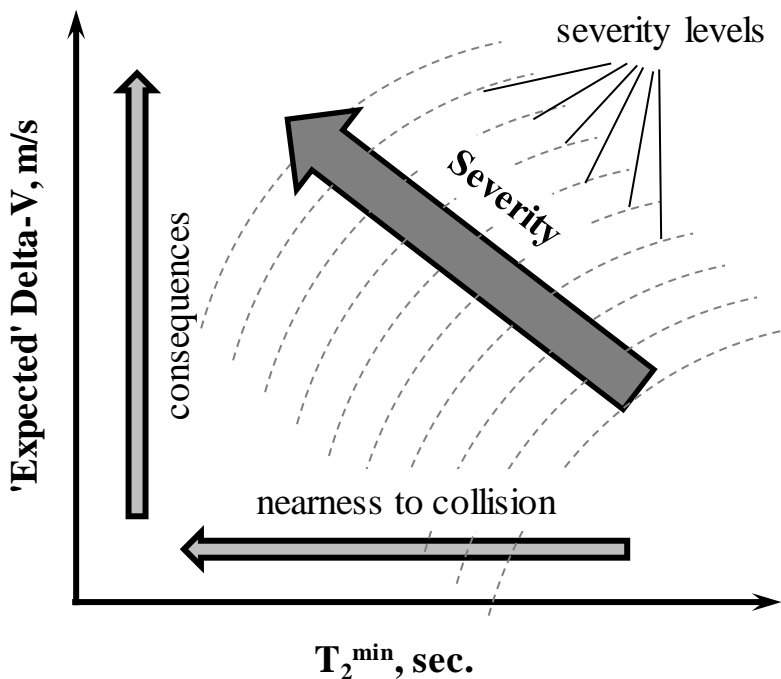


Figure 24 – Conceptual illustration of the main dimensions of conflict severity.

The problem of the 'expected' Delta-V is that it assumes a crash at the current speeds of the involved road users and does not take into account any available opportunity to take an evasive action and decrease the consequences of the hypothetical crash. We suggest a new severity indicator – Extended Delta-V – that is calculated with speeds that are reduced based on the assumption that the two

road users spent the time available to brake before arriving at the collision point. The final speed,  $v$ , is then calculated as

$$v = \begin{cases} v_0 - at, & \text{if } (v_0 - at) \geq 0; \\ 0, & \text{if } (v_0 - at) < 0, \end{cases}$$

where  $v_0$  is the initial speed;  
 $a$  is the assumed deceleration rate;  
 $t$  – time remaining for the evasive manoeuvre.

The definition of the time available is quite straightforward in situations with a collision course; here, the current TTC value can be used. If there is no strict collision course, the two road users actually have different times until they arrive at the potential collision point. In this context, it is the time for the latest-to-arrive road user, i.e.  $T_2$  indicator, that appears to be most relevant, as it is objectively the maximal available time until a crash may happen (in case the first road user would 'freeze' at the collision point).

One final point that needs to be addressed is the assumed deceleration of the involved road users. First of all, it depends on the behaviour of the involved road users. Will they brake in a normal way, or will they apply maximum braking force? In this study, we will test two simplified deceleration assumptions as a first case study. We will apply a deceleration of 4 m/s<sup>2</sup> for normal braking, and a deceleration of 8 m/s<sup>2</sup> for emergency braking; the latter is a conservative value for maximum deceleration that nearly all automobiles can achieve (Burg & Moser, 2007). These surrogate safety measures will be referred to as Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub>, respectively. The base Delta-V values, assuming no braking, will be referred to as Delta-V<sub>0</sub>.

### 3.3 The dataset used to illustrate the concept

As a first test case, an intersection in the city of Minsk (Belarus) was analysed for three full days (6 a.m. till 9 p.m.). The intersection is a four-leg intersection equipped with classic two-phase traffic lights. Video footage of two cameras, installed at a rooftop close to the intersection, was used for the analyses.

The videos were analysed using T-Analyst, a semi-automated video analysis tool developed at Lund University (T-Analyst, 2016). The software allows for manually setting up 3D models of road users in video images and projecting their position on real-world coordinates. In this way, the software allows manual tracking of road users in one or more camera views and the calculation of some safety indicators such as TTC, Time Advantage,  $T_2$  and relative speed (Laureshyn et al., 2010). It allows for dealing with large numbers of detections in one database. Figure 25 shows a screenshot of the program.

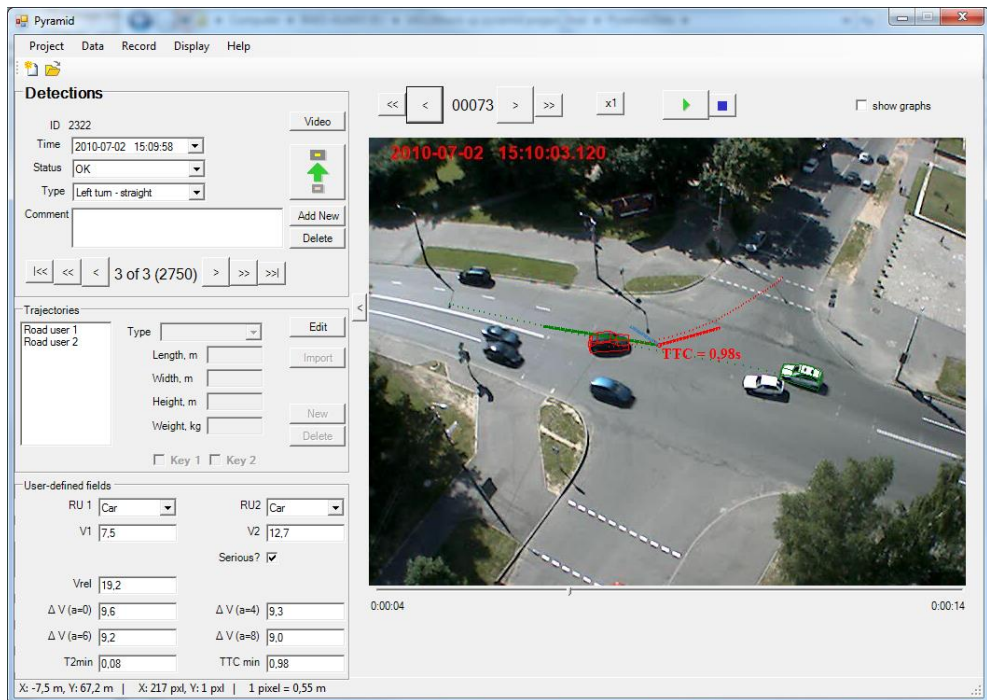


Figure 25 – Screenshot T-Analyst (only one camera view shown).

For illustrative purposes, it was decided to focus only on situations with a left-turning vehicle approaching from the left-hand side in the camera view, and a straight-travelling vehicle coming from the right-hand side in the camera view. This provided a relatively large number of interactions for analysis, while most of the ambiguity in defining the 'planned' trajectories was avoided.

The two cameras' view allowed observing two approaching vehicles approximately 3-4 seconds before the potential conflict area. Simultaneous arrivals (situations of a vehicle intending to make a left-turn while there was a visible straight-travelling vehicle approaching) were counted as 'elementary exposure units' (Elvik et al., 2009b). If the left turn was done in front of the straight-travelling vehicle, it was considered a 'potential conflict' and the trajectories for the two vehicles were extracted and analysed using T-Analyst. Free passages with no straight-travelling vehicle present were not considered 'exposure units' and were not included in the analyses.

### 3.4 Results

Three full days of observations resulted in a total exposure of 12,342 simultaneous arrivals. Of these simultaneous arrivals, 1,165 involved a vehicle turning left in front of a vehicle driving straight through. For all of these situations, a non-zero Delta- $V_0$  value could be calculated. Of these 1,165 situations, 564 had a non-zero Extended Delta- $V_4$  value and 104 had a non-zero Extended Delta- $V_8$  value. Extended Delta- $V$  becomes zero in case both of the vehicles would come to a full stop before reaching the collision point if they had braked at the assumed

deceleration rate (obviously, the higher a deceleration rate that is assumed, the earlier vehicles can stop and thus the more situations will have zero value of the Extended Delta-V). A clear safety hierarchy could be observed: events of low severity were much more common than events of higher severity (see Figure 26).

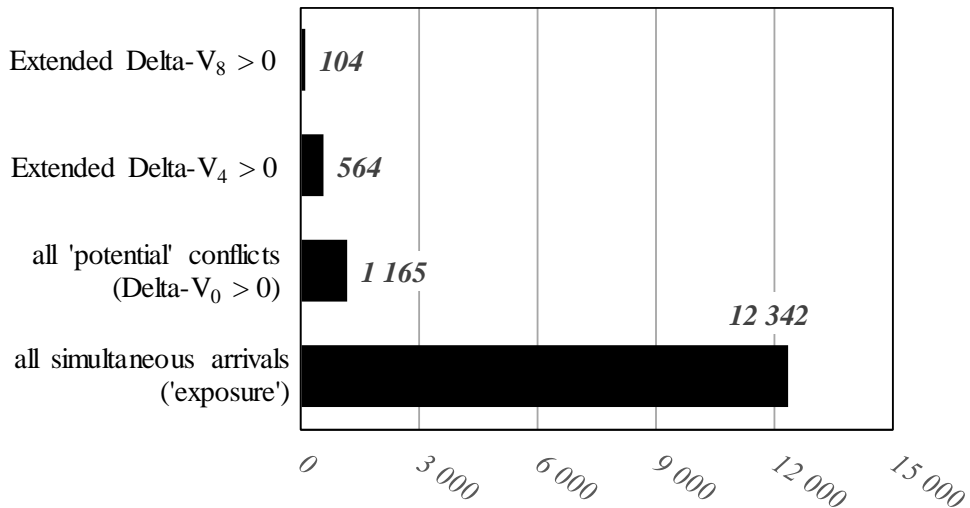


Figure 26 – Frequency of events by severity.

All variables that have been collected for the records with non-zero Delta-V<sub>0</sub> values and their descriptive statistics are presented in Table 2.

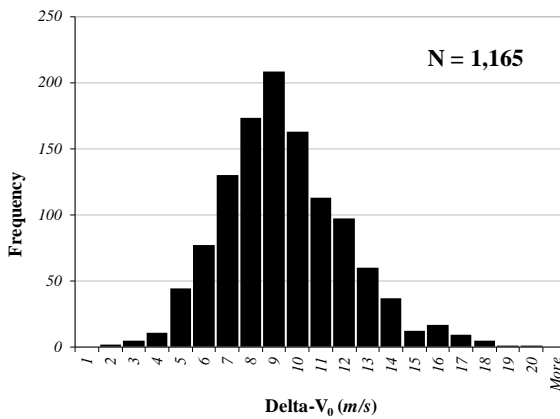
Table 2 – Descriptive statistics of the dataset.

Variable	Descriptive statistics (N = 1,165)
Delta-V <sub>0</sub> (m/s)	Non-zero values = 1,165 Mean = 8.98; St. Dev. = 2.66; Min = 1.5; Max = 19.2
Extended Delta-V <sub>4</sub> (m/s)	Non-zero values = 564 Mean = 2.56; St. Dev. = 1.79; Min = 0.1; Max = 11.1
Extended Delta-V <sub>8</sub> (m/s)	Non-zero values = 104 Mean = 1.76; St. Dev. = 1.59; Min = 0.1; Max = 9.0
T <sub>2</sub> <sup>min</sup> (s)	Available values = 1,163 Mean = 4.05; St. Dev. = 13.99; Min = 0.08; Max = 473.33
TTC <sub>min</sub> (s)	Available values = 247 Mean = 5.19; St. Dev. = 2.38; Min = 0.98; Max = 32.83
Relative speed (m/s)	Mean = 15.5; St. Dev. = 3.96; Min = 3.1; Max = 29.9

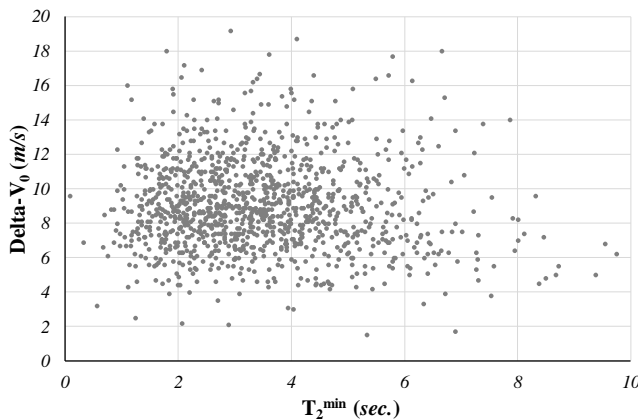
Table 2 – Descriptive statistics of the dataset [cont.].

Left-turning vehicle type	Available values = 1,132 Car = 1024; Heavy goods vehicle (HGV) = 78; Bus = 0; Van = 62
Left-turning vehicle speed (m/s)	Mean = 5.35; St. Dev. = 1.79; Min = 0.4; Max = 12.9
Straight through vehicle type	Available values = 1,132 Car = 844; HGV = 170; Bus = 56; Van = 94
Straight through vehicle speed (m/s)	Mean = 12.02; St. Dev. = 3.76; Min = 0.1; Max = 21.7

The distribution of the Delta- $V_0$  values is shown in Figure 27. The scatterplot in which the Delta- $V_0$  values are plotted against their corresponding  $T_2^{\min}$  values does not show very clear patterns. The histogram shows a two-tailed bell curve, meaning that both the very low values and the very high values of Delta- $V_0$  are relatively uncommon.



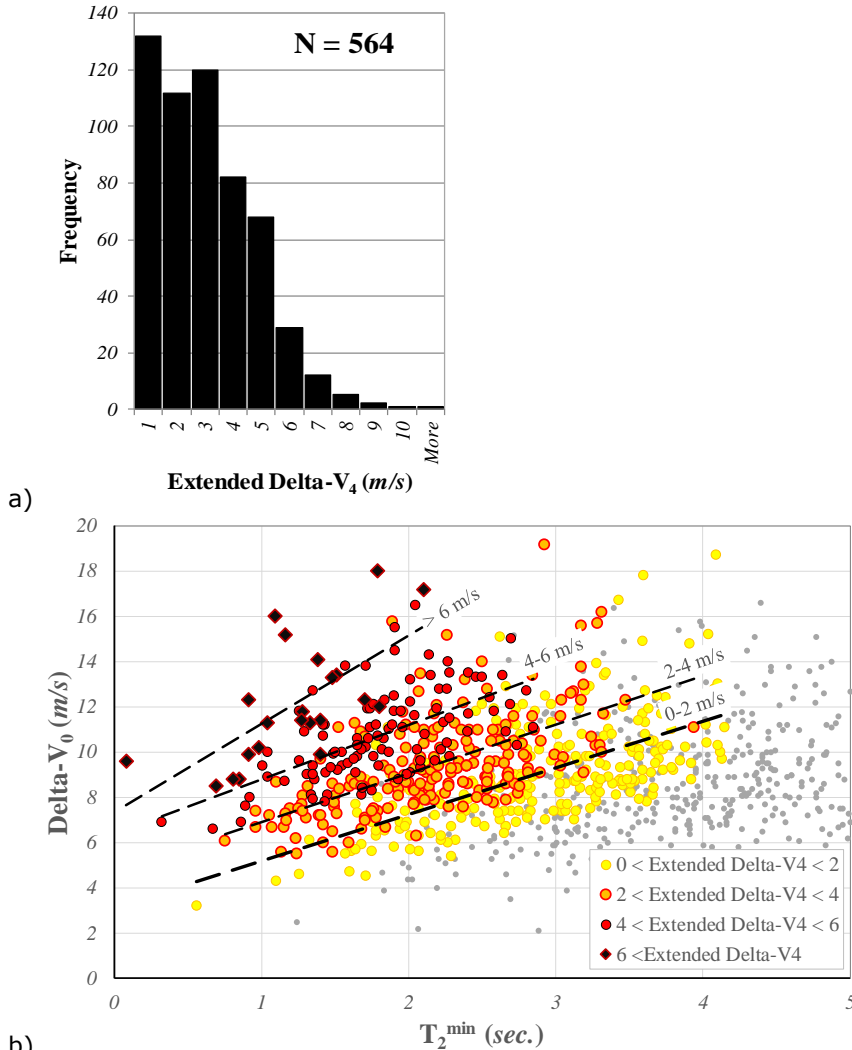
a)



b)

Figure 27 – Delta- $V_0$  values: a) histogram; b) scatterplot against  $T_2^{\min}$ .

The patterns become clearer when Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub> are used to set the severity of the individual interactions (Figure 28 and Figure 29, respectively). Both histograms show a one-tailed shape with a high number of low values and a few high values. This pattern is a bit more distinct in the Extended Delta-V<sub>8</sub> histogram than in the Extended Delta-V<sub>4</sub> histogram.



b) Figure 28 – Extended Delta-V<sub>4</sub> values: a) histogram; b) marked on Delta-V<sub>0</sub> scatterplot.

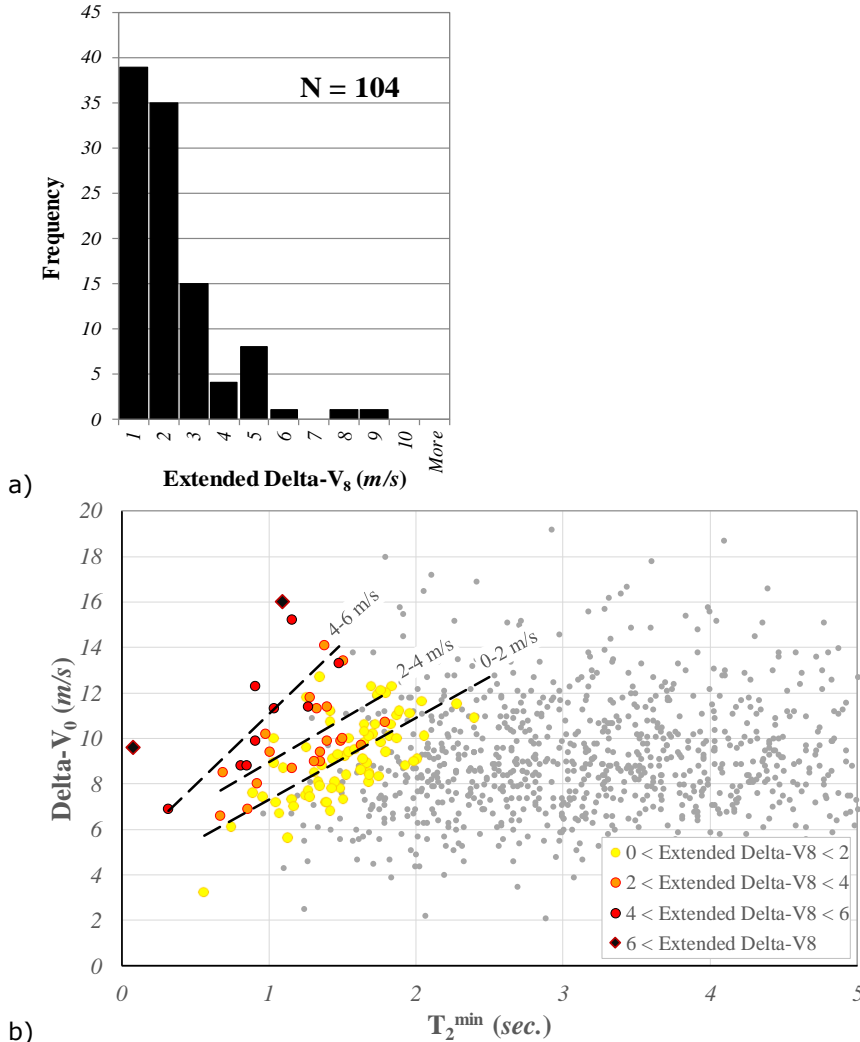


Figure 29 – Extended Delta-V<sub>8</sub> values: a) histogram; b) marked on Delta-V<sub>0</sub> scatterplot.

The scatterplots shown in Figure 28 and Figure 29 are the same as the scatterplot of Delta-V<sub>0</sub> values (Figure 27), but non-zero Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub> values are highlighted in colour. The colour of these points provides the magnitude of the Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub> values in a categorical way (increments of 2 m/s are chosen because they provide a suitable trade-off between accuracy and readability of the graphs). Also, the horizontal axis ( $T_2^{\min}$ ) has been adjusted to focus on the range in which these values occur to make the plot more readable. The dashed lines indicate the trend line of the selected Delta-V<sub>0</sub> versus  $T_2^{\min}$  values (based on ordinary linear regression) for each category of the Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub> values and may be seen as a first approximation of the “severity levels” conceptually introduced in Figure 24 (we omit  $R^2$  values and regression equations as the trend lines are based on a limited number of data points and their purpose is mainly illustrative).

The trend lines of higher categories of Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub> values are positioned more to the top left of the graph than the trend lines of lower categories of Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub>. This shift towards the top left of the graph should be interpreted that generally events of higher severity correspond with higher values of Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub>. The graphs therefore show that both Extended Delta-V<sub>4</sub> and Extended Delta-V<sub>8</sub> identify quite well what can be believed to be the most dangerous conflicts from the dataset. The events of highest severity are a combination of high Delta-V<sub>0</sub> values and low  $T_2^{\min}$  values and are, as mentioned earlier, assumed to be closest to a severe crash. While Extended Delta-V<sub>4</sub> leads to a higher number of selected events, it seems that Extended Delta-V<sub>8</sub> is more selective. Also, it is worth noting that the trend lines for Extended Delta-V<sub>8</sub> are steeper than for Extended Delta-V<sub>4</sub> which means that in weighing together the two dimensions of the severity more weight is given to  $T_2^{\min}$ .

Table 3 shows the 20 most severe Extended Delta-V<sub>8</sub> situations, and how these situations rank for a number of other indicators. Quite some disagreement can be seen among the indicators. The most severe situation according to Extended Delta-V<sub>8</sub> is also considered the most severe situation according to  $TTC_{\min}$  and  $T_2^{\min}$ , while this situation is the second most severe situation according to Extended Delta-V<sub>4</sub>. However, according to Extended Delta-V<sub>0</sub>, this situation is only average; this results from the fact that it is a car-car situation (no differences in mass), with only a moderate relative speed. The extreme closeness in time most strongly defines the severity of this situation; a  $T_2^{\min}$  of 0.08 s implies a very narrow miss. The value considered the second most severe by Extended Delta-V<sub>8</sub> is considered the most severe by Extended Delta-V<sub>4</sub>. This situation has a rather high Delta-V<sub>0</sub> value, caused by a moderate relative speed in combination with a large difference in mass (car-HGV situation). There is, however, a slightly higher time margin that can still be used to brake, which explains the difference in ranking between the two Extended Delta-V indicators.

As a result of the difference in the assumed deceleration rate between Extended Delta-V<sub>8</sub> and Extended Delta-V<sub>4</sub>, it can be seen that the Extended Delta-V<sub>4</sub> indicator places a bit more emphasis on the combination of the relative speed and the mass ratio of the situation, while the closeness in time is a much stronger determinant for the Extended Delta-V<sub>8</sub> situations.

Table 3 – Comparison ranking of the 20 most severe Extended Delta-V8 situations.

Rank $\Delta V_8$	Value $\Delta V_8$ (m/s)	Rank $\Delta V_4$	Value $\Delta V_4$ (m/s)	Rank $\Delta V_0$	Value $\Delta V_0$ (m/s)	Rank $T_2^{\min}$	Value $T_2^{\min}$ (s)	Rank $TTC_{\min}$	Value $TTC_{\min}$ (s)	Rank relative speed	Value relative speed (m/s)	Type of situation	mass ratio
1	9	2	9.3	409	9.6	1	0.08	1	0.98	191	19.2	car-car	1.00
2	7.7	1	11.1	17	16	23	1.09	58	3.99	135	20.2	car-HGV	3.85
3	5.8	3	8.7	119	12.3	12	0.91	-	no value	577	15.5	car-HGV	3.85
4	5	7	7.6	202	11.3	19	1.04	35	3.42	293	18	car-minivan	1.69
5	4.7	24	5.8	908	6.9	2	0.32	12	2.87	741	14.1	car-car	1.00
6	4.5	8	7.3	194	11.4	40	1.27	-	no value	38	22.8	car-car	1.00
7	4.4	19	6.2	561	8.8	8	0.85	-	no value	327	17.7	car-car	1.00
8	4.3	17	6.3	561	8.8	7	0.81	-	no value	338	17.6	car-car	1.00
8	4.3	4	8.2	27	15.2	28	1.16	-	no value	390	17.2	car-HGV	3.85
10	4.2	11	6.9	367	9.9	11	0.91	9	2.29	154	19.8	car-car	1.00
10	4.2	6	7.8	75	13.3	72	1.48	-	no value	5	26.6	car-car	1.00
12	3.9	16	6.4	327	10.2	16	0.98	66	4.1	491	16.2	car-minivan	1.69
13	3.7	13	6.5	367	9.9	59	1.4	31	3.4	154	19.8	car-car	1.00
13	3.7	20	6.1	628	8.5	5	0.69	4	1.92	413	17	car-car	1.00
15	3.6	5	8	43	14.1	57	1.38	-	no value	327	17.7	car-HGV	3.85
16	3	14	6.5	202	11.3	49	1.33	-	no value	44	22.6	car-car	1.00
17	2.9	23	5.9	353	10	79	1.5	-	no value	146	20	car-car	1.00
17	2.9	31	5.5	516	9	47	1.31	14	2.91	293	18	car-car	1.00
17	2.9	15	6.4	194	11.4	59	1.4	-	no value	38	22.8	car-car	1.00
17	2.9	53	5	724	8	13	0.92	20	3.17	526	16	car-car	1.00

In general, it can be seen that the closeness in time still highly defines the severity of an interaction. The 20 most severe situations according to Extended Delta- $V_8$  all have a  $T_2^{\min}$  value of 1.5 s or lower, and all rank in the top 80 most severe situations according to  $T_2^{\min}$ . A high closeness in time is, therefore, still an important prerequisite for an encounter to be considered severe by the Extended Delta-V indicators. This is an important characteristic from a theoretical point of view, since medium-severity time margins are not to be considered dangerous. Rather, they represent the normal traffic process where road users balance the need to behave sufficiently safe with the desire to maintain a sufficiently high level of mobility (Hydén, 1987; Laureshyn et al., 2010; Svensson & Hydén, 2006). On the other hand, a high Extended Delta- $V_0$  value is less essential to be considered a rather severe situation; as long as the time margin is small enough, moderate values of Extended Delta- $V_0$  can also be considered situations of fairly high severity.

It is noteworthy that there is little correspondence between Extended Delta- $V_8$  and  $TTC_{\min}$ . Many of the most severe Extended Delta- $V_8$  situations have no  $TTC$  value at all, i.e. there was no collision course. On the one hand, there is strong evidence for  $TTC$  to be related to the severity of the situation. For example, in a calibration study comparing the severity ranking of situations using different traffic conflict techniques,  $TTC_{\min}$  was found to be a dominant component that the scores of all techniques correlated with<sup>1</sup> (Grayson et al., 1984). On the other hand, there might be advantages in including situations without a collision course, too. For example, the DOCTOR technique (Kraay et al., 2013) uses  $TTC_{\min}$  as one of the main values to assess traffic conflict severity, but also considers close encounters without a collision course serious conflicts.

## 3.5 Discussion

### 3.5.1 Strengths and applications

The Extended Delta-V indicator builds on well-established concepts of crash reconstructions in order to represent the risk of serious injuries or fatalities as closely as possible (Augenstein et al., 2003; Evans, 1994; Gabauer & Gabler, 2008; Jokschi, 1993; Ryb et al., 2007). Integrating the 'Delta-V' element with the time proximity to crashes adds a severity dimension to existing conflict indicators. As the biggest societal burden comes from crashes with the most severe outcomes, attempts to predict and prevent the highest level injuries have been at the core of traffic safety policy and research for a long time. Therefore, valid surrogate safety indicators should by nature be capable of predicting the most relevant crash scenarios, i.e. those with the most severe outcomes. Thus, adding a severity dimension to a conflict indicator might improve the validity of conflict

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<sup>1</sup> One could speculate, however, about the accuracy of the measurements done in the calibration study. Even though the measurements were actually taken from videos, many factors, such as a simplified camera calibration model and calculation procedures for  $TTC$ , low resolution of the images, etc., could contribute to situations whereby very small time gaps are labelled as having a collision course.

indicators as predictors for crashes. Obviously, further assessment is needed to verify this.

The Extended Delta-V indicator is sufficiently flexible to include collision course and non-collision course events, as well as crash and non-crash events.  $T_2$  has been developed explicitly with the aim of allowing for the smooth transfer between collision course and non-collision course events (Laureshyn et al., 2010). In the event of an actual crash,  $T_2^{\min}$  becomes zero, and all variations of the Extended Delta-V values converge to the 'true' Delta-V value experienced by the vehicles involved in the actual crash. This seems to make the indicator flexible enough to cover the whole spectrum of safety relevant situations, ranging from normal encounters over serious conflicts up to and including crashes. This is a major strength of the developed indicator, and it is an adaptation towards use in real-world observations (that often have no collision course) as well as an extension of the Delta-V concept as it has been implemented in microsimulation (Gettman et al., 2008).

A noticeable feature of the indicator is that the severity of some conflicts, those with high Extended Delta-V values, may be considered higher than the severity of some actual crashes. Imagine a crash between two cars manoeuvring at very low speeds in a parking lot. In this situation, the risk for a severe injury is low and the actual Delta-V values that take place during the crash are also low. On the other hand, a narrow miss between two vehicles with high differences in mass and speed is likely to have a much higher (calculated) Extended Delta-V value. Although there is no actual crash, the situation is still severe since the road users come very close to a situation with a high risk of serious injury. However, this does make sense if one's purpose is to assess the severity of a traffic situation, not only in terms of its proximity to a crash, but in terms of its closeness to a serious injury.

The suggested indicator can be used in fully automated surrogate safety measurements, since all required parameters (speeds, trajectories, road user type estimates) can be retrieved from video footage, and with slight alterations, also from data from other sensors. Given the rapid evolution of the domain of site-based observations of surrogate safety measures towards automated analyses (Laureshyn et al., 2010; Saunier et al., 2010), this is an important advantage of the indicator.

### 3.5.2 Challenges and future research

For reasons of feasibility, this first operationalisation of the Extended Delta-V indicator accepted a number of simplified assumptions. Making them reflect realistic situations more closely should improve the performance of the indicator:

- 1) The assumed braking force is now a constant. The true maximum braking force, however, depends on the maximum tyre-roadway friction which, in turn, depends on the weather, the type and condition of the pavement, the vehicle type, the type and condition of the tyres, the speed of the vehicle, etc. (Roe et al., 1991; Warner et al., 1983). While it will not be feasible to include all of these aspects (for instance, video footage does not allow for retrieving information about the tyres of the vehicle), a number of refinements can be introduced;

2) While it is expected that Extended Delta-V will especially highlight VRU-related conflicts, the evasive actions of pedestrians and cyclists are not the same as motor vehicles. For example, cyclists were found to swerve rather than brake (Laureshyn et al., 2017b) while pedestrians have an ability to stop in a fraction of a second and even change direction to the opposite (jump back). Assumptions of 'a tyre braking on dry asphalt' are definitely not ideal here. Elaborating the framework to include other types of possible evasive actions such as swerving and accelerating could be a useful direction for future research;

3) Only four different vehicle masses were distinguished (car, HGV, bus, minivan). These assumptions can be refined. Information about the mass of vehicles can usually be retrieved from various databases. For efficiency reasons, it would be best if the estimated mass of vehicles could be retrieved automatically by the video analysis software. One possibility could be to relate the mass of the vehicle to its length, which is a feature that can be retrieved automatically relatively easily;

4) In the current calculations, a completely inelastic crash is assumed. This can be seen as a crash between two clay balls, which will stick together after the crash and proceed along the same post-crash trajectory. While this is a reasonable approximation, in reality, motor vehicle crashes exhibit a somewhat elastic effect, where the vehicles slightly rebound off each other again (Shelby, 2011). This effect is modelled using a so-called coefficient of restitution, which equals zero (0.0) for completely inelastic crashes (as was assumed here), and one (1.0) for completely elastic crashes. In practice, low speed crashes have a coefficient of restitution of around 0.4, while this coefficient decreases at higher impact speeds to around 0.1 (Nordhoff, 2005).

5) It should be pointed out that, while there is a clear correlation between the (actual) Delta-V endured by a road user during a crash and the likelihood of (severe) injury, the relationship between crash impact and injury outcome is quite complex and the resulting severity of injuries from a crash are affected by many factors. For example, elderly vehicle occupants are more likely than younger occupants to be severely injured in similar crashes (Evans, 2001; Farmer et al., 1997; Li et al., 2003). The crashworthiness of a vehicle (including passive safety systems) also affects the probability and severity of injuries in a given crash substantially. Additionally, motor vehicles can absorb more impact energy in frontal impacts than in side impacts due to the presence of crumple zones in the front of the vehicle. Occupants who are seated more closely to the point of impact have a higher probability of sustaining severe injuries than occupants farther away from the impact point (Evans & Frick, 1988). While some of these aspects could be taken into account when further advancing the conflict indicator, others cannot.

Apart from optimising the theoretical framework and the parameters of the calculation, validation research is needed to check whether a surrogate safety indicator can be used as a true measure of safety. This implies that a sufficiently large body of evidence must be found, showing close correlations between crashes and the calculated values of the indicator. This need for validity research does not only apply to the Extended Delta-V indicator as it was introduced in this chapter,

but also to many of the indicators that are applied today (Laureshyn et al., 2017b; Zheng et al., 2014a).

While this study shows that the applied Extended Delta-V indicators allow for ranking the severity of traffic encounters, it is not yet clear how the values should be interpreted from a safety perspective. For instance, it is unclear whether a threshold value should be defined between what is considered a severe and a non-severe traffic event, or that the results should be interpreted from a continuous perspective.

One of the approaches in surrogate safety analysis is the use of extreme value theory, i.e. calculations of probabilities to get very extreme (having low probability) values of an indicator based on the distribution of the 'normal' values (Songchitruksa & Tarko, 2006). For example, if the PET indicator is used, one could formulate the problem as 'what is the probability of observing  $PET < 0 \text{ sec}$ ', which means a crash. While studying the Delta-Vs from actual crashes, one can find a threshold after which severe injuries become very probable; however, in the case of a hypothetical Extended Delta-V value, it is not clear how the threshold should be defined, and once defined, how it should be interpreted.

The case study only applied to one type of manoeuvre, one type of intersection, and only to motorised vehicles. It will be necessary to test the indicator in other circumstances and for other types of road users. It will be especially relevant to see how the indicator will behave when applied to situations with VRUs. Existing surrogate safety measures are usually optimised for encounters among car drivers, but are often less suitable for applying to VRUs (Shbeeb, 2000).

### 3.6 Conclusions

We suggest Extended Delta-V as a measurement of the severity of traffic events that takes into account both proximity to a crash and severity of its potential consequences. The indicator is applicable to situations in which two road users are heading towards a common conflict area. Extended Delta-V is calculated as the expected change of velocity experienced by a road user in the event that the conflict would have resulted in a crash. The relevant value is the one that applies to the moment  $T_2^{\min}$  takes place, which is the moment when the expected time for the last-to-arrive road user to arrive at the common conflict point becomes minimal. A first case study suggests that the indicator succeeds quite well at integrating both dimensions of conflict severity and selecting the most severe events in traffic. While this is a promising first step towards operationalising an improved surrogate safety indicator, further research is needed on the development of the indicator itself as well as on the validity of selected events as predictors for the eventual safety level.



## Chapter 4. Sharing is (s)caring? Interactions between buses and bicyclists on bus lanes shared with bicyclists

This chapter assesses the safety of bicyclists on bus lanes shared with bicyclists through a mixture of surrogate safety indicators and behavioural indicators. The surrogate safety indicators that are used to assess the severity of interactions between bicyclists and buses are  $TTC_{min}$ , Time Gap and lateral overtaking distance. Behavioural indicators that are analysed include lateral position, riding speed and overtaking speed. By combining these indicators, the study aims to contribute to answering the second research question, "How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed?".

The findings included in this chapter are published in De Ceunynck et al. (2017b). Data were collected and some first analyses were performed within the frame of the Master thesis of the second author of the paper. My role in this study was to design the study set-up, guide the Master thesis, perform the final analyses that have been included in the paper and in this chapter, and write the paper.

### 4.1 Introduction

Available space is often limited and may not allow for the provision of separate facilities for all road users. This is especially the case in urban areas. Allowing bicyclists to make use of bus lanes may be considered as a compromise to balance the needs of all road users. However, the safety effects of allowing bicyclists to make use of bus lanes have scarcely been investigated. Whether or not bicyclists should be allowed to make use of bus lanes is therefore a subject of debate for policy makers and traffic engineers on an international level (Weinstein Agrawal et al., 2012).

This study makes use of semi-automated video observation software with the aim of analysing bicyclists' safety on bus lanes shared with bicyclists. Two straight sections of bus lanes shared with bicyclists in Belgium have been selected for detailed analysis, and two full weeks of video footage have been analysed for each bus lane. Interactions between bicyclists and buses are analysed using surrogate safety indicators (overtaking proximity, time gap and  $TTC_{min}$ ), and the behaviour of bicyclists who are in interaction with buses is compared with the behaviour of bicyclists who are not in interaction with buses.

### 4.2 Background

#### 4.2.1 Bus lane safety and bus-bicycle crashes

While there is a significant body of literature assessing the impact of bus lanes on traffic flow (for buses as well as other traffic) and on bus punctuality, the impact of bus lanes on traffic safety has largely been overlooked (Tse et al., 2014). A meta-analysis of the effects of bus lanes on traffic safety suggests that bus lanes generally lead to an increase in the number of injury crashes (Elvik et al., 2009a).

It is, however, unclear what types of crashes increase due to the presence of bus lanes. Moreover, only one study was found that specifically investigated the impact of bus lanes on bicycle crashes. The study found indications that an increase in bicycle crashes may take place after the implementation of a bus lane (Devenport, 1987).

A study of seven major cities in different countries shows that some allow bicyclists to share bus lanes, while others do not (Weinstein Agrawal et al., 2012). This indicates that there is some disagreement on whether or not it is desirable to allow bicyclists to share bus lanes. No studies have been found that specifically examine the safety of bicyclists when sharing bus lanes.

Buses and bicycles are at the opposite ends of the spectrum in terms of size, mass and manoeuvrability; while bicycles are small, light and agile, buses are large, heavy and rigid (Austroads, 2005). Therefore, safety conflicts may arise when buses and bicycles are sharing the same space on the roadway (Baumann et al., 2012). An Australian study (Austroads, 2005), focusing on bus–bicycle crashes on all roads, shows that the majority (55%) of crashes between buses and bicycles takes place at intersections. For non-intersection crashes, the most frequent type of crashes are angular crashes (60% of all non-intersection crashes). Angular crashes are crashes in which at least one of the vehicles is hit at the side in the crash. These non-intersection angular crashes are mostly related to lateral movements of buses on the roadway, such as overtaking. The study also points out that of all the types of bus–bicycle crashes, angular crashes and rear-end crashes have the highest probability of resulting in a fatal outcome.

#### 4.2.2 Subjective safety of bus–bicycle interactions

Baumann et al. (2012) performed a survey with bus drivers and bicyclists regarding bus–bicycle interactions. They concluded that the overtaking of a bicycle by a bus is considered an uncomfortable manoeuvre for both parties; 59% of bicyclists and 68% of bus drivers indicated that they feel uncomfortable while interacting with each other. This finding is indirectly confirmed by a stated preference survey on bicycle infrastructure preferences. Caulfield et al. (2012) find that bicyclists are less likely to choose routes that have a bus lane with shared use with bicyclists. The only type of infrastructure that is considered as undesirable as the shared-use bus lane is mixed traffic (i.e. no bicycle facilities present). Research also suggests that close-passing motor vehicles can create a subjective experience of being unsafe, which is a disincentive to travel by bicycle (Guthrie et al., 2001; Parkin et al., 2007).

#### 4.2.3 Overtaking of bicyclists

This section explores the issue of overtaking bicyclists. The overtaking of bicyclists by bus drivers seems to have an important impact on safety. Research suggests that crashes where bicyclists are struck by an overtaking motorist are disproportionately dangerous to the bicyclists, because in such crashes motor vehicles usually drive much faster than, for instance, in crashes with turning vehicles (Pai, 2011; Stone & Broughton, 2003; Transport for London, 2005; Walker et al., 2014).

An analysis of injury crashes involving a bicyclist in 2010 in London shows that passing a bicyclist too close is among the most frequently registered contributory factors of bicycle crashes (Transport for London, 2011). Walker (2007) found that large vehicles (including buses) pass bicyclists much closer than other types of vehicles, a finding that was later confirmed by Parkin and Meyers (2010). Due to their length and poor acceleration, buses and heavy-goods vehicles take much longer to pass a bicyclist than shorter vehicles. Walker (2007) suggests that the close proximities and frequent conflicts are caused by a reluctance of drivers to stay out-of-lane, a lack of lengthy gaps in oncoming traffic and vehicle design issues which put bicyclists out of sight before overtaking is complete. Chuang et al. (2013) found a lower mean overtaking distance for buses than for other categories of road users as well, although it must be mentioned that the number of overtaking events by buses was relatively low in their sample. These results are also largely confirmed by a study by Pai (2011), who investigated overtaking, rear-end and door crashes involving bicyclists. The author found that the variable 'bus as crash partner' statistically significantly increased the probability of a crash being an overtaking crash. This implies that buses are particularly associated with bicycle overtaking crashes. Kim et al. (2007) found a higher involvement of long vehicles in bicycle overtaking crashes as well. Pai (2011) and Walker et al. (2014) conclude that the finding that longer vehicles overtake bicyclists with a closer proximity (Parkin & Meyers, 2010; Walker, 2007) in combination with the finding that these vehicles have a higher involvement in bicycle overtaking crashes (Kim et al., 2007; Pai, 2011) indirectly suggests that these closer overtaking proximities indeed translate into real crashes.

A particular point of concern in allowing bicyclists on bus lanes is the very different speed profile of buses and bicyclists. While buses and bicyclists appear to have a similar average speed, this average speed results from a constant relatively low speed for bicyclists and from a combination of frequent stops and relatively high driving speeds for buses. This difference in speed profiles leads to frequent overtaking manoeuvres between both types of road users, an issue that is commonly referred to as 'leap-frogging' (Veith & Eady, 2014; Weinstein Agrawal et al., 2012).

In order to reduce the probability of overtaking crashes, traffic regulations in a number of countries stipulate minimal overtaking distances. For instance, Belgian traffic regulations (art. 40ter of the Belgian Traffic Code) state that drivers need to keep a lateral distance of at least one meter while overtaking a bicyclist. This rule is quite similar to the 'three-foot bicycle passing law' (3 ft. = 0.91 m) that is in place in a number of States in the USA (Love et al., 2012).

Dutch research shows that motor vehicle drivers very rarely pass a bicyclist with a lateral distance of less than 0.85 m (CROW, 2006). At 50 km/h (approximately 30 mph), and where the overall width permits, the passing distance is typically around 1.05 m. On the other hand, the study by Love et al. (2012) found that 17% of all motor vehicle drivers did not respect the three-foot bicycle passing law and overtook the bicyclist with a distance of less than 3 ft. Walker (2007) found a mean overtaking distance for buses of 1.10 m.

Chuang et al. (2013) found that bicyclists demonstrate weaker lateral control when they are being passed by a bus compared to when they are being passed

by a different type of road user. The authors suggest that the size of a bus makes it appear to be closer to the bicyclists than smaller vehicles, which can affect the steering control behaviour of the bicyclists.

#### 4.2.4 Other influences that affect the overtaking distance

Walker (2007) indicates that the further away from the road edge a bicyclist is riding, the more likely an overtaking event with a smaller lateral distance is. Walker (2007) therefore recommends that bicyclists should not ride too far away from the road edge. On the other hand, riding too close to the road edge can bring more potentially hazardous obstacles into the rider's path, such as drainage grates, road debris and car doors. A position around 0.5–0.75 m therefore seems to be a reasonable compromise between both dangers, according to Walker (2007).

Shackel and Parkin (2014) found that wider roads lead to larger overtaking distances but also to higher overtaking speeds. Higher overtaking speeds can lead to a higher instability of the bicyclist due to turbulence. Also, higher overtaking speeds can lead to more severe injuries in the case a crash should take place.

#### 4.2.5 Official roadway design guidelines for bus lanes shared with bicyclists

As mentioned, an international comparison shows that different countries are divided on whether to allow bicycles to use bus lanes (Weinstein Agrawal et al., 2012). Most of the countries that do allow the shared use of bus lanes with bicyclists have some specific design recommendations for bus lanes that can be accessed by bicyclists. A non-exhaustive overview of the guidelines in some of these countries is provided below. For a more elaborate description of regulations and recommendations for bus lanes shared with bicyclists in different countries, the reader is referred to Sørensen (2012).

In the region of Flanders (Belgium) where this study took place, bicyclists are not by default allowed to use a bus lane. Apart from buses, only emergency vehicles and taxis are by default allowed to make use of bus lanes (Flemish Government – Roads and Traffic Agency, 2009). Road authorities can, however, allow bicyclists to use a bus lane by placing a specific traffic sign that indicates this permission. Additionally, road authorities have the possibility to stress this permission by painting a bicycle symbol on the pavement. The Flemish road design guidelines distinguish three types of situations for bus lanes shared with bicyclists (Flemish Government, 2014) as follows:

- Bus lane width is less than 3.5 m: bicyclists can be allowed to share the bus lane in built-up areas, preferably only for short distances. The rationale behind this is that buses cannot overtake a bicyclist within the boundaries of this bus lane, since a bicyclist is assumed to have a width of 1 m from the edge of the road, and a bus has a width of around 2.50 m. The bus therefore needs to exit the bus lane to overtake a bicyclist.
- Bus lane width is 3.5–4.5 m: the guidelines do not recommend allowing bicyclists to share bus lanes that are 3.5–4.5 m wide. The rationale is that this width could allow buses to overtake bicyclists within the boundaries of the bus lane but only with a lateral margin that is considered too small

from a safety perspective ( $<1$  m). The hypothesis is that this type of bus lane could therefore lead to dangerous situations.

- Bus lane width is more than 4.5 m: it is assumed that bicyclists could be overtaken safely (lateral margin of 1 m or more) within the boundaries of the bus lane. However, in this situation, a separate bicycle lane of at least 1.50 m and a bus lane of at least 3.00 m are preferred over a shared-use bus lane.

The overall recommended minimum width for all bus lanes with a speed limit of 50 km/h is 3.05 m (Flemish Government – Roads and Traffic Agency, 2009). It should be kept in mind that road authorities are not obliged to follow these recommendations. Therefore, in practice, all three types can be implemented.

A number of countries such as Germany and Austria have guidelines similar to those of Flanders. In Germany, bus lane widths of less than 3.5 m or more than 4.75 m are considered to be safe designs, while a width between 3.5 m and 4.75 m is considered unsafe (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2010). Austrian guidelines recommend a bus lane width of 3.0–3.25 m or 4.25–4.75 m (Österreichischen Forschungsgesellschaft Straße – Schiene – Verkehr, 2014).

A number of other countries, however, take a very different departure point. They only recommend a minimum bus lane width for bus lanes shared with bicyclists in order to facilitate (safe) overtaking manoeuvres. The Australian design guidelines recommend a minimum bus lane width of 3.7–4.3 m, depending on the speed limit for the buses (Veith & Eady, 2014). In the United Kingdom, bicyclists are generally allowed to make use of the bus lane. A width of at least 4.0 m (but preferably 4.5 m) is therefore recommended in English guidelines (Department for Transport, 2008). In Denmark, a minimum bus lane width of 4.5 m is suggested in cases of moderate volumes of bicyclists; for high volumes, separate bicycle facilities are recommended (Vejdirektoratet, 2009). In Sweden, a minimum width of 4.5–5.0 m is recommended for bus lanes shared with bicyclists, depending on the speed limit for the buses (Vägverket & Svenska Kommunförbundet, 2004).

It can be concluded that there are two dominant views on how bus lanes should be designed in cases in which it is decided to allow bicyclists to use the bus lane. A number of countries suggest making the bus lane either wide enough to facilitate the safe overtaking of bicyclists by buses *or* narrow enough to prevent the overtaking of the bicyclists within the borders of the bus lane, while a number of countries only suggest a minimum width in order to facilitate overtaking.

### 4.3 Research questions

In order to explore the safety of bicyclists on bus lanes shared with bicyclists, the following research questions will be investigated in this study:

- 1) Does the presence of an approaching bus have an influence on the bicyclists' behaviour when riding on a shared-use bus lane?
- 2) How frequently are bicyclists on shared-use bus lanes involved in close interactions with buses?
- 3) Do differences exist between narrower and wider bus lanes?

## 4.4 Methodology

### 4.4.1 Study locations

We observed two bus lanes that allow shared use with bicyclists in the region of Flanders, Belgium. One bus lane is located in the city of Kortrijk and has a width of 3.1 m (Figure 30, left side). This bus lane is in line with the official road design guidelines (width <3.5 m). The second bus lane is located in the city of Ghent and has a width of 4.2 m (Figure 30, right side). This bus lane is not in line with the road design guidelines (width 3.5–4.5 m). No bus lane of the widest type (width >4.5 m) could be found; therefore, this type of bus lane is not included in the observations.



*Figure 30 – Observation sites: Kortrijk (left) (3.1 m wide – in line with guidelines) and Ghent (right) (4.2 m wide – not in line with guidelines).*

More details about both bus lanes are presented in Table 4. It can be seen that the narrower bus lane has higher volumes of bicyclists and buses than the wider bus lane. The volume of motorized vehicles on the adjacent lane is, however, quite comparable. One slight injury crash involving a bicyclist has been registered on the narrower bus lane, and no crashes involving bicyclists have been registered on the wider bus lane.

### 4.4.2 Video data collection and analysis

At each site, a video camera was mounted on a light pole to record oncoming bicyclists and buses on the bus lane. The images in Figure 30 are snapshots from the video footage that is analysed. Two full weeks of video, recorded in fall 2014, are analysed. A habituation period of six weeks was respected between the opening of the wider bus lane (September 2014) and the start of the observations to allow bus drivers and bicyclists to adapt their behaviour to the new infrastructure. The recorded time period is identical for both locations to keep elements such as length of day and weather conditions equal.

Table 4 – Characteristics of both analysed bus lanes.

Characteristic	Narrower bus lane	Wider bus lane
City	Kortrijk	Ghent
Bus lane width	3.1 m	4.2 m
In line with guidelines?	Yes	No
Speed limit	50 km/h	50 km/h
Hourly volume motorized vehicles adjacent lane (peak)	393 mv/h	289 mv/h
Hourly volume motorized vehicles adjacent lane (off-peak)	367 mv/h	364 mv/h
Daily volume of bicyclists (work day)	1610 bicyclists/day	780 bicyclists/day
Daily volume of bicyclists (weekend day)	423 bicyclists/day	386 bicyclists/day
Daily volume of buses (work day)	466 buses/day	119 buses/day
Daily volume of buses (weekend day)	197 buses/day	64 buses/day
Operational since	January 2009	September 2014
Number of crashes involving bicyclists since opening until April 2016	1 (slight injury)	0

The video footage is processed using T-Analyst, a semi-automated video analysis software developed at Lund University (T-Analyst, 2016). The software is calibrated to transform the image coordinates of each individual pixel to road plane coordinates, which allows the accurate determination of the position of an object in the image and the calculation of its trajectory. This allows the calculation of road users' speeds and positions, distances and traffic conflict indicators in an accurate and objective way (Polders et al., 2015).

Some of the collected indicators (such as lateral position – see below) require a high level of accuracy in the measurements. To ensure a sufficiently high accuracy, the length of the stretch of road that is analysed is limited to 40 m at each observation site. No intersections are present on the observed road stretches.

All interactions between bicyclists and buses that take place on this road stretch during the observation period are selected for detailed analysis. An interaction is defined as a situation in which two road users approach each other with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other (De Ceunynck et al., 2013b). It can be seen as an elementary event in the traffic process that has the potential to end in a crash (Laureshyn et al., 2010). This definition is operationalised as each situation at the observation sites where a bus approaches a bicyclist to a distance of less than 28 m, which equals the distance covered by a bus in 2 s at a speed of 50 km/h. This is derived from the so-called two-second rule, which states that a vehicle should keep a time gap of at least two seconds from the vehicle in front of it (see section 4.4.4 for further details). These situations can either be bicycle-following situations where a bus is driving behind a bicyclist or situations where the bicyclist gets overtaken by the bus. Since there are no bus stops present in

the observed road stretches, no situations where a bicycle overtakes a bus have been observed.

To answer the first research question ('does the presence of an approaching bus have an influence on the bicyclists' behaviour?'), data from a random sample of free-flow bicyclists (i.e. bicyclists who are not in interaction with a bus) have been collected from the same observation period at both study locations. The behaviour of bicyclists who are in interaction with a bus is compared with the behaviour of these free-flow bicyclists to see whether they behave differently.

#### 4.4.3 Collected variables about behaviour

For all events (both interactions and free-flow bicyclists), the following data related to bicyclists' behaviour are registered:

- Lateral position of the bicyclist at five points (every 10 m of the 40 m road stretch)
- Speed of the bicyclist at five points

For all interactions, a number of additional variables are registered that describe the following:

- Distance gap and time gap at the five measurement points of the bicyclist. Distance gap is measured as the distance between the back of the bicyclist and the front of the bus. Time gap is estimated by dividing the distance gap by the speed of the bicyclist at that measurement point. This way, the time gap value is calculated as if the approaching bus has the same speed as the bicyclist. This approximation was needed because the speed of the bus at the exact moment the bicyclist passes the measurement points was not measured. Since only the minimum value of time gap is used in the analyses, and this value usually occurred when the bus had approached the bicyclist closest and was following it at a fairly constant speed that approximated that of the bicyclist, we believe this is a reasonable approximation of the true minimal time gap
- Lateral position and speed of the bus at the same five measurement points
- Specifically for interactions that include an overtaking manoeuvre, the following variables are registered additionally:
  - o Lateral overtaking proximity
  - o Position of the bus during overtaking (within bus lane, entirely on the adjacent roadway or partly on both)
  - o Speed and lateral position of the bicyclist during overtaking (this is therefore one more measurement, additional to the five fixed measurement points)
- A number of situational aspects that could affect the process of the interaction as follows:
  - o The presence of a barrier on the adjacent lane (i.e. a vehicle that could prevent the bus from leaving the bus lane to overtake)
  - o The presence of a barrier downstream on the bus lane (e.g. other bicyclists or buses that could discourage the bus driver from overtaking the bicyclist)
  - o Weather and light conditions

#### 4.4.4 Indicators to describe closeness of interactions

The minimum time-to-collision ( $TTC_{min}$ ), the overtaking proximity and the time gap are the surrogate safety measures that are used to evaluate the closeness of the interactions (research questions 2 and 3).

Time-to-collision is defined as 'the time remaining until a crash between the vehicles would occur if they continued on their present course at their present rates' (Hayward, 1972). Research suggests that  $TTC_{min}$  values lower than 1.5 s are rarely observed in normal interactions and can therefore be considered close interactions (Brown, 1994; van der Horst, 1990).

The literature review has shown that the overtaking proximity is an important aspect of bicyclists' safety. Since the Belgian Traffic Code imposes a minimum lateral distance of one meter when overtaking a bicyclist, overtaking manoeuvres with a margin of less than one meter are in this study considered to be close interactions.

Time gaps (the gap between two vehicles driving in front of/behind one another, expressed in seconds) are highly defining for the risk of rear-end crashes (Evans & Wasieleski, 1982). In case the leading vehicle needs to make an emergency stop, a sufficiently large time gap is needed to allow the following vehicle to react and stop in time as well. A general rule of thumb is that a vehicle should keep a time gap of at least two seconds from the vehicle in front of it (the so-called two-second rule) (Michael et al., 2000). This rule is based on the reaction time of drivers, which can vary from less than one second to about two seconds (Lamm et al., 1999). Some may consider a time gap of 2 s quite conservative and difficult to maintain in everyday traffic. However, it should be noted that reaction time is dependent on the complexity of a decision (Alexander & Lunenfeld, 1990). A bus driver's decision on whether to make an emergency stop or not is considered to be more complex than for most other drivers, because the bus driver needs to take the presence of passengers into account. An emergency stop could lead to injuries for passengers on the bus. Therefore, a relatively long reaction time of 2 s is often assumed for bus drivers in the crash reconstruction literature (Burg & Moser, 2007). As a result, time gaps of less than 2 s will in this study be considered close interactions.

#### 4.5 Results

The database consists of 519 records in total, 262 of which are bicycle-bus interactions and 257 are free-flow bicyclists (see Table 5). It can be seen that for the narrower bus lane, 60% of all interactions lead to overtaking, while this number rises to 72% for the wider bus lane. Given the limited length of the analysed road sections, these numbers are very high. It therefore seems that buses will overtake bicyclists whenever they can. The proportion of interactions leading to overtaking is slightly higher on the wider bus lane, but the difference is not statistically significant and therefore only indicative ( $X^2(1)=2.04$ ;  $p=0.153$ ).

*Table 5 – Number of observed situations.*

	Narrower bus lane	Wider bus lane	Total
Free-flow bicyclists (no interaction)	171	86	257
Interaction without overtaking	91	10	101
Interaction with overtaking	135	26	161
Total	397	122	519

The following sections will analyse behavioural aspects of bus–bicycle interactions, such as lateral position and speed and the occurrence of close interactions between bicyclists and buses.

#### 4.5.1 Behavioural aspects of bus–bicycle interactions

##### 4.5.1.1 Analysis of bicyclists’ lateral position and speed

To answer the question of whether the presence of a bus has an effect on the behaviour of a bicyclist, a between-within multivariate analysis of variance (MANOVA) is conducted for both locations separately. The dependent variables are the bicyclists’ lateral position and riding speed (each with 5 measurement points per bicyclist). The lateral position is expressed as the lateral distance (in meters) between the edge of the roadway and the centroid of the bounding box around the bicyclist (which approximately corresponds with the contact point of the tyres on the road). Lower values therefore indicate a position more closely to the edge of the road. The riding speed is expressed in m/s. The independent variable is the condition (free-flow bicyclist, interaction without overtaking, interaction with overtaking). For all analyses, post-hoc univariate tests were conducted and the p-value was set at 0.05 to determine statistical significance. For MANOVAs, F- and probability values (Wilks’ Lambda) are reported. For ANOVA tests, corrected F- and probability values (Greenhouse-Geisser) are described.

The MANOVA tests for both locations show a statistically significant main effect for condition (see Table 6), which implies that the different conditions are not independent from each other and that, therefore, the condition the bicyclist is involved in has an effect on his/her behaviour.

On the narrower bus lane, the between subjects ANOVAs show that speed and lateral position are both statistically significantly different among the different conditions. Looking at the pairwise comparisons of the speed, we can see that bicyclists involved in interactions without overtaking ride statistically significantly faster than bicyclists in the other two conditions. Looking at the pairwise comparisons of lateral position, it can be seen that bicyclists involved in an interaction with overtaking ride statistically significantly more closely to the edge of the bus lane than bicyclists in other conditions.

On the wider bus lane, it can be observed that the ANOVA test for speed shows no statistically significant difference between the different conditions. Therefore, no pairwise comparisons are calculated for speed on the wider bus lane. The ANOVA test for lateral position shows that there are statistically significant differences in lateral position among the different conditions. Looking at the

pairwise comparisons, it can be seen that bicyclists in interactions with overtaking take a position statistically significantly more closely to the edge of the bus lane than bicyclists in the free-flow condition.

At both locations, the MANOVA test shows that the speed and lateral position are not independent of the measurement point (within subjects). Since the within subjects evolution of the lateral position and the riding speed as such are not of real interest for our research questions, we will not go into further detail about these. It is however interesting to have a look at the within subjects interaction between the variables 'measurement point' and 'condition'. This interaction could show whether the behavioural patterns across the different measurement points are different for the different groups of bicyclists. This could, for instance, help to clarify whether the fact that bicyclists involved in interactions with overtaking mainly ride more closely to the edge of the lane from the start of the observation section or that they move more closely to the edge of the bus lane over the course of the interaction (possibly as a consequence of being overtaken).

On the narrower bus lane, the interaction between the variables 'measurement point' and 'condition' is not statistically significant, which suggests that the behavioural patterns across the different measurement points are not different for the different groups of bicyclists. Therefore, this suggests that bicyclists who are overtaken by buses mostly are not really modifying their lateral position as a consequence of being overtaken but are instead already riding more closely to the edge of the road than the other groups of bicyclists from the start of the observation section.

On the wider bus lane, the interaction between the variables 'measurement point' and 'condition' is almost statistically significant ( $p=0.065$ ). Therefore, the corresponding univariate tests for speed and lateral position are analysed. There is no statistically significant relationship with speed, but there is a statistically significant relationship with lateral position. To investigate this relationship further, Figure 31 plots the lateral position of the bicyclists on the wider bus lane at each measurement point for the three conditions. It can be seen that both groups of bicyclists who are involved in an interaction are taking a position more closely to the edge of the bus lane over the course of the interaction. Additionally, however, it can be seen that bicyclists who get overtaken by a bus are already riding more closely to the edge of the lane than bicyclists in other conditions. A combination of these two elements therefore seems to explain the differences in lateral position between the different conditions on the wider bus lane.

Table 6 – Analysis of bicyclists' lateral position and speed.

	Narrower bus lane	Wider bus lane
<b>Mean values</b>		
<i>Overall mean speed</i>		
Free-flow condition	5.039 m/s	5.042 m/s
No overtaking condition	5.426 m/s	5.294 m/s
Overtaking condition	4.846 m/s	5.352 m/s
<i>Overall mean lateral position</i>		
Free-flow condition	0.557 m	0.825 m
No overtaking condition	0.557 m	0.796 m
Overtaking condition	0.315 m	0.452 m
<b>MANOVA</b>		
MANOVA test condition (between subjects)	F(4, 784)=11.477, p<0.001	F(4, 234)=4.366, p=0.002
MANOVA test measurement point (within subjects)	F(8, 386)=10.527, p<0.001	F(8, 111)=17.866, p<0.001
Within subjects interaction between variables measurement point * condition	F(16, 772)=1.169, p=0.287	F(16, 222)=1.620, p=0.065
<b>ANOVA</b>		
<i>ANOVA condition (between subjects)</i>		
speed	F(2)=8.728, p<0.001	F(2)=1.086, p=0.341
lateral position	F(2)=15.974, p<0.001	F(2)=6.021, p=0.003
<i>ANOVA measurement point (within subjects)</i>		
speed	F(2.884)=5.844, p=0.001	F(2.654)=13.806, p<0.001
lateral position	F(1.902)=29.000, p<0.001	F(2.843)=42.278, p<0.001
<i>ANOVA measurement point * condition</i>		
Speed	/	F(5.308)=1.589, p=0.159
Lateral position	/	F(5.685)=3.090, p=0.007

Table 6 – Analysis of bicyclists' lateral position and speed [cont.].

<b>Pairwise comparisons</b> (Bonferroni correction for multiple comparisons applied) Difference [95% CI], p-value		
<i>Speed (in m/s)</i>		
free-flow vs. no overtaking	-0.387 [-0.707; -0.066], p=0.012	/
free-flow vs. overtaking	0.193 [-0.090; 0.477], p=0.306	/
no overtaking vs. overtaking	0.580 [0.245; 0.915], p<0.001	/
<i>lateral position (in m)</i>		
free-flow vs. no overtaking	0.000 [-0.126; 0.127], p=1.000	0.029 [-0.362; 0.420], p=1.000
free-flow vs. overtaking	0.242 [0.130; 0.354], p<0.001	0.372 [0.110; 0.634], p=0.002
no overtaking vs. overtaking	0.242 [0.110; 0.374], p<0.001	0.344 [-0.091; 0.779], p=0.173

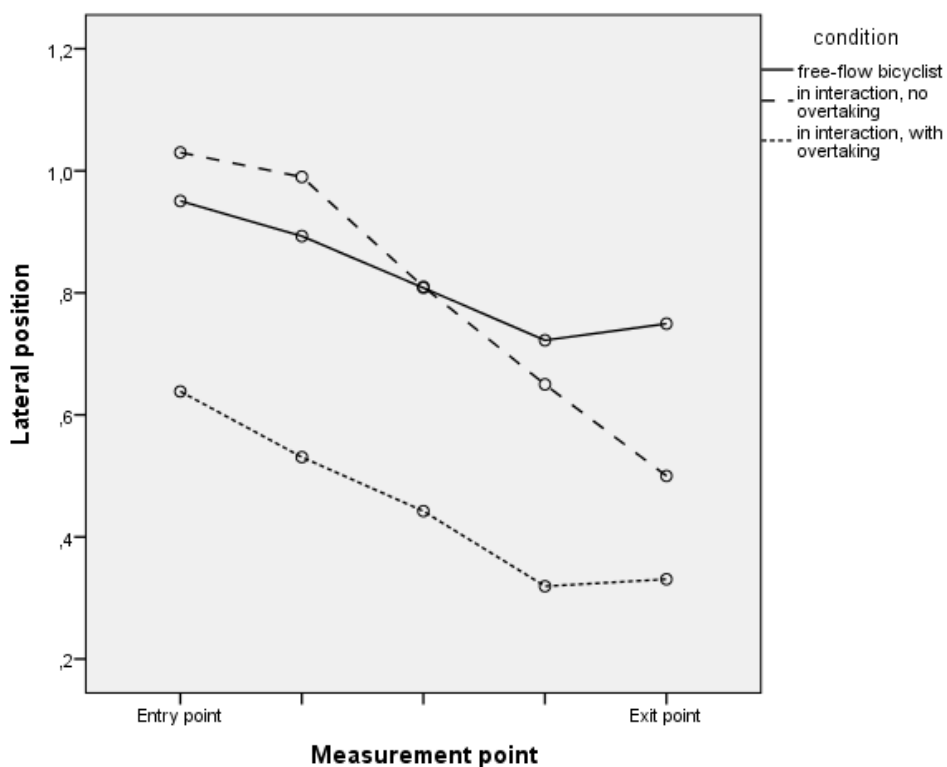


Figure 31 – Lateral position of the bicyclists on the wider bus lane at each measurement point for the three conditions.

#### 4.5.1.2 Standard deviation of lateral position of bicyclists

The absolute position is only one element of the lateral position of bicyclists. Since we have multiple measurement points, the standard deviation of the lateral position (SDLP) can be calculated. The SDLP provides an indication of the lateral stability or the amount of swaying of the bicyclist. The SDLPs for the three types of situations are compared for each of the two locations using ANOVA tests (Table 7). As can be seen from the table, there are no statistically significant differences between the three types of observed situations. This suggests that it could not be shown that the SDLP of bicyclists would differ between free-flow bicyclists and bicyclists who are in interaction with buses.

*Table 7 – SDLP of bicyclists.*

	SDLP Narrower bus lane	SDLP Wider bus lane
Free-flow bicyclists	0.147 m	0.177 m
Interactions without overtaking	0.188 m	0.254 m
Interactions with overtaking	0.164 m	0.177 m
ANOVA	$F(2,394)=1.616$ ; $p=0.200$	$F(2,119)=2.328$ ; $p=0.102$

#### 4.5.1.3 Speed of buses during overtaking

The driving speed of the buses while overtaking a bicyclist is shown in Table 8. It can be seen that the overtaking speed of the bus is higher on the wider bus lane than at the narrower bus lane. An ANOVA-test shows that this difference is statistically significant,  $F(1, 133)=15.567$ ;  $p<0.001$ .

*Table 8 – Overtaking speed of buses.*

	Narrower bus lane (N=111)	Wider bus lane (N=24)
Mean	11.8 m/s (42.4 km/h)	13.7 m/s (49.3 km/h)
Standard error	0.198 m/s	0.426 m/s
Minimum	4.7 m/s	8.4 m/s
Maximum	18.8 m/s	19.0 m/s

#### 4.5.2 Occurrence of close interactions

##### 4.5.2.1 $TTC_{min}$

Close  $TTC_{min}$ -values would generally occur when a bus approaches a bicyclist at relatively high speed and only brakes very late to avoid a rear-end crash. Figure 32 shows histograms of the observed  $TTC_{min}$ -values of bus-bicycle interactions on both bus lanes. The red vertical line indicates the defined threshold between close events and regular events. It can be seen that very few close  $TTC_{min}$ -values were observed. Most  $TTC_{min}$ -values are well above the defined threshold value of 1.5s.

This suggests that such aggressive approaching of a bicyclist by a bus driver is very infrequent on bus lanes with shared use by bicyclists.

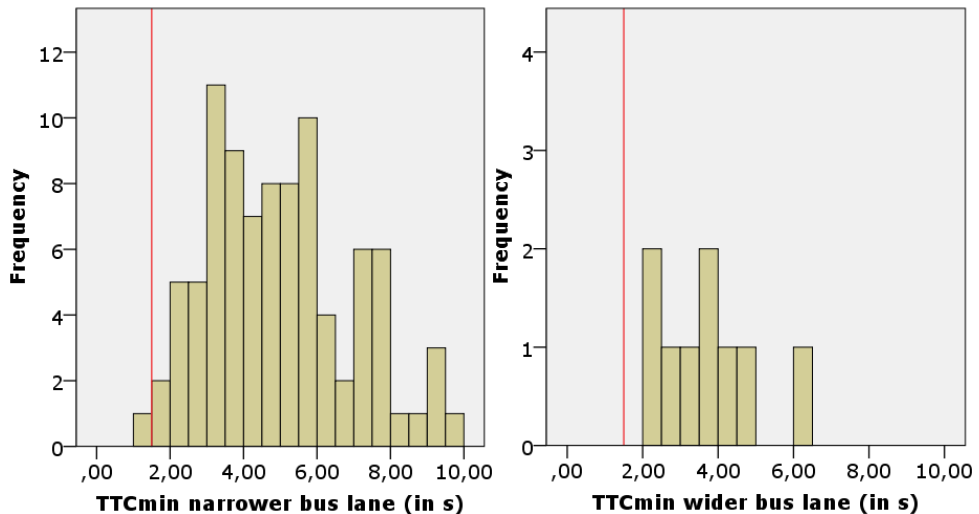


Figure 32 – Distribution of  $TTC_{min}$ -values (left: narrower bus lane; right: wider bus lane).

#### 4.5.2.2 Overtaking proximity

The distribution of the overtaking proximity for all interactions with overtaking on both bus lanes is shown in the box plots in Figure 33. The black line inside the box represents the median value, and the sides of the boxes represent the upper and lower quartile values. The whiskers indicate the variability outside the upper and lower quartiles, and the individual points that are plotted are deemed to be outliers. The threshold value of 1 m is indicated by the red vertical line.

The box plots show that the median overtaking distance is the same on both bus lanes, 1.1 m. A higher dispersion of overtaking distances is however observed on the narrower bus lane. This implies that there are more situations with a large overtaking distance on the narrower bus lane but also more situations with a close overtaking distance. On the narrower bus lane, 33% of all overtaking manoeuvres take place with an overtaking distance of less than 1 m, while this is the case for 21% of the overtaking manoeuvres on the wider bus lane. The proportion of overtaking manoeuvres that has an overtaking distance of less than 1 m is however not statistically significantly different between both bus lanes,  $\chi^2(1)=1.312$ ;  $p=0.252$ .

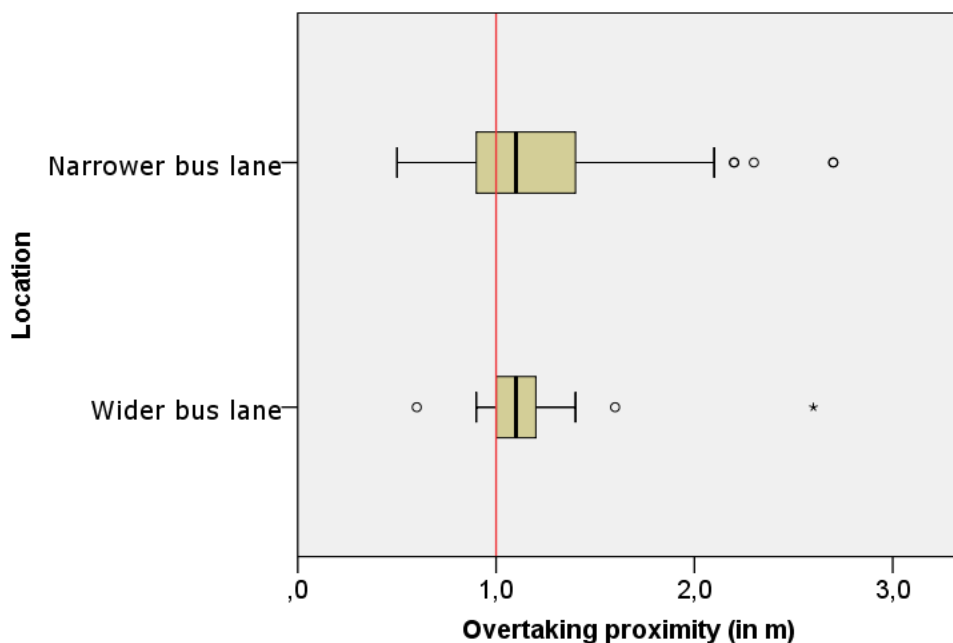


Figure 33 – Overtaking proximity on both bus lanes.

#### 4.5.2.3 Time Gap

The distribution of time gaps for all interactions without overtaking are shown in Figure 34. The red vertical line indicates the threshold value of 2 s. The minimal time gap value for each interaction is taken. It can be seen that the number of interactions that have a time gap lower than 2 s is quite high. On the narrower bus lane, 56% of all interactions without overtaking have a minimal time gap less than 2 s, while 22% of these interactions even have a minimal time gap of less than 1 s. On the wider bus lane, 30% of all interactions without overtaking have a minimal time gap less than 2 s. Since these values are all below 1 s, the percentage of interactions with a minimal time gap less than 1 s on the wider bus lane is also 30%. Fisher's Exact Tests show that the proportion of interactions with a minimal time gap below the threshold value does not statistically significantly differ between both locations (threshold < 2 s:  $X^2(1)=2.456$ ;  $p=0.182$ ; threshold < 1 s:  $X^2(1)=0.566$ ;  $p=0.691$ ).

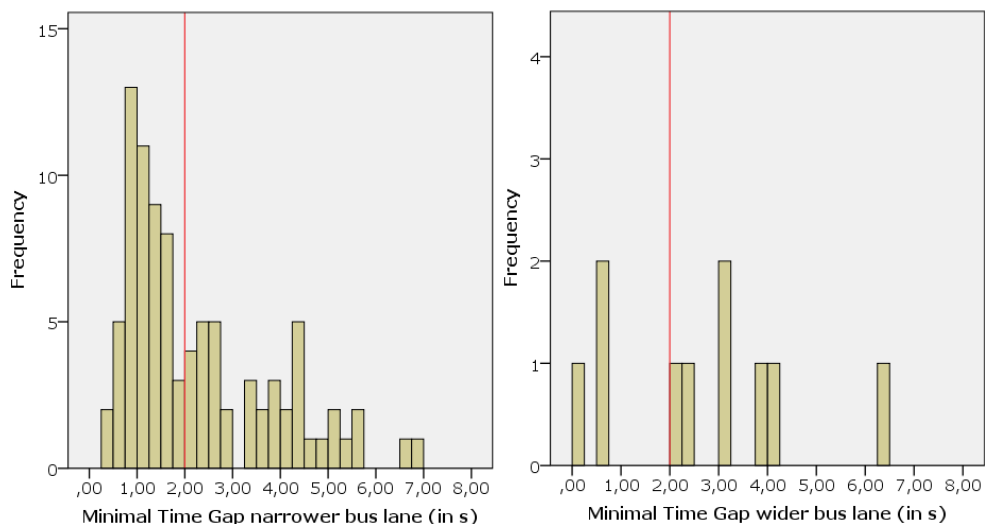


Figure 34 – Distribution of observed time gaps of interactions without overtaking (left: narrower bus lane; right: wider bus lane).

## 4.6 Discussion

### 4.6.1 Discussion of behavioural aspects and occurring close interactions

The road design guidelines in Flanders-Belgium (and a number of other countries) recommend that bus lanes shared with bicyclists be either designed narrow enough ( $\leq 3.5$  m) to prevent close overtaking manoeuvres within the borders of the bus lanes or wide enough ( $> 4.5$  m) to allow buses to overtake the bicyclists with a sufficient lateral margin within the borders of the bus lanes. In the latter case, however, it is argued that a separate bicycle track is to be preferred over a shared-use bus lane (Flemish Government, 2014). As a result, no bus lanes shared with bicyclists with a width of more than 4.5 m have been found. Therefore, this study has put an emphasis on comparing the narrow (recommended) type of bus lane with the medium-width (3.5 m–4.5 m) bus lane that is hypothesised to be less safe. Therefore, this study does not allow any direct conclusions to be drawn for the widest type of bus lanes shared with bicyclists, which is recommended by road design guidelines in a number of other countries.

#### 4.6.1.1 Overtaking manoeuvres

When summarizing the results from the analyses of close interactions, it should be concluded that the hypothesis that bus lanes narrower than 3.5 m are safer than bus lanes with a width between 3.5 m and 4.5 m cannot be confirmed. Firstly, it is hypothesized by the road design guidelines that the narrower bus lane prevents close overtaking manoeuvres by impeding overtaking within the borders of the bus lane itself. The results of the overtaking proximity show however that close overtaking manoeuvres are quite common on the narrow bus lane (33% of all overtaking manoeuvres). The proportion of close overtaking manoeuvres on this bus lane that is designed according to the road design guidelines is not lower

than on the bus lane that is not in line with the guidelines. On the contrary, there is even a (statistically non-significant) indication that there are more close overtaking manoeuvres on the recommended narrower bus lane. This finding can be related to the study by Shackel and Parkin (2014), who observed that wider roads generally lead to larger lateral overtaking distances. The median overtaking distance on both bus lanes (1.1 m) is similar to the overtaking distance of buses overtaking bicyclists that was recorded by Walker (2007).

This finding could be partly related to the underlying assumption of the space taken up by the bicyclist. It is hypothesized that a bicyclist has a width of one meter, measured from the edge of the road (Flemish Government, 2014). However, the analyses show that bicyclists take up less than one meter from the edge of the road, especially at the moment they are being overtaken. The lateral position of a bicyclist (the centroid of the bounding box) while being overtaken is on average 0.21 m and 0.36 m on the narrower and on the wider bus lane, respectively. This implies that, during overtaking, many bicyclists are so close to the edge of the road that part of their physical width (i.e. part of their handlebar) even falls outside the bus lane. Since a bicyclist has a physical width of 0.75 m (AASHTO, 2012; CROW, 2004), this means that the bicyclists on average only take up a total width of 0.585 m and 0.735 m (average lateral position plus half of the physical width) from the edge of the road on both bus lanes, respectively, while being overtaken. On the narrower bus lane, four overtaking manoeuvres were registered where the adjacent traffic lane was blocked by car traffic, and the bus could therefore not leave the bus lane for overtaking. These overtaking manoeuvres should theoretically be impossible on this type of bus lane. While these situations are rather infrequent, they all correspond with very low overtaking distances (0.6–0.7 m), and therefore these situations are highly undesirable. It is remarkable that even on a bus lane with a width of only 3.1 m, which is well below the prescribed upper limit of 3.5 m and only marginally above the recommended minimum width of 3.05 m for 50 km/h bus lanes, overtaking manoeuvres are still occasionally possible when the adjacent road is blocked. In the majority of situations with a close overtaking distance, however, the adjacent traffic lane is free from traffic, and the bus could therefore easily have kept a larger distance. A reluctance of bus drivers to stay out-of-lane might be one of the causes for this finding (Walker, 2007).

#### 4.6.1.2 Bicycle-following situations

In addition to the issue of close overtaking manoeuvres, there also seems to be an issue with close bicycle-following situations. On the narrower bus lane, 56% of all interactions without overtaking have a time gap less than 2 s, while 30% of such interactions have a time gap less than 2 s on the wider bus lane. This difference is not statistically significant, but this is strongly influenced by the low number of interactions without overtaking on the wider bus lane (N=10).

At both locations, a very high proportion of bus–bicycle interactions leads to overtaking. This proportion is however even slightly higher on the wider bus lane. Or, in other words, the problem of close bicycle-following situations might be more pronounced on the narrower bus lane. Since the traffic volumes on the adjacent traffic lanes are highly comparable between both locations, it is justified to argue that this difference in overtaking probability is mostly due to the difference in the

width of both bus lanes. This also means that the issue of close interactions without overtaking can be considered to be more pronounced on the narrower bus lane. One could therefore question whether it is desirable to limit the possibilities for buses to overtake bicyclists.

To some extent, there could be a substitution effect between (close) overtaking manoeuvres and (close) bicycle-following situations; reducing the number of events of one type might increase the number of events of the other. However, at this point, it is unclear whether close overtaking manoeuvres and close bicycle-following situations are equally safety-critical, or whether one of them is more critical than the other.

#### 4.6.1.3 Road users' speed

While the frequency of close interactions therefore generally seems to be higher on the narrower bus lane, it must be mentioned that the overtaking speed of the bus is statistically significantly higher on the wider bus lane. The higher overtaking speed on the wider bus lane is in line with the study by Shackel and Parkin (2014). The higher overtaking speed poses a safety threat to bicyclists as well, since the consequences in case a crash would take place are likely to be higher.

A comparison of the riding speed of bicyclists over the different conditions shows mixed results. On the narrower bus lane, bicyclists involved in an interaction without overtaking have a statistically significantly higher riding speed than free-flow bicyclists as well as bicyclists involved in an interaction with overtaking. On the wider bus lane, no statistically significant differences in riding speed are observed over the different conditions. It should however be added that slower bicyclists theoretically have a higher chance of getting involved in an interaction, because they linger a longer time in the observation area. Therefore, slower bicyclists might be slightly overrepresented in the sample of bicyclists who are in interaction with buses compared to the group of free-flow bicyclists.

While the patterns are not fully clear and unequivocal, it can be suggested that at least on the narrower bus lane there are some indications that cyclists who have a bus driving behind them have a tendency to ride faster than other bicyclists. This is confirmed by a small-scale follow-up survey, for which we stopped 101 bicyclists at both research locations and asked whether they adapt their speed to the presence of a bus. In total, 33% of all bicyclists stated that they increase their speed when they notice that a bus is approaching from behind. On the narrower bus lane, the proportion of respondents stating that they increase their speed is higher than on the wider bus lane (40% and 25%, respectively). A total of 46% of respondents stated that they do not change their riding speed, 17% stated that they reduce their speed and 4% stated that they stop completely. This increased riding speed of bicyclists who have a bus driving behind them could indicate a feeling of discomfort of the bicyclists, which would be in line with the study by Baumann et al. (2012).

#### 4.6.1.4 Bicyclists' lateral position

The presence of a bus has an influence on the lateral position of the bicyclist. Mainly bicyclists who get overtaken by a bus ride more closely to the edge of the road. This could indicate that some bicyclists, either consciously or unconsciously, ride more closely to the edge of the road when in interaction with a bus. If this is a conscious behaviour, it could possibly indicate that bicyclists do not like having a bus driving behind them and hope that they get overtaken more easily when they are riding more closely to the edge of the road.

Respondents from the small-scale survey were also asked whether they adjust their lateral position when they notice that a bus is approaching from behind. In total, 57% of the respondents stated that they move more towards the edge of the road, 39% stated that they keep the same lateral position and 4% indicated that they will leave the bus lane altogether. No respondents stated that they take a position closer to the middle of the road. This suggests that some bicyclists deliberately take a position closer to the edge of the road when they get involved in an interaction with buses, most likely to facilitate overtaking. No statistically significant difference was found between free-flow bicyclists and bicyclists who are involved in an interaction with a bus regarding the SDLP. Therefore, the finding by Chuang et al. (2013) that bicyclists have weaker lateral control while being overtaken by a bus cannot be confirmed.

#### 4.6.2 Strengths, limitations and further research

Research into the safety of bus lanes is relatively limited, and to the best of our knowledge this is the first study to explicitly address the issue of the shared use of bus lanes with bicyclists. An additional strength is the use of observed (revealed) behaviour and interactions. The detailed analysis of interactions on video footage has provided a deeper insight into the behaviour of bicyclists and buses on bus lanes shared with bicyclists as well as into patterns of close interactions that take place on bus lanes shared with bicyclists.

The use of indicators such as overtaking proximity and time gap, the applied threshold values to distinguish between close and regular situations and their link to traffic safety could be debated. The validity of these indicators as surrogate measures of safety has not been sufficiently investigated by research. It is therefore somewhat uncertain how strongly these indicators correlate with the prevalence of actual crashes. Most of the traditional traffic conflict indicators and techniques (e.g. Swedish Traffic Conflict Technique, DOCTOR technique etc.) are however mostly suitable and validated for assessing interactions with crossing courses. Therefore, they are much less suitable for the types of interactions that take place on straight stretches of bus lanes shared with bicyclists. The applied indicators do however describe the interactions in terms of temporal and spatial proximity, which is an element underlying most surrogate measures of safety (Zheng et al., 2014a). Research has shown strong correlations between surrogate measures of safety (defined in various ways) and traffic crashes (Brown, 1994; El-Basyouny & Sayed, 2013; Hydén, 1987; Lord, 1996; Peesapati et al., 2013; Sacchi et al., 2013; Songchitruksa & Tarko, 2006). Therefore, we believe that it is reasonable to assume that the applied indicators are sufficiently suitable to assess the safety of bicyclists on bus lanes shared with bicyclists.

A major disadvantage of crash data is that they are a very coarse indicator. Crashes are rare events, which often makes it difficult to draw statistically meaningful conclusions. Moreover, there is a well-known problem with underreporting, and the limited information about the behavioural and situational aspects preceding the crash makes it difficult to gain insight into the actual causes of the crash (Laureshyn et al., 2010). Due to the limited number of bus lanes shared with bicyclists, analyses of crashes on these bus lanes do not provide much insight into this subject. Despite their limitations, the use of surrogate measures of safety has provided some insights into the safety of bicyclists on bus lanes shared with bicyclists.

A limitation of the study is the low number of research locations. Only short stretches of two bus lanes were analysed in the present study. Two full weeks of video were analysed at both locations, which should be considered a rather extensive observation period. While there are no reasons to believe that the observed bus lanes are atypical in any way, the generalizability of the results cannot be guaranteed. Some site-specific characteristics or differences between both sites that have not been accounted for might have affected the results. For example, we cannot exclude that the differences in bicycle and bus volumes could have affected the results. Some evidence suggests that the crash risk for each individual bicyclist reduces when bicyclists' volumes increase (the so-called safety-in-numbers effect) (Elvik, 2016; Elvik & Bjørnskau, 2017; Jacobsen, 2003). If this mechanism were to apply to the case of bicyclists on bus lanes shared with bicyclists, it could imply that the number of close encounters for bicyclists on the narrower bus lane compared to the wider bus lane might be somewhat underestimated. This study should therefore be seen as an exploratory study on the subject that provides some first indications and raises some points for discussion that should be further investigated in future research.

Further research is needed to clarify which policy recommendations should be made regarding bus lanes shared with bicyclists. The study cannot confirm the hypothesis underlying road design guidelines in some countries that bus lanes shared with bicyclists narrower than 3.5 m are safer than bus lanes with a width of 3.5–4.5 m. The findings even indicate a somewhat higher occurrence of close interactions on the narrower bus lanes, although these findings are not statistically significant and are therefore only indicative. It is however unclear what the recommendations regarding the design width of bus lanes shared with bicyclists should be then. Should it be recommended that the design guidelines of the narrow design should be even narrower to prevent close overtaking? Or should only a wider design be recommended that facilitates overtaking, as is recommended in a few countries such as Australia, Denmark and Sweden? Another possibility could be to refrain from allowing bicyclists to make use of bus lanes. Alternatively, raising bus drivers' awareness of this problem might be considered as a mediating measure. This could increase the distance they keep when following or overtaking bicyclists.

It can be concluded that close interactions seem to be quite frequent on both analysed types of bus lanes. Based on these results, it seems that there might be some issues regarding bicyclists' safety on bus lanes shared with bicyclists. The design guidelines in some countries implicitly seem to acknowledge that bus lanes

shared with bicyclists are a suboptimal solution. Some of the national road design guidelines explicitly state that separate bicycle lanes are to be preferred or that the shared use of bus lanes with bicyclists should only be implemented for short distances (e.g. Flemish Government, 2014; Forschungsgesellschaft für Straßen- und Verkehrswesen, 2010). The results of this study seem to confirm that bus lanes shared with bicyclists are a compromise that might have a negative effect on bicyclists' safety. However, the study does not make a direct comparison with possible alternatives for a bus lane shared with bicyclists, such as mixed traffic or a separate bicycle path instead of a shared-use bus lane, and can therefore not provide a final recommendation on how these alternatives would perform compared to a bus lane shared with bicyclists.

## 4.7 Conclusions

Observations at two bus lanes shared with bicyclists revealed that close interactions between bicyclists and buses are relatively frequent at both locations. Close overtaking manoeuvres (a bus overtakes a bicyclist with a small lateral margin) as well as close bicycle-following situations (a bus drives behind a bicyclist with a small time gap) are quite common at both observed bus lanes. At both bus lanes, the majority of interactions between bicyclists and buses results in an overtaking manoeuvre. The percentage of interactions leading to an overtaking manoeuvre is slightly (but not statistically significantly) higher at the wider bus lane than at the narrower bus lane (72% at the wider bus lane versus 60% at the narrower bus lane).

The analyses could not confirm the hypothesis that is made in a number of national road design guidelines that a sufficiently narrow bus lane (<3.5 m) is safer than a medium-wide bus lane (3.5–4.5 m). On the contrary, close interactions seem even slightly more common on the narrower bus lane. Somewhat more close overtaking manoeuvres seem to take place on the narrower bus lane (33% of all overtaking manoeuvres versus 21% on the wider bus lane), but the difference is not statistically significant. Additionally, more interactions without overtaking (i.e. situations where a bus is driving behind a bicyclist but does not overtake) take place on the narrower bus lane. The results show that buses often maintain close time gaps in these situations. On the narrower bus lane, 56% of all interactions without overtaking have a time gap lower than 2 s, while this is the case in 30% of the interactions without overtaking on the wider bus lane. The overtaking speed of the bus is however statistically significantly higher on the wider bus lane compared to the narrower bus lane.

The presence of a bus has an influence on the behaviour of the bicyclists. Bicyclists who get overtaken by a bus ride more closely to the edge of the road than bicyclists who are not in interaction with a bus. While the road design guidelines assume that bicyclists take up a width of one meter from the edge on bus lanes shared with bicyclists, the observations show that bicyclists take up much less space while being overtaken. The presence of a bus does not have a significant influence on the standard deviation of the lateral position of the bicyclist. On the narrower bus lane, there are also some indications that bicyclists who are involved in an interaction with a bus without overtaking ride faster than bicyclists who are not involved in an interaction with a bus.

## Chapter 5. The effect of wind turbines alongside motorways on drivers' behaviour

This chapter investigates the influence of wind turbines alongside motorways on drivers' behaviour. To this aim, data are collected from loop detectors and temporary video cameras in a before-and-after setting at a stretch of motorway along which wind turbines have been erected. Because any possible effects of the wind turbines on passing drivers were expected to be relatively subtle, and because severe events tend to occur quite dispersed on a stretch of motorway anyway, the number of severe events was anticipated to be low. Therefore, a strong emphasis has been put in this study on behavioural indicators to draw inferences on the possible safety effects of wind turbines alongside roads. The behavioural indicators that are applied in this chapter are mean speed, standard deviation of driving speed, lateral position and standard deviation of lateral position. Surrogate safety measures, more specifically the Swedish Traffic Conflict Technique and  $TTC_{min}$ , are applied to identify serious traffic conflicts. This study thus aims to contribute to the second research question, "How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed?".

The findings included in this chapter are published in De Ceunynck et al. (2017a). I contributed to this study by defining the setup of the study, collecting and analysing the behavioural and surrogate safety data and writing the paper. The data collection and analyses of the speed data were mostly done by the second author. I wish to thank Paul Schepers and Rien van der Drift from Rijkswaterstaat for their guidance and practical support during this study.

### 5.1 Introduction

Wind power plays a significant role in the current conversion to renewable energy sources that can be observed in many countries (Pedersen et al., 2010). Wind turbines are devices that convert the kinetic energy from wind into electrical power. However, wind turbines are often opposed by the local community because they are considered to be a visual and acoustic annoyance (Breukers and Wolsink, 2007). On the other hand, more remote places with a low population density are not necessarily better alternatives, since they often constitute otherwise unspoiled landscapes with high values for recreation and tourism that could be diminished due to the construction of wind turbines (Pedersen et al., 2010). Additionally, such locations are quite uncommon in densely populated regions such as Western Europe.

The land adjacent to motorways seems to be a potentially desirable location to erect wind turbines. They often pass through less densely populated areas, and placing wind turbines near motorways avoids long and expensive connections to the existing power grid as well as the necessity to build additional access roads for construction and maintenance (Seifert et al., 2003). However, wind turbines are conspicuous objects in the landscape due to their size and the movement of the rotor blades. In that respect, the wind turbines might be a potential source of

distraction for drivers when the wind turbines are positioned near roads, which could, in turn, lead to road safety issues.

The aim of this study is to examine the effects of wind turbines in close proximity to motorways on observable road user behaviour. A deeper insight into the possible behavioural adaptations of drivers can contribute to assessing the possible safety effects of constructing wind turbines in close proximity to motorways. To this aim, analyses of driving speed and standard deviation of speed, analyses of the lateral position and standard deviation of the lateral position, and an observation of serious traffic conflicts are performed.

## 5.2 Background

### 5.2.1 The impact of roadside objects on drivers' behaviour

Drivers' distraction from the primary task of driving, and the role it plays in motor vehicle crashes, has been the subject of a great deal of research in recent years, and it has been shown to be a contributing factor in many crashes (Stavrinos et al., 2016). The importance of distraction as a contributory factor to crashes produces a variety of estimates depending on the criteria used to attribute distraction. Most estimations fall within the range of 25-50% (Recarte & Nunes, 2009). Driver distraction is found to negatively affect driving performance, as measured by for instance higher levels of drivers having no hands on the steering wheel, their eyes directed inside rather than outside the vehicle, and their vehicles wandering in the driving lane or crossing into another lane (Stutts et al., 2005).

Research towards drivers' distraction has mostly focused on distraction as a result of in-vehicle distractors (e.g. mobile phone use, radio tuning, conversations with passengers,...) (Antonson et al., 2014). Distraction caused by aspects of the road environment is, however, an important issue as well (Horberry et al., 2006). Two American studies suggest that 29-35% of reported distractions in crashes relate to distractions outside the vehicle (Glaze & Ellis, 2003; Stutts et al., 2001). It is important to remember that these figures may underestimate the impact of external distraction, because the determination of contributing factors of fatal crashes relies on witness reports and/or a reconstruction of the crashes, which may fail to identify some of the contributing factors (Stavrinos et al., 2016). Stutts et al. (2005) also identified distractions outside the vehicle as one of the most common types of distraction during normal driving conditions.

Studies on specific features outside the vehicle that may cause driver distraction are few, studies about roadside billboards or other advertisements being an exception. A study by Antonson et al. (2014) found that drivers' behaviour was affected by objects in the landscape. Roadside objects close to the roadway caused a shift in lateral position towards the centre of the road. They also found an increase in the variability of lateral position when drivers pass a roadside object, especially when the object was located far away from the road.

The amount of visual information in road environments is generally increasing, which implies that the road environment is increasingly prone to producing information that may distract the driver (Horberry & Edquist, 2009). Visual clutter (objects not relevant to the driving task) in the road scene is likely to have

negative safety implications (Horberry et al., 2006). Potentially risky situations can emerge in case irrelevant objects attract the attention of the drivers to such an extent that too little attention remains for the actual driving task (Schreuder, 1992).

In summary, research suggests that conspicuous features outside the car (such as roadside objects) can distract drivers, and may therefore lead to crashes (Antonson et al., 2014).

### 5.2.2 The impact of wind turbines near roads on passing drivers

The effect of wind turbines near roads on passing drivers is a topic that has been largely unexplored. One driving simulator study was found in which the effects of wind turbines on drivers were examined (Alferdinck et al., 2012). The study consisted of different scenarios of a motorway stretch in The Netherlands. Two conditions for the position of the wind turbines were included, one in which the wind turbines were positioned at 55 m from the pavement and one in which they were more closely located to the roadway at about 26 m from the pavement. The official guidelines in The Netherlands state that wind turbines are allowed at a distance of at least 30 m from the outer edge of the pavement, or in the case of a rotor diameter larger than 60 m, at a distance of at least half of the rotor diameter. The scenario with the wind turbines positioned at 55 m from the pavement is therefore in line with the official guidelines, whereas the scenario with the wind turbines positioned at 26 m is not. In locations near interchanges or in situations where the rotor blades would rotate above the pavement, wind turbines are allowed only when additional research shows that there will be no unacceptable increase in risks to road safety.

The primary goal of the study by Alferdinck et al. (2012) was to examine whether a planned stretch of wind turbines positioned more closely to the pavement than prescribed by the official guidelines would cause unacceptable risks to road safety. Two conditions for the rotor blades of the wind turbines were defined: one 'favourable condition' (rotor blades parallel to the roadway and with a slower rotation speed of 7.8 rpm) and one 'unfavourable condition' (rotor blades perpendicular to the direction of travel, which implies that they rotate partly above the pavement, with a higher rotation speed of 13.7 rpm).

The results of the study indicated that the standard deviation of driving speed (SDDS) is higher when the wind turbines are positioned at 26 m from the pavement instead of in line with the official guidelines. Also, the standard deviation of the lateral position (SDLP) is higher in the plan condition compared to that in the policy condition. In addition, it was found that participants gazed longer at the wind turbines when they were located at the planned locations compared to those at the official guideline locations. With the rotor blades in the unfavourable condition of being perpendicular to the road, the average speed was slightly lower than in the favourable condition. In the unfavourable condition, participants also gazed longer at the wind turbines than when they were in the favourable condition.

The authors concluded that the participants were more distracted by the wind turbines when these were positioned according to the project plan, compared to

when they were positioned in line with the official guidelines. The found effects are statistically significant, but their order of magnitude is small. The authors therefore concluded that there are no indications of an unacceptable increase in a risk to road safety, and they gave a positive recommendation for the implementation of the project plan. Note that the study presented in this chapter is a follow-up on the simulator study by Alferdinck et al. (2012) in which the revealed behaviour of drivers was explored using empirical data in a study with a before-and-after design.

## 5.3 Methodology

The possible effects of erecting wind turbines in close proximity to a motorway on drivers were analysed in an empirical before-and-after study design at a test site near Rotterdam, The Netherlands. Three types of analyses were performed:

- A before-after analysis of driving speed using data from loop detectors and controlled for confounding factors by the use of a control group;
- A before-after analysis of the lateral position of vehicles within their driving lane using video footage collected at the research location;
- An analysis of occurring traffic conflicts.

### 5.3.1 Research location

The research location was a section of motorway N15 near Rotterdam, The Netherlands. In 2014, a windfarm of eight wind turbines was constructed alongside the motorway. The wind turbines are of the horizontal axis type, and they have a hub height of 90 m and a rotor diameter of 110 m. The nacelle and rotor blades of the wind turbines are rotatable, and are pointed automatically facing into the wind for maximum operation efficiency. Due to space constraints, most of the wind turbines of this windfarm are placed approximately 26 m from the pavement (see Figure 35, red pins), which implies that, during some wind conditions, the rotor blades of the wind turbines rotate partly above the pavement. The research location was the same as the one that was simulated in the driving simulation study by Alferdinck et al. (2012) which has been described in section 5.2.2. The motorway has two driving lanes in each direction and a speed limit of 100 km/h. The south-eastern driving direction was observed for this study since this direction is closest to the wind turbines, and it was therefore judged to be the one where the drivers would be most sensitive to possible effects due to the presence of the wind turbines. A street view picture of the research location is shown in Figure 36.

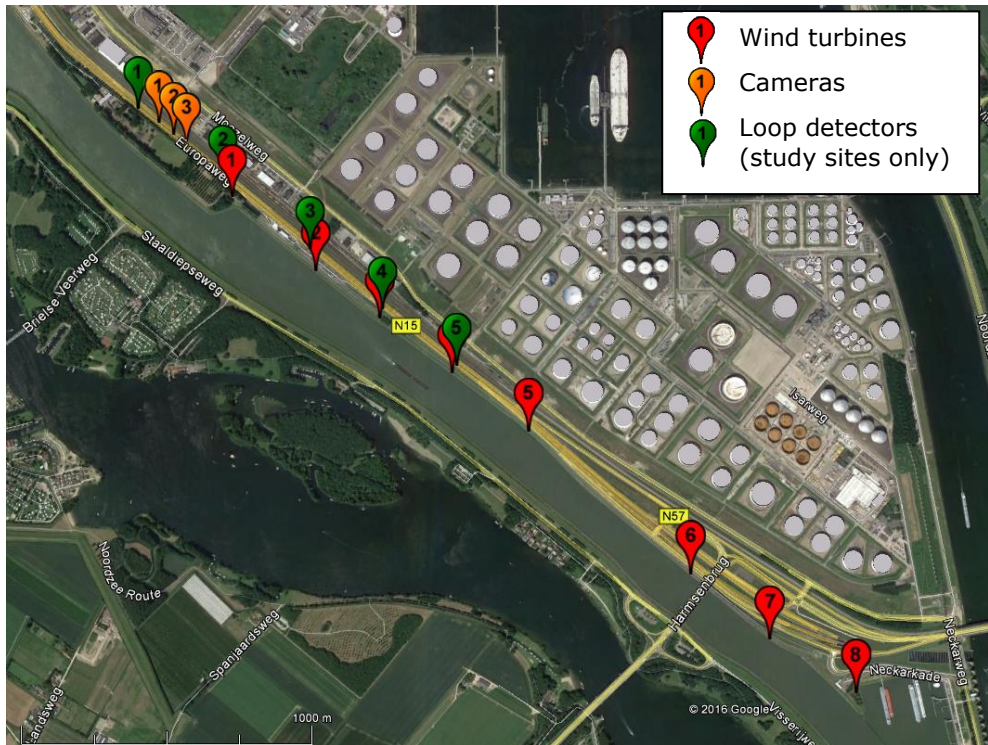


Figure 35 – Research location. Positions of wind turbines, temporary cameras and loop detectors (study sites only) are indicated (image adopted from Google Earth).



Figure 36 – Research location. Street view near camera 1 after construction of wind turbines (image adopted from Google Street View).

### 5.3.2 Analysis of drivers' speed

To gain a deeper insight into the possible effects of wind turbines on drivers' speed, two full months of speed data were analysed in the before period and in the after period. The before period was selected as October 1, 2013 through November 30, 2013, and the after period as February 1, 2015 through March 31, 2015. These periods were chosen to match the period of the video observations (see subsection 5.3.3). Speed data were obtained from the Dutch National Database of Road Traffic Data (Nationale Databank Wegverkeersgegevens) which stores data from inductive loops on the Dutch road network. In order to make the analyses as detailed as possible, the most disaggregated data available were used, which were speed data on the level of one minute per driving lane. Individual vehicle speeds were not available. Possible confounding factors such as seasonal effects and traffic volumes were controlled through the inclusion of control sites that were as similar to the treatment sites as possible except for the fact that they had not undergone the treatment that we were interested in evaluating, i.e., the construction of wind turbines alongside the road (Elvik, 2002).

We used the data of five consecutive loop detectors over a stretch of road of 1.5 km near the wind turbines (see Figure 1, green pins). The detectors were placed in the south-eastern driving direction, which was closest to the wind turbines. The first loop was located approximately 400 m before the first wind turbine, and the last loop was located further down the wind farm, close to the fourth wind turbine. In addition, two control sites had been selected: one downstream from the treatment sites and one upstream (control sites are not visible in Figure 1). Consequently, we were able to analyse speed data from five treatment locations and two control sites before and after the construction of the wind turbines. For each of these locations, we obtained on average 114,559 speed observations, ranging from 110,212 to 118,720, each observation being the average speed for one lane during one minute. Data were left out for minutes during which no vehicles passed. It should be mentioned that the pavement of the treatment sites was resurfaced between the before and after periods. One of the selected control sites (the downstream location) underwent similar resurfacing work between the before and after period which enabled us to account for the possible effects of such work. The second control site did not experience any road works between the before and after period. No other control sites in the vicinity of the study sites could be included because of missing data for the before or after periods.

Preliminary analyses showed an overrepresentation of relatively low driving speeds (65–75 km/h) during night time, which appeared to be caused by occasional roadside maintenance works. To avoid possible biases because of this work, only data of the period 06:00–21:59 were used in the analyses of speed.

To estimate the change in mean speeds at treated locations, taking general trend effects into account, a linear regression model with normal distribution and identity link function was fitted using the SPSS GENLIN procedure. The model can be expressed as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \varepsilon ,$$

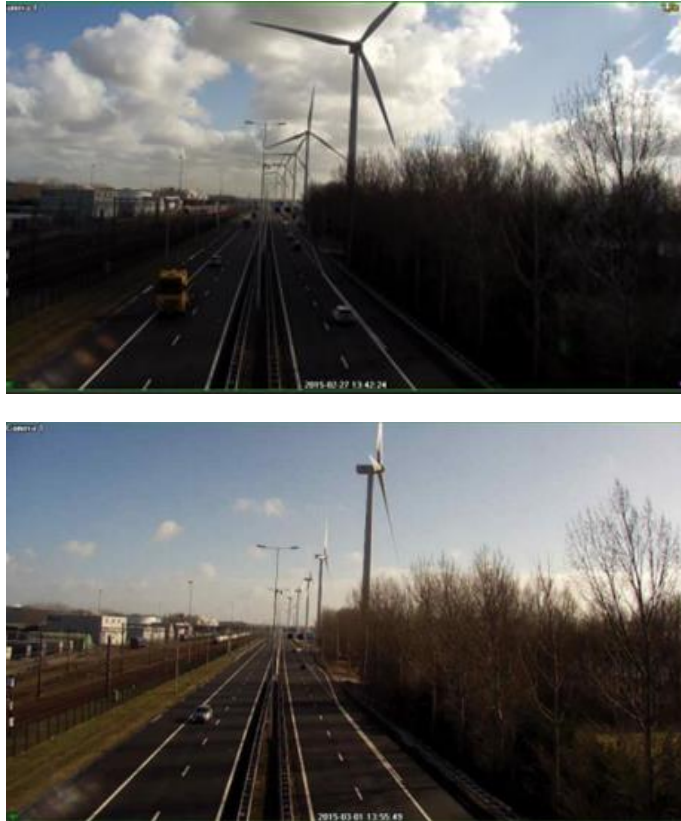
where  $Y$  = average speed at a location in a certain period;  $X_1$  = location (treatment/control);  $X_2$  = period (before/after);  $\beta_1$  = difference in mean speed between the treated locations and the control sites;  $\beta_2$  = difference in mean speed between the before and after period;  $\beta_3$  = interaction effect, which indicates the difference in the mean speed between the before and the after period in the treated group, with control for other factors that had an influence on the driving speed through the use of the data of the control sites.

Weighted averages of the speed were used that took into account the number of vehicles that passed during each minute (procedure SCALEWEIGHT in SPSS). Histograms and normal probability plots show that the residuals of the mean speeds are approximately normally distributed. Differences of the standard deviations of the speeds between the before and the after period were assessed by means of Levene's tests.

### 5.3.3 Analysis of observed lane position

Video footage from temporary cameras was collected for the analyses of drivers' lane positions. The cameras were mounted on three consecutive lamp posts, covering a road segment of 200 m shortly before where the drivers arrived at the first wind turbine of the wind farm (see Figure 35, yellow pins). This segment was selected because we hypothesized that behavioural changes, if present, would be most plausible at this point because the visual impact of the wind turbines on the drivers would be strongest there. At this point, drivers would have approached the first turbine closely enough so that the turning rotor blades would be a very prominent element in their field of view, but not so close that the view of the rotor blades would be occluded by the top of their windscreen. Three conditions were measured: no wind turbines (before period), wind turbines parallel to the roadway and wind turbines perpendicular to the roadway. Both conditions of the after period are shown in Figure 37. Note that these are shots taken from an overview camera that was installed for the sole purpose of monitoring the status of the wind turbines; the cameras that were used for the analyses of lane position and traffic conflicts were tilted more downwards, which allowed for more accurate measurements.

Video footage was collected during one week in the before period (early November 2013) and during 3.5 weeks in the after period (February–March 2015). More video footage of the after period was collected in order to ensure that a sufficient amount of video footage would be available for both conditions (rotor blades parallel to the roadway and perpendicular to the roadway). A total of 24 h was selected from the before period and 24 h from the after period (12 h with rotor blades in perpendicular condition and 12 h with rotor blades in parallel condition). Eighteen h from both the before and the after period were selected during daylight (8 h – 17 h) and 6 h were selected during night time.



*Figure 37 – View of the project site with wind turbines in perpendicular condition (top) and parallel condition (bottom).*

Wind direction data for the study site were retrieved from the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut) on an hourly basis. When the wind either blows from the ESE-SE ( $129^\circ$ ) or from the WNW-NW ( $309^\circ$ ), the wind turbines are perfectly perpendicular to the roadway. Wind directions deviating less than  $20^\circ$  from these ideal positions are considered appropriate to include in the perpendicular condition. A similar approach was applied to preselect potential hours for the parallel condition. Only hours without precipitation were selected, and only with an average hourly wind speed between 6 km/h and 38 km/h (2–5 Beaufort). These wind speeds were considered sufficiently strong to make the rotor blades rotate enough to be conspicuous, but not so strong as to have an effect on driver behaviour (e.g., vehicle instability due to gusts of wind).

For the final selection, first the hours with wind turbines in perpendicular position were chosen, since these were the least common. Based on these hours, matching hours were selected for the before period and for the parallel condition. These hours were selected so that the traffic volumes between the different conditions were as similar as possible. Nearly all matched hours differed less than 10% from each other regarding traffic volume.

Videos were analysed using T-Analyst, a semi-automated video analysis tool developed at Lund University, Sweden (T-Analyst, 2016). The software was calibrated to transform the image coordinates of each individual pixel to road plane coordinates, which allows to accurately determine the position of an object (Laureshyn et al., 2017a). This way, the lateral position of vehicles within the lane could be measured.

The lateral position of every tenth passing vehicle was measured at three measurement points (one per camera). The lateral positions were measured immediately after the vehicle entered the view of the camera because the measurement accuracy is highest closest to the camera. Since the cameras were set up in the median of the road, the left-hand side of the vehicles was the most visible to camera. Therefore, the lateral distances were measured from the left-hand side of the vehicle (outermost contact point of the tire on the pavement) and the inside (right-hand side) of the pavement marking left of the vehicle. In cases where the vehicle was driving in the right-hand lane, the distance was therefore measured to the centre line. In cases where the vehicle was driving in the left-hand lane, the distance was measured to the left edge line. For each vehicle, the standard deviation of the three lateral positions was calculated as well. The standard deviation of lateral position indicates the degree of swerving of the vehicle.

Apart from the lateral position, a number of other elements were registered that could have had an effect on the lateral position of the vehicle as well. These elements were the lane that the vehicle was driving in (left or right), the vehicle type (heavy goods vehicle [HGV], minivan, passenger car) and whether it was day or night.

It should be mentioned that there was an exit toward a petrol station shortly downstream of the study section that had been slightly extended during the resurfacing works that took place on the motorway between the before and after period. It was therefore decided to omit all vehicles that took this exit to the petrol station as well as any vehicles driving immediately in front or behind a vehicle taking the exit to avoid any possible biases due to this change. In addition to these vehicles, vehicles that switched lanes within the observed road section were omitted from the analyses because their choice of lateral position was mainly the consequence of their decision to switch lanes.

Similar to what was done in the analyses of driving speed, two linear regression models were built. The first model investigated which elements had an impact on the lateral position of the driver in absolute terms (the mean of the three measurement points was the dependent variable). The second regression model investigated which elements affected the standard deviation of the three measured lateral positions, which was an indicator of how much the vehicles weaved.

### 5.3.4 Analysis of traffic conflicts

In this study, situations were considered serious traffic conflicts if they fulfilled one of the following criteria:

- They were considered to be a serious traffic conflict according to the Swedish Traffic Conflict Technique (STCT) (Hydén, 1987). Based on driving speed and the distance to the projected (imaginary) collision point, the so-called time-to-accident (TA) value can be calculated. Based on the TA-value, it can be decided whether a traffic conflict is serious or not. The STCT defines a threshold value to distinguish between serious and non-serious TA-values that depends on the driving speed.
- They had a minimal time-to-collision (TTC<sub>min</sub>) value lower than 1.5 s. The time-to-collision is the time remaining before a potential collision if direction and speed are unchanged. Research has shown that such values rarely happen in normal traffic interactions (van der Horst, 1990).

For the traffic conflict observations, the same 48 h of video footage were used as in the analyses of the lateral position of vehicles. First, all interactions that seemed dangerous were manually preselected by the observer. Next, T-Analyst was used to accurately measure the severity of the situation and to decide whether it was a serious traffic conflict or not.

## 5.4 Results

### 5.4.1 Analyses of drivers' speed

The results of the analyses of drivers' mean speed are shown in Table 9. Overall, the mean speed was 2.24 km/h lower in the after period compared to the before period. This was the result of an observed reduction in mean speed of 0.44–1.75 km/h at the study sites, combined with an increase in mean speed of 1.23–2.29 km/h at the control sites. There seemed to be a tendency that the difference in mean speed between the before and after period gradually increased when the driver got further into the wind farm.

Also, the results of the analyses of the standard deviation of driving speed (SDDS) at each site are shown in Table 9. An increase in the SDDS was observed at each study site. Levene's tests for homogeneity of variance showed that these increases were all statistically significant. The greatest increase in the SDDS was observed at the first study site, while the increase in SDDS gradually lessened towards the last study site. On the other hand, the control sites either showed a negligible difference (control site upstream) or even a reduction in the standard deviation of speed (control site downstream).

Table 9 – Differences in mean speed and SDDS between the before and after period.

Location	No. of observations before (= minutes and lanes with vehicle flow > 0)	No. of observations after (= minutes and lanes with vehicle flow > 0)	Overall effect			SDDS before (km/h)	SDDS after (km/h)	Evolution of SDDS (km/h)
			Mean speed before (km/h)	Mean speed after (km/h)	Evolution before-after (km/h) [95%CI]			
Study site 1	117,695	118,720	99.75	99.31	-0.44 [-0.44; -0.44]	9.24	10.57	+1.33
Study site 2	115,636	118,011	99.70	98.65	-1.05 [-1.06; -1.05]	9.70	10.67	+0.97
Study site 3	115,392	116,407	99.58	98.78	-0.79 [-0.80; -0.79]	9.45	10.33	+0.88
Study site 4	114,342	114,352	100.11	98.36	-1.75 [-1.75; -1.74]	9.67	10.29	+0.62
Study site 5	112,090	113,732	98.99	97.39	-1.60 [-1.61; -1.60]	9.86	10.07	+0.21
Control site 1 (upstream)	110,759	115,054	95.36	96.59	+1.23 [+1.23; +1.24]	7.67	7.69	+0.02
Control site 2 (downstream)	111,427	110,212	107.85	110.51	+2.29 [+2.28; +2.29]	11.09	9.90	-1.19

<sup>1</sup> Parameter estimates for  $\beta_3$  in Eq. 1 with 95% CI.

#### 5.4.2 Analyses of observed lateral position

In total, the lateral positions of 3,649 vehicles were analysed (1,879 in the before period, 882 in the after period with rotor blades in parallel condition and 888 in the after period with rotor blades in perpendicular condition). The results of the regression model for the lateral position are shown in Table 10. Recall that measurements were taken from the left-hand side of the lane. This means that estimates with a positive sign indicate a lateral position closer to the right-hand side of the lane, while negative estimates indicate a position closer to the left-hand side of the lane.

All collected variables had a statistically significant effect on the lateral position. Vehicle type had a significant effect on the lateral position; HGVs drove closest to the left-side markings, followed by minivans, and passenger cars were positioned the farthest away from the left-side markings. This is quite straightforward, since HGVs are the widest vehicles and are therefore by definition closer to the pavement markings on both sides. It can also be seen that drivers in the left-hand lane were generally positioned closer to the left-side marking. Most probably, this resulted from the fact that most drivers in the left-hand lane were overtaking a vehicle in the right-hand lane and that they wished to keep a somewhat wider lateral distance from this vehicle by positioning themselves farther to the left of their driving lane. Drivers generally drove more closely to the left-hand markings during the night than during daytime.

The previous variables are mainly included in the model to correct for any possible confounding effects on the lateral position in order to be able to investigate the pure effect of the condition of the wind turbines, which is our main interest here. It appears that in both conditions of the after period, vehicles were positioned closer to the left-hand side of the driving lane. The results show that this tendency to drive closer to the left-hand side of the lane was more pronounced in the condition with the blades parallel to the roadway than in the condition with the blades perpendicular to the roadway. The mean lateral position indicated a shift of 13.6 cm to the left-hand side of the lane when the rotor blades were parallel to the roadway compared to the condition without wind turbines. In the condition with rotor blades perpendicular to the roadway, the lateral position showed a shift of 7.8 cm to the left compared to the condition without wind turbines.

Following the finding that drivers in the after period tended to choose a lateral position more to the left-hand side of their driving lane, a hypothesis could be that they also more often tend to drive in the left-hand lane instead of the right. Therefore, a  $\chi^2$ -test was performed to see if there was a correlation between the driving lane and the condition of the wind turbine. The null hypothesis was that there would be no correlation between both variables. The test showed that this null hypothesis could not be rejected at the 95% confidence interval,  $\chi^2(2) = 1.092$ ;  $p = 0.579$ . Also, in the case where the comparison was made between the before and after periods (hence merging both rotor blade conditions into one category), the null hypothesis could not be rejected,  $\chi^2(1) = 0.326$ ;  $p = 0.568$ . This indicates that the presence of the wind turbines had no effect on the choice of driving lane.

Table 10 – Regression model lateral position.

Variable	p-value of variable	Category	Estimate	S.E.	p-value of category
Constant	< 0.001		0.847	0.008	< 0.001
Vehicle type	< 0.001	HGV	-0.165	0.008	< 0.001
		Minivan	-0.045	0.015	0.003
		Passenger car	0 (ref.)		
Lane	< 0.001	Left	-0.156	0.009	< 0.001
		Right	0 (ref.)		
Time	< 0.001	Night	-0.066	0.015	< 0.001
		Day	0 (ref.)		
Condition	< 0.001	Blades parallel (after)	-0.136	0.009	< 0.001
		Blades perpendicular (after)	-0.078	0.009	< 0.001
		No turbines (before)	0 (ref.)		

Table 11 shows the results of the regression model for the SDLP. Vehicle type has a statistically significant influence on the SDLP. There was no statistically significant difference between passenger cars and minivans, but HGVs showed a statistically significantly lower SDLP than both other categories. Most likely, this was caused by the fact that HGVs are less agile vehicles than minivans and passenger cars and because of the fact that HGVs' larger width allows for less lateral displacement than that of the other two types of vehicles. Vehicles in the left-hand lane showed a statistically significantly lower SDLP than vehicles in the right-hand lane, and the SDLP was higher during daytime than during the night.

It needs to be noted that the condition of the wind turbines was again the main independent variable of interest. It can be seen that the variable "condition" was not statistically significant in the model. If we focus closely on the individual categories, it can however be observed that the difference between the "no turbines" condition and the "blades perpendicular" condition was very close to the level of 0.05 significance ( $p=0.057$ ), which can be seen as an indication of a possible effect. It should also be mentioned that the order of magnitude of the effect was limited.

### 5.4.3 Analyses of traffic conflicts

For both the before and after period, only a few situations were preselected by the observer for detailed measurement. Generally, very few dangerous situations took place. The few noteworthy situations that did take place were mainly situations where a vehicle changed lanes, impeding the path of an approaching vehicle in that lane. Further measurements of these preselected situations showed, however, that none satisfied the criteria to be considered a serious traffic conflict. Hence, no serious traffic conflicts were found in the before situation or in the after situation.

Table 11 – Regression model standard deviation of lateral position.

Variable	p-value of variable	Category	Estimate	S.E.	p-value of category
Constant	< 0.001		0.141	0.003	<0.001
Vehicle type	< 0.001	HGV	-0.027	0.003	<0.001
		Minivan	-0.003	0.006	0.609
		Passenger car	0 (ref.)		
Lane	< 0.001	Left	-0.020	0.004	<0.001
		Right	0 (ref.)		
Time	0.011	Night	-0.015	0.006	0.011
		Day	0 (ref.)		
Condition	0.156	Blades parallel (after)	0.001	0.004	0.736
		Blades perpendicular (after)	0.007	0.004	0.057
		No turbines (before)	0 (ref.)		

## 5.5 Discussion

### 5.5.1 Impact on driving speed

The analyses showed that the mean driving speed at the study sites decreased between the before and after periods, while the mean speed at the control sites increased during the same time periods. It was concluded that the mean speed decreased by 2.24 km/h as a consequence of constructing the wind turbines. This indicates a substantially stronger effect than that found by Alferdinck et al. (2012), who only found a slightly lower (0.4km/h) driving speed with rotor blades in the unfavourable (perpendicular) position compared to the favourable (parallel) condition, but found no effect caused by the position of the wind turbines themselves (26 m from the roadside in the project plan condition compared to 55 m in the official guidelines condition). The cause of the reduction in driving speed cannot be proven by the data analysed, but may be the result of distraction of the drivers because of the presence of the wind turbines.

Driving speed is an important factor in road safety; it strongly affects the risk of being involved in a crash as well as the severity of crashes (Aarts and van Schagen, 2006; Elvik et al., 2004). The relationship between changes in mean driving speed and their effect on traffic crashes is frequently expressed as an exponential function, also known as the Power Model (Elvik, 2009, 2013; Elvik et al., 2004; Nilsson, 2004). Using the exponents found by Elvik (2009) that apply specifically to motorways, the observed reduction in mean speed of 2.24 km/h is estimated to lead to a reduction in injury crashes by 3.6% and a reduction in fatal crashes by 8.9%. Everything else being equal, the effect of the found reduction in mean speed on traffic safety would therefore be positive, with a considerable decrease in especially the most severe crashes.

On the other hand, it should be kept in mind that a lower driving speed might be a compensatory mechanism of drivers to increase their margin for error when they

are distracted (Horberry et al., 2006). In that respect, it could also be an indirect indicator of a reduced driving performance as a result of being distracted. Additionally, the reduction of the speed seems to be a local effect only that is not sustained over a longer distance, since the downstream control site does not show a lower mean speed after the construction of the wind turbines. On the contrary, the mean speed is even significantly higher at this control site, although it is unsure whether this could be a (negative) spillover effect that is attributable to the wind turbines.

The SDDS increased statistically significantly between the before and after periods, ranging from +0.21km/h to +1.31km/h, while the SDDS did not change substantially or even decreased at the control sites. This indicated an increase in the heterogeneity of driving speed in the traffic flow. Comparable effects were found in the simulator study by Alferdinck et al. (2012). They found an increase of the SDDS by 0.41 km/h when the wind turbines were positioned according to the project plan condition compared to the official guidelines condition, and an increase in the SDDS by 0.3km/h in the perpendicular condition of the rotor blades compared to the parallel condition.

An increase in the differences in speed between vehicles generally tends to have a negative effect on road safety (Aarts and van Schagen, 2006). Detailed empirical analyses by Salusjärvi (1990), however, suggest that increases in the SDDS up to 2km/h do not have an effect on the risk of traffic crashes. The found effects on SDDS in this study were well below this threshold value. Therefore, it can be concluded that the small increase in the SDDS that was found would be unlikely to have a substantial effect on road safety.

### 5.5.2 Impact on lateral position

The analyses showed that the presence of the wind turbines had a statistically significant impact on the lateral position of vehicles. In the after period, when wind turbines were present alongside the right-hand side of the roadway, it was observed that drivers drove more to the left within their driving lane. This could be an indication that drivers noticed the wind turbines and had a conscious or unconscious tendency to take a position on the road farther away from the wind turbines. This finding is in line with Antonson et al. (2014), who found that roadside objects close to the roadway lead to a lateral shift towards the middle of the roadway. The presence of the wind turbines did not, however, affect the drivers' lane choice.

Dutch traffic rules stipulate that drivers are, in general, obliged to stay as far to the right-hand side as possible ("keep right unless to overtake"). This rule is similar in most right-hand traffic countries that do not apply the "keep your lane" principle. Since the presence of wind turbines seems to lead drivers to position themselves more to the left-hand side of the lane, this principle is somewhat undermined by the presence of wind turbines. However, to the best of our knowledge, there is no research that suggests that a shift in the (mean) lateral position, as such, has a direct negative impact on road safety. The shift in lateral position does, however, suggest that the presence of the wind turbines could possibly have a distracting effect on some drivers. This increased distraction might have negative effects on road safety as demonstrated by Dingus et al. (2016).

However, it is remarkable that the tendency of drivers to take a position closer to the left-hand side of the lane was more pronounced when the rotor blades were in parallel position compared to the perpendicular condition. Our initial hypothesis was that the effect on the lateral position, if present, would be strongest with the rotor blades in the perpendicular condition because the rotor blades would be more conspicuous to the drivers in that condition. The reason for this finding remains uncertain.

The lack of a harmonised horizontal position of a vehicle within the driving lane is one of the primary factors in single-vehicle run-off the road crashes and of head-on crashes on undivided two directional roadways (Rosey et al., 2008). SDLP is often used as an indicator for lateral trajectory control. A higher SDLP, indicating a higher amount of “weaving” by the driver, is considered to be unfavourable for road safety (Helland et al., 2013; Verster and Roth, 2011). The analyses of the SDLP in our study showed an indication very close to the level of 0.05 statistical significance ( $p=0.057$ ) of a limited increase in the SDLP in the condition with rotor blades perpendicular to the roadway, compared to the condition without wind turbines.

Brookhuis et al. (2003) have formulated threshold values for SDLP. According to the authors, the SDLP should be lower than 0.25 m, and the relative change between the two conditions should be maximally 0.04 m. It is somewhat uncertain whether these values should be directly transferred as reference points for our study, since these values were based on a very large number of measurement points over an entire route, while our values were calculated using only three measurement points over a short road section. It is, however, clear that the values found in this study (on average 0.123 m and 0.129 m for the condition without wind turbines and the condition with rotor blades in perpendicular condition, respectively) were well below these threshold values, both in terms of absolute values and relative change. It can be concluded that it is unlikely that this minor increase in SDLP represents an increase in the risk of traffic crashes.

The simulator study by Alferdinck et al. (2012) found an increase in SDLP in the condition with wind turbines in the project plan position compared to the position according to official guidelines condition. The effects found in the study stayed within the limits defined by Brookhuis et al. (2003) as well. Since our own observational study did not have a condition with wind turbines positioned according to the official guidelines, a direct comparison of the results of both studies was not possible. Generally, however, both studies suggest a limited increase in the SDLP, which is not thought to lead to an increase in risk.

### 5.5.3 Impact on traffic conflicts

The fact that no serious traffic conflicts have been registered after the construction of the wind turbines can be seen as a positive indication from the perspective of traffic safety. It suggests that the presence of wind turbines does not directly lead to unexpected and very dangerous traffic interactions.

However, it should be emphasized that both the duration of the traffic conflict observations (2 x 24 h) and the length of the observed road stretch (200 m) were

fairly limited. On road sections, traffic conflicts tend to be very dispersed, as opposed to intersections where they are strongly concentrated due to the large number of crossing and merging movements. Moreover, the complexity of a straight section of a motorway is quite low. Therefore, it would have been surprising if a high number of traffic conflicts had been observed.

#### 5.5.4 Strengths, limitations and further research

A strength of the study is the fact that it is one of the first studies to analyse the effects of wind turbines alongside roads on drivers and on road safety. Since the roadsides of motorways can be desirable locations to erect wind turbines from an economic perspective and from the perspective of public acceptance, the results can be relevant for policymakers in the fields of traffic safety and sustainable energy.

A limitation of the study is the fact that only one study location could be observed. While there are no indications that the effects of wind turbines on drivers would be different at other locations, this still implies that generalization of the results cannot be guaranteed. This study should be seen as a first study on the subject that provides some first indications and raises some points for discussion that should be further investigated in future research.

An additional limitation is the fact that some minor adaptations were made to the infrastructure between the before and after period. While we do not immediately expect an influence of these minor adaptations on drivers' behaviour and measures were taken to avoid and/or account for possible adaptations, it cannot be completely excluded that these adaptations may have had an effect on the measurements.

This study focused on the possible effect of directly perceiving the wind turbines as objects alongside the motorway. An additional element that could play a role is the cast shade on the pavement caused by the moving rotor blades during sunny days. This aspect is beyond the scope of this study, and it should be further investigated in future research.

A strength of the study is the use of empirical (observed) data. This is beneficial for the validity of the research results because there should not be any doubt about whether the registered behaviours will take place in practice, as opposed to, for example, driving simulator data or survey data (De Ceunynck et al., 2015). An additional strength is the large sample sizes used for the analyses of speed and lateral position, which makes these analyses and the conclusions drawn from them quite robust.

A final strength is that the results from this study and the driving simulator study by Alferdinck et al. (2012) complement and strengthen each other. Earlier research has demonstrated the benefits of combining the results from a driving simulator study with the results from site-based observations (Polders et al., 2015). By combining the results of both studies, a more holistic view of the effects of wind turbines on drivers' behaviour and road safety is obtained.

### 5.5.5 Policy recommendations

Increases in standard deviation of driving speed (SDDS) and SDLP are two factors that could have a negative effect on road safety. The observed order of magnitude of the changes in our study, however, was limited, and earlier research suggests that, for both indicators, negative effects on road safety are only expected as a result of changes substantially greater than the ones that were observed in this study (Brookhuis et al., 2003; Salusjärvi, 1990). On the other hand, our study showed a statistically significant reduction in mean driving speed, which might reduce the expected number and severity of crashes, although it could also be a compensatory mechanism that indirectly indicates a reduced driving performance.

No substantial negative effects for road safety were therefore found due to the presence of wind turbines. Nevertheless, both this study and an earlier driving simulator study on the topic found some clear effects of the presence of wind turbines alongside the motorway on drivers' behaviour, which could indicate an increased amount of distraction. Reasoning from the cautionary principle, it might be advised to maintain adequate regulatory distances between pavement and turbines wherever possible, and not to position wind turbines close to locations that require an increased attention from drivers, such as motorway interchanges or road segments that are sensitive to traffic jams. Continuous monitoring and further research on the topic are recommended.

## 5.6 Conclusions

The conclusion of this study is that the presence of wind turbines alongside the investigated motorway stretch leads to observable behavioural adaptation effects among passing drivers.

Drivers drove statistically significantly slower (-2.24 km/h) than before the construction of wind turbines. However, the SDDS across drivers increased. Drivers chose a lateral position more closely to the left-hand side of their driving lane when wind turbines were present. There was some indication of a limited increase in the SDLP in the condition with rotor blades in perpendicular position compared to the condition with no wind turbines, while no effects on the number of traffic conflicts were found.

The increase in SDDS and SDLP are two effects that intrinsically could have an unfavourable effect on road safety. However, the observed order of magnitude of the change is limited, and earlier research suggests that negative effects on road safety are only expected at changes substantially greater than the ones that were observed in this study. On the other hand, there is a statistically significant reduction in driving speed, which might have a favourable effect on the expected number and severity of crashes, although it could also be a compensatory mechanism that indirectly indicates a reduced driving performance. From these findings, it can be concluded that, based on the observed variables, no substantial negative effects for road safety were found in the present case. The authors recommend continuous monitoring and further research on the topic.

## Chapter 6. Road Safety Differences Between Priority-Controlled Intersections and Right-Hand Priority Intersections: a Behavioural Analysis of Vehicle-Vehicle Interactions

In this chapter, data collected through behavioural observations by on-site human observers are used to investigate road safety differences between priority-controlled intersections and right-hand priority intersections. More specifically, yielding behaviour and looking behaviour are analysed in order to draw inferences on road safety. This study aims to contribute to the second research question, "How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed?". The study mostly contributes to answering this question by investigating to what extent conclusions on road safety can be drawn solely based on behavioural observations.

The results from this chapter are published in De Ceunynck et al. (2013b). Data were collected and first analyses were performed within the frame of the Master thesis of the second author of the paper. My role in this study was to design the study set-up, guide all stages of the Master thesis, participate as second observer for the intercoder reliability assessment, run the final analyses that have been included in the paper and in this dissertation, and write the vast majority of the paper.

### 6.1 Introduction

Intersections are complex locations with many different movements, resulting in a wide range of possible interactions among 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 unsignalised 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, scientific literature is inconclusive about which of both intersection types should be preferred in which situations from a safety point of view. Generally, no statistically significant difference in the number of crashes is found when transforming right-hand priority intersections to priority-controlled intersections, which indicates that a higher level of control does not guarantee an

improvement in safety (Elvik et al., 2009a). Since the low level of control at both intersection types necessitates a lot of interaction between road users, a deeper insight in 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 between both types of intersections.

## 6.2 Background

### 6.2.1 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 to right-hand priority intersections (Elvik et al., 2009a).

However, an overview based on 14 studies (Elvik et al., 2009a) concludes that the number of injury crashes is generally only reduced by 3% (95% CI [-9; +3]) when converting right-hand priority intersections to priority-controlled intersections. Elvik et al. (2009a) mention that some studies even indicate an increase in the number of crashes, for instance in 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., 2009a). 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 & Nuytens, 2009).

### 6.2.2 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,...) (Lawton et al., 1997). Behavioural, personal and environmental elements can have an influence on the occurrence of violations. When behaviour that is in contradiction

with formal rules becomes common in particular situations, this 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.

#### 6.2.2.1 Yielding behaviour

Research indicates that failure to yield is one of the primary factors leading to crashes at unsignalised 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., 2009a; Helmers & Åberg, 1978). Helmers & Åberg (1978), cited by Björklund & 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 both 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 to four-leg intersections. Johannessen (1984), cited by Björklund & 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.

#### 6.2.2.2 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. This 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 non-official communication. However, most communication signals can be ambiguous and may therefore also lead to dangerous situations when misinterpreted (Risser, 1985).

#### 6.2.2.3 Approach behaviour

The speed of another approaching vehicle is an important factor for a driver's decision to give way or not (Janssen et al., 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 speed than when the other driver slows down (Björklund & Åberg, 2005).

#### 6.2.2.4 Looking behaviour

Detection errors (i.e. not seeing another road user) are an important cause of crashes, 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 head. Drivers who look to the right do this at lower approach speeds than other drivers. Looking behavior can also be a form of communication, for instance not looking to a driver coming from a side road may express that one has no intention to yield.

#### 6.2.3 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 et al., 2008; McGwin & Brown, 1999). Search and detection errors and evaluation errors have the highest contribution 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 due to a combination of speeding, slow hazard perception and a firmness to enforce their right-of-way (Braitman et al., 2008). Middle-aged drivers are also less likely to be at-fault in failure to yield crashes (Mayhew et al., 2006).

Older drivers are overrepresented in most types of intersection crashes (Keskinen et al., 1998). At unsignalised intersections, failure to yield crashes are most common (Braitman et al., 2008; Oxley et al., 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 difficulties 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 et al., 1991). Older drivers tend to drive and accelerate slower than other drivers, which might lead to dangerous situations when interacting at unsignalised 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 statistically significantly more often involved in crashes involving right-of-way violations than women (Al-Balbissi, 2003). Kulmala (1990) indicates that women enter right-hand priority intersections on average 3-4 km/h slower than men.

## 6.2.4 Status

It can be concluded that 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 based on 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.

## 6.3 Methodology

### 6.3.1 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 right-of-way rules. The study focuses on side interactions between two vehicles. Observable elements of interactions that are potentially relevant to road safety are collected, including yielding, looking and approaching behaviour, communication, gender and age of the involved drivers.

#### 6.3.1.1 Selection of study locations

One priority-controlled intersection and one right-hand priority intersection are selected in the province of Limburg (Belgium) for extensive observation. At the priority-controlled intersection, the right-of-way is indicated by yield signs and pavement markings. When no yield signs or pavement markings are present, the right-hand priority rule applies by default. This 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 by specific intersection characteristics other than the type of priority control as possible. For that reason, two "basic" intersections are chosen that have no geometrical particularities such as bicycle paths, crossings, speed reducing measures etc. that may influence the way interactions between drivers take place. The road widths are the same for both intersections and for all approaching legs 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 legs. 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 (7a.m. till 6p.m. period) of 2441 PCE (passenger car equivalent) on the primary (in-priority) road and 278 PCE on the secondary road, the right-hand priority intersection has traffic volumes of 2648 PCE and 289 PCE respectively. For reasons of brevity, we refer to the higher volume road at the right-hand priority intersection also as the “primary road” and the lower volume road as the “secondary road”, although the terms do not indicate a hierarchy here.

#### 6.3.1.2 Definition and operationalization of the concept “interaction”

A first crucial element is what is to be considered an “interaction”. We define an interaction 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 up in a crash (Laureshyn et al., 2010).

To facilitate and objectify the observations, this definition is operationalized as a geographical space around the intersection. The limits of this space are at both intersections 50m away from the intersection plane on both sides of the primary road, and 25m on both sides of the secondary road. The choice for two different distances is based on speed measurements that indicate a substantially 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 ( $\pm 3$  km/h) at the priority-controlled intersection compared to the right-hand priority intersection. The distances are chosen based on pilot tests that have indicated that this is in most occurring situations a good cut-off value to distinguish between vehicles that have an influence on each other and vehicles that do not.

#### 6.3.1.3 Observation protocol

Each intersection is observed for 30 hours during the period November 24<sup>th</sup> till December 5<sup>th</sup> 2011. All observations have taken place in dry weather conditions during daytime because of the need to look inside vehicles to collect information about drivers’ gender, age and looking behaviour. Twilight, night and rainy conditions do not allow this. The observations are done in blocks of 2-3 hours, spread evenly throughout the hours of the day and days of the week (including weekends) for both intersections to avoid possible biases. All observations have been executed by one observer using a standardized observation form. All variables have been objectified and standardized as binary or categorical variables to allow quantitative analyses of the interactions.

#### 6.3.2 Ensuring and assessing the reliability of the data collection

A second observer has 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 et al., 2002). A high level of agreement between coders is considered as a sign of theoretical solidity of the applied method and a good training of the observers, while large differences among coders suggest weaknesses in the research methods, such as poor operational definitions or training of the observers (De Ceunynck et al., 2013a; Hak & Bernts, 1996; Lombard et al., 2002).

Furthermore, all interactions are recorded, which allows to validate 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.

### 6.3.3 Analysis of the collected behavioural data

The data are analysed using logistic regression models, which can be used to predict the probability of a certain event when the dependent variable is dichotomous (Allison, 2008). Firth's penalized maximum likelihood is applied because it avoids the problem of quasi-complete separation, which is the most common convergence failure in logistic regression (Allison, 2008; Heinze & Schemper, 2002).

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

## 6.4 Results and discussion

### 6.4.1 Intercoder reliability

An extensive intercoder reliability assessment is performed based on 113 of the 483 interactions (23% of all data). The intercoder reliability is assessed by using two measures: Cohen's  $\kappa$  and percent agreement. Percent agreement is the simplest intercoder reliability measure and expresses the percentage of cases for which the observers agree. Cohen's  $\kappa$  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 is calculated as well because some of the calculations suffer from the so-called " $\kappa$  paradox". These are situations where the Cohen's  $\kappa$  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 since this measure is not susceptible to the  $\kappa$  paradox (Krippendorff, 2004).

A  $\kappa$ -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 have a reliable  $\kappa$ -value exceed the 0.70 threshold for Cohen's  $\kappa$ , and all-but-one (i.e. gender of the driver on the primary road) even exceed the stricter criterion of 0.80. All variables (including those with an unreliable  $\kappa$ -value) have a percent agreement of 0.85 or higher. Most importantly, the agreement on which situations are considered "interactions" and which ones are not is 100%. The differences in reliability between both intersection types are minimal. In conclusion, the intercoder reliability values are high and quite stable across all variables and intersections.

#### 6.4.2 Descriptive statistics

Descriptive statistics are presented in Table 12. 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 either be the in-priority vehicle and 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 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 prior experience (Sivak & Schoettle, 2011). Therefore, especially drivers who are familiar with the intersection may not expect drivers arriving from the secondary road, and therefore 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. Therefore, it is decided to analyse the data according to both possibilities to check whether the results differ. The variables recorded 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), which is very similar to Johannessen (1984), who indicates 75% compliance. The compliance at the priority-controlled intersection (92%) is statistically significantly higher than at the right-hand priority intersection ( $\chi^2(1, N=483)=22.46$ ,  $p<0.001$ ), which is in line with Helmers & Åberg (1978).

Table 12 – Descriptive statistics.

Variable name and description – Distinction prim/sec <i>Distinction in-priority/no-priority</i>	Priority- controlled intersection (N=182)	Right-hand priority intersection (N=201) (distinction prim/sec)	Right-hand priority intersection (N=201) – (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	
HasPriority prim – vehicle on primary road has priority <i>HasPriority VP – in-priority vehicle has priority</i>	Yes:182 ; No:0	Yes:86 ; No:115	<i>Yes:201 ; No:0</i>
HasPriority sec – vehicle of secondary road has priority <i>HasPriority VNP – no-priority vehicle has priority</i>	Yes:0 ; No:182	Yes:115 ; No:86	<i>Yes:0 ; No:201</i>
GetPriority prim – vehicle on primary road gets priority <i>GetPriority VP – in-priority vehicle gets priority</i>	Yes:167 ; No:15	Yes:124 ; No:77	<i>Yes:147 ; No:54</i>
GetPriority sec – vehicle of secondary road gets priority <i>GetPriority VNP – no-priority vehicle gets priority</i>	Yes:15 ; No:167	Yes:77 ; No:124	<i>Yes:54 ; No:147</i>
Demographic variables			
Gender prim – gender of driver on primary road <i>Gender VP – gender of in-priority driver</i> M = male; F = female	M: 125 ; F: 57	M:138 ; F: 63	<i>M:121 ; F: 80</i>
Gender sec – gender of driver on secondary road <i>Gender VNP – gender of no-priority driver</i> M = male; F = female	M: 104 ; F: 78	M:108 ; F: 93	<i>M:125 ; F: 76</i>
Age prim – age of driver on primary road <i>Age VP – age of in-priority driver</i> Y = young driver; M = middle-age driver; O = older driver	Y: 5 ; M:159 ; O:18	Y:5 ; M:186 ; O:10	<i>Y:4 ; M:174 ; O:23</i>
Age sec – age of driver on secondary road <i>Age VNP – age of no-priority driver</i> Y = young driver; M = middle-age driver; O = older driver	Y: 3 ; M:150; O:29	Y:6 ; M:166; O:29	<i>Y:7 ; M:178 ; O:16</i>
Approaching behaviour			
Prim arrives first – vehicle on primary road reaches junction plane first <i>VP arrives first – in-priority vehicle reaches junction plane first</i>	Yes:15 ; No:167	Yes:58 ; No:143	<i>Yes:77 ; No:124</i>

**Table 12 – Descriptive statistics [cont.].**

Sec arrives first – vehicle on secondary road reaches junction plane first <i>VNP arrives first – no-priority vehicle reaches junction plane first</i>	Yes:112 ; No:70	Yes:90 ; No:111	<i>Yes:71 ; No:130</i>
Arrive same time – vehicle on primary and secondary road reach junction plane at the same time <i>Same time –in-priority and no-priority vehicle reach junction plane at the same time</i>	Yes:55 ; No:127	Yes:53 ; No:148	
Approach prim – approach behaviour of vehicle on primary road at junction plane <i>Approach VP – approach behaviour of in-priority vehicle at junction plane</i> Stop = stops completely; Dec. = decelerates; Hold= holds same speed; Acc. = accelerates	Stop: 1 ; Dec.: 24 ; Hold: 157 ; Acc.: 0	Stop:40 ; Dec.:53 ; Hold:106 ; Acc.:2	<i>Stop:52 ; Dec.:64 ; Hold:84 ; Acc.:1</i>
Approach sec – approach behaviour of vehicle on secondary road at junction plane <i>Approach VNP – approach behaviour of no-priority vehicle at junction plane</i> Stop = stops completely; Dec. = decelerates; Hold = holds same speed; Acc. = accelerates	Stop:179 ; Dec.:1 ; Hold:2 ; Acc.:0	Stop:110 ; Dec.:69 ; Hold:22 ; Acc.:0	<i>Stop:98 ; Dec.:58 ; Hold:44 ; Acc.:1</i>
Drivers' looking behaviour			
LookLeft prim – driver on primary road looks left <i>LookLeft VP – in-priority driver looks left</i>	Yes:21 ; No:161	Yes:22 ; No:179	<i>Yes: 123 ; No: 78</i>
LookRight prim – driver on primary road looks right <i>LookRight VP – in-priority driver looks right</i>	Yes:10 ; No:172	Yes:90 ; No:111	<i>Yes:128 ; No:73</i>
DontLook prim – driver on primary road does not look right or left <i>DontLook VP – in-priority driver does not look right or left</i>	Yes:155 ; No:27	Yes:107 ; No:94	<i>Yes:160 ; No:41</i>
LookLeft sec – driver on secondary road looks left <i>LookLeft VNP – no-priority driver looks left</i>	Yes:182 ; No:0	Yes:198 ; No:3	<i>Yes:97 ; No:104</i>
LookRight sec – driver on secondary road looks right <i>LookLeft VNP – no-priority driver looks right</i>	Yes:181 ; No:1	Yes:198 ; No:3	<i>Yes:66 ; No:135</i>
DontLook sec – driver on secondary road does not look right or left <i>DontLook VNP – no-priority driver does not look right or left</i>	Yes:0 ; No:182	Yes:0 ; No:201	<i>Yes:41 ; No:160</i>

Table 12 – Descriptive statistics [cont.].

Manoeuvre			
TurnLeft prim – vehicle on primary road turns left <i>TurnLeft VP – in-priority vehicle turns left</i>	Yes:14 ; No:168	Yes:9 ; No:192	<i>Yes:85 ; No:116</i>
TurnRight prim – vehicle on primary road turns right <i>TurnRight VP – in-priority vehicle turns right</i>	Yes:0 ; No:182	Yes:2 ; No:199	<i>Yes:28 ; No:173</i>
DontTurn prim – vehicle on primary road does not turn <i>DontTurn VP – in-priority vehicle does not turn</i>	Yes:168 ; No:14	Yes:190 ; No:11	<i>Yes:88 ; No:113</i>
TurnLeft sec – vehicle on secondary road turns left <i>TurnLeft VNP – no-priority vehicle turns left</i>	Yes:83 ; No:99	Yes:144 ; No:57	<i>Yes:68 ; No:133</i>
TurnRight sec – vehicle on secondary road turns right <i>TurnRight VNP – no-priority vehicle turns right</i>	Yes:58 ; No:124	Yes:29 ; No:172	<i>Yes:3 ; No:198</i>
DontTurn sec – vehicle on secondary road does not turn <i>DontTurn VNP – no-priority vehicle does not turn</i>	Yes:41 ; No:141	Yes:28 ; No:173	<i>Yes:130 ; No:71</i>
Communication data			
Direction prim – driver on primary road uses direction indicator <i>Direction VP – in-priority driver uses direction indicator</i>	Yes:168 ; No:14	Yes:11 ; No:190	<i>Yes:99 ; No:102</i>
Direction sec – driver on secondary road uses direction indicator <i>Direction VNP – no-priority driver uses direction indicator</i>	Yes:116 ; No:66	Yes:153 ; No:48	<i>Yes:65 ; No:136</i>
Gesture prim – driver on primary road uses horn, hand gesture or flash of headlights to communicate <i>Gesture VP – in-priority driver uses horn, hand gesture or flash of headlights to communicate</i>	Yes:1 ; No:181	Yes:1 ; No:200	<i>Yes:8 ; No:193</i>
Gesture sec – driver on secondary road uses horn, hand gesture or lights to communicate <i>Gesture VNP – no-priority driver uses horn, hand gesture or flash of headlights to communicate</i>	Yes:0 ; No:182	Yes:8 ; No:193	<i>Yes:1 ; No:200</i>

### 6.4.3 Priority violations models

The models in Table 13 indicate 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 at the intersection first than when the vehicle on the secondary road does not arrive first.

The priority-controlled intersection model shows three statistically significant variables. "Sec arrives first" indicates that a violation is statistically 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 to when it only slows down. Perhaps the most remarkable finding is that the probability of a right-of-way violation is statistically 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 (1990) findings, although his observations only apply 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 either sees this as implicit communication indicating that the driver on the primary road may give way (Risser, 1985), or as an opportunity to infringe on the primary road driver's right-of-way with a low perceived personal risk. 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 in case the vehicle on the secondary road arrives first. Both variables seem to confirm that the primary road is indeed considered as 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 can either indicate that these drivers approach the intersection at higher speeds (in line with Kulmala (1990)), this way discouraging the driver on the secondary road to enforce his right-of-way for safety reasons, or as 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 statistically significantly higher chance of a right-of-way violation when the no-priority vehicle arrives first at the intersection. "Approach VP" indicates the highest probability of a priority violation in case the in-priority vehicle comes to a full stop. "Approach VNP" indicates a statistically significantly higher chance of violation when the no-priority vehicle maintains its speed, and a statistically significantly lower chance when the no-priority vehicle comes to a stop.

Table 13 – Factors influencing the probability of a right-of-way violation.

Variables	Priority-controlled intersection	Right-hand priority intersection (distinction prim/sec) ("model A")	Right-hand priority intersection – (distinction VP/VNP) <sup>1</sup> ("model B")
Intercept	0.027 (p=0.980) <sup>o</sup>	-1.591 (p<0.001)***	-0.765 (p=0.365) <sup>o</sup>
HasPriority sec		1.281 (p<0.001)	
Sec arrives first	1.5265 (p=0.034)**	-0.473 (p=0.013)**	
VNP arrives first			1.198 (p<0.001)***
Approach VP			Stop: 2.153 (p=0.004)*** Dec.: 0 Hold: -1.009 (p=0.150) <sup>o</sup> Acc.: -1.134 (p=0.526) <sup>o</sup> (p<0.001)***
Approach sec	Stop: -2.653 (p=0.017)** Dec.: 0 Hold: 1.154 (p=0.451) <sup>o</sup> (p=0.050)**		
Approach VNP			Stop: -1.823 (p=0.007)*** Dec.: 0 Hold: 1.544 (p=0.023)** Acc.: 0.677 (p=0.702) <sup>o</sup> (p<0.001)***
LookRight prim	1.098 (p=0.009)***		
DontLook prim		0.771 (p<0.001)***	
<sup>1</sup> VP= in-priority vehicle; VNP = no-priority vehicle *** p≤0.01 (significant at 99% CI) ** p≤0.05 (significant at 95% CI) * p≤0.10 (significant at 90% CI) <sup>o</sup> p>0.10 (not significant at 90% CI)			

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 statistically significantly higher when the no-priority

vehicle arrives first at the intersection. This 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 and/or speed 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 statistically significantly reduces when the no-priority vehicle stops, compared to the reference category of only decelerating. This 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, i.e. a statistically significantly higher probability of a violation when the in-priority vehicle stops, and a lower (although statistically not significant) probability in case the in-priority vehicle maintains its speed.

#### 6.4.4 Looking behaviour models

Table 14 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, both 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 only includes "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 case he arrives first, but the estimate is not statistically significant. There is a statistically significantly higher probability that the driver looks to the sides in case he 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 statistically 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 (statistically non-significant) higher probability of looking to the sides in case 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 vehicle 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 arrives at the intersection first. Furthermore, in-priority male drivers tend to look less to the

sides than female drivers, although the difference is statistically 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 statistically 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.

At the right-hand priority intersection, drivers are generally more likely to look to the sides in case they yield to the other road user. 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 statistically significantly higher probability of looking to the sides when the driver comes to a full stop, while this probability is statistically significantly lower when the driver holds his speed.

*Table 14 – Factors influencing the likelihood that a driver looks to the sides on approach to the 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=0.951) <sup>o</sup>	1.368 (p=0.028)**	2.260 (p<0.001)***	1.570 (p=0.013)**
GetsPriority sec GetsPriority VNP		0.5124 (p=0.036)**	1.262 (p<0.001)***	
GetsPriority VP				0.561 (p=0.052)*
Prim arrives first VP arrives first	0.502 (p=0.171) <sup>o</sup>		0.4649 (p=0.008)***	

Table 14 – Factors influencing the likelihood that a driver looks to the sides on approach to the intersection [cont.].

Approach prim		Stop: 2.056 (p=0.006)*** Dec.: 0 Hold: -2.218 (p<0.001)*** Acc.: -0.200 (p=0.856)° (p<0.001)***		
Approach VNP				Stop: 2.173 (p=0.013)** Dec.: 0 Hold: -2.472 (p<0.001)*** Acc.: 0.090 (p=0.960)° (p<0.001)***
Turn prim	1.904 (p<0.001)***	0.655 (p=0.185)°		
Gender VP			F: 0 M: -0.287 (p=0.101)°	
Age VP			Y: -0.529 (p=0.528)° M: 0 O: 1.248 (p=0.081)* (p=0.095)*	
<sup>1</sup> VP= vehicle in priority; VNP = vehicle no-priority *** p≤0.01 (significant at 99% CI) ** p≤0.05 (significant at 95% CI) * p≤0.10 (significant at 90% CI) ° p>0.10 (not significant at 90% CI)				

## 6.5 Study limitations and further research

As this study is based on observations on two intersections, the possibilities to draw generalized 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 et al., 2011; Rosenbloom, 2009; Saunier et al., 2011; St-Aubin et al., 2013; Svensson & Hydén, 2006). Nevertheless, the study can be considered as a pilot project that tests a standardized observation protocol and reveals some interesting hypotheses and topics for further research. Research should investigate the generalizability 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 with, 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, i.e. conflicts and crashes, should be further investigated. This 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 is often unclear whether looking to the side is a proxy for a lower approach speed, as suggested by literature (Kulmala, 1990), or a directly influencing factor.

## 6.6 Conclusions

The number of priority violations appears to be statistically 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 statistically significantly higher when the no-priority vehicle arrives at the intersection first, indicating a “first come, first served” tendency. Furthermore, approach behaviour is statistically 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 statistically significantly influence drivers’ yielding behaviour at either intersection.

At the priority-controlled intersection, there is also a higher probability of a violation in case the driver on the primary road looks to his 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 statistically significantly higher chance of a right-of-way violation when the secondary road driver has priority, this indicates 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 as 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.

Regarding 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 as 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, this merits further research.

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.

## Chapter 7. Final discussion and conclusions

The main goal of this dissertation is to contribute to filling methodological knowledge gaps in site-based observations of surrogate safety measures and road users' behaviour, and to investigate how such observations can be applied to study road safety issues for which crash data appear to be less suitable. This goal has been operationalised in two research questions that will be recapitulated in the following subsection. This chapter discusses and summarizes the contributions this work makes to answering those research questions.

- 1) How are surrogate safety measures applied in scientific literature, and how can measures be improved/defined to mitigate current limitations?
- 2) How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed?

In addition, the possibilities and benefits of combining multiple techniques of road safety research and final conclusions and implications for research and practice are listed.

### 7.1 RQ1: How are surrogate safety measures applied in scientific literature, and how can measures be improved/defined to mitigate current limitations?

Chapter 2 has provided an elaborate overview of how surrogate safety measures have been applied in scientific literature over the years. A substantial increase in publications since 2010 indicates a strongly increasing interest in this field of road safety research. The most remarkable conclusion is that an overwhelming variety and creativity is found in literature with regard to the applied surrogate safety indicators and traffic conflict techniques, threshold values that are applied to distinguish between severe and non-severe events, number of observation sites and duration of the observations, data analysis techniques that are applied, and supplementary data that are collected and analysed. As a result, the quality of studies, and therefore the reliability of their results, varies strongly.

This suggests that there is a need for a framework of good practice with hands-on guidelines and recommendations for applying surrogate safety measures. This could help to increase the quality of future studies and the reliability of their results. While providing such a framework was beyond the scope of our review study, the review might serve as a useful starting point for such recommendations by providing an "inventory" of how surrogate safety measures have been applied to date.

While a large number of surrogate safety indicators and traffic conflict techniques have been identified from literature, none of them really outperforms the other ones. The three main identified limitations of existing surrogate safety indicators and traffic conflict techniques are recapitulated in the following paragraphs.

Firstly, it was found that the vast majority of surrogate safety measures describe the severity of an event only in terms of the nearness to a crash (i.e., the proximity of the involved road users in time and/or space). The potential outcome severity in case the event had led to a crash is rarely included. As indicated, this

is an important limitation because the main goal of road safety policies such as Vision Zero is to prevent the most severe crashes, including fatalities and serious injuries from happening. To be optimally suited to support such policies, surrogate safety measures should therefore be able to include the potential outcome severity of traffic events as well.

Secondly, not all surrogate safety indicators and traffic conflict techniques are suitable to measure the severity of all potentially relevant situations in traffic. For example, TTC-based indicators, which are the largest and most commonly applied family of indicators that was identified, can only be applied in case road users are on a collision course. The Swedish Traffic Conflict Technique, which is partly based on the TTC concept, also requires road users to be on a collision course as well as an evasive action by one of the involved road users in order to assess a traffic event.

Thirdly, it was found that all surrogate safety indicators and traffic conflict techniques require further validation. Each indicator or technique has been validated in only a few studies at best; most of them have never been formally validated against crashes. Additionally, many validation studies are relatively old and were undertaken using human observers, so a critical re-evaluation of their relevance and transferability towards data collection through (semi-) automated video analysis is needed. None of the surrogate safety indicators or traffic conflict techniques can be claimed to outperform the others in terms of validity.

Apart from these three limitations, two promising directions for further improvement of surrogate safety measures have been identified from literature. Firstly, it was observed that many existing surrogate safety indicators and traffic conflict techniques express the severity of an event as a single value. This value thus aims to represent the process of the entire interaction. This way, however, very dissimilar events can have the same calculated value, and could therefore incorrectly be considered as being very similar (Hydén, 1987). A limitation of this approach is that it is an important loss of information; while the whole interaction is being observed, only a fraction of this information is put to use. One of the advantages of site-based observations over traditional crash analyses is that they are a richer source of information because more information can be observed about behavioural and situational elements that play a role. Making use of an indicator describing the continuous process of the event rather than a single value indicator seems a logical extension of this aspect. One of only few applications of continuous surrogate safety indicators is found in the study by Saunier & Mohamed (2014). They applied measurements of continuous indicators to a video dataset that contains conflicts as well as crashes. The study found that the process of many traffic conflicts had close similarities to traffic crashes. However, the study also highlights that some severe non-crash events share little similarities with observed crashes. The latter finding suggests that not all severe interactions might be suitable for surrogate safety analysis.

Secondly, an important feature of many surrogate safety indicators and traffic conflict techniques is that they make use of some assumption about the projected or planned path of the road users. For instance, TTC assumes that road users will continue to move at their current pace and direction until a crash takes place. This could be considered a strong and restrictive hypothesis. If one “replays” a crash,

it is very rare that, even before at least one of the road users attempted an evasive action (if there was any attempt at all), the road users were moving in a straight line at constant speed. However, if one were to relax this restriction and accept that a road user has, at any point in the interaction, multiple options on how to proceed, there are several possible trajectories per road user that could at some point end up in a crash. Some of these possible trajectories are more likely than others. Using motion prediction models, one can predict for each instant of the interaction where and how road users may collide in the future at several potential collision points. By summing the probabilities of each of the possible scenarios to end up in a crash, an overall severity can be computed for each event without a need to restrict assumptions about the road users' paths. This method is referred to as a "probabilistic framework" (Saunier & Sayed, 2008). The application of severity assessments that make no (or fewer) assumptions about road users' planned or projected paths seems a promising methodological improvement towards the future. Currently, however, the framework still poses major challenges in term of how to interpret the output from a road safety perspective.

By defining a new surrogate safety indicator, Extended Delta-V, we have made an attempt to address limitations of existing surrogate safety measures. The primary starting point was to better reflect the outcome severity of a traffic event, which we considered to be the most critical and most common shortcoming of existing surrogate safety measures. The indicator is founded on a solid relationship with outcome severity that originates from crash reconstruction research. Additionally, the link with closeness to a crash is made through a flexible time-proximity-based indicator. We therefore believe that both dimensions are represented by the indicator in a well-supported way, hence addressing the first limitation.

The point that is probably most open for debate, is how both proximity to a crash and potential outcome severity should be weighed together. Both presented operationalisations (Extended Delta-V4 and Extended Delta-V8) reflect in some way a change in balance between both aspects. At this point, it is unclear which of both measurements is to be preferred, or if there are better alternatives to weigh both aspects. Additionally, while the first case study provides promising results, the indicator should be thoroughly tested on other types of interactions and other types of road users. These are important directions for future research.

The second limitation is also addressed in the sense that Extended Delta-V is based on underlying indicators that allow to calculate the severity of all traffic events of road users with crossing paths. The indicator is therefore highly flexible since it can measure the severity of collision course and non-collision course events, as well as crash and non-crash events. A related advantage of the Extended Delta-V indicator in view of the emerging automated video analysis tools is that all required parameters could potentially be retrieved automatically from video footage.

Relating to the third limitation, our indicator has not been validated yet. While the first results are promising, and the underlying framework seems to have the potential for having a high validity as a surrogate for (severe) crashes, formal validation research is strongly needed to prove the value of the indicator as a surrogate for crashes. This is an important direction for future research.

The additional two promising directions for further improvement have not been incorporated in the current operationalisation of the indicator. This could be a promising direction for future research. The Extended Delta-V indicator in its current operationalisation expresses the severity of traffic events in a single value. However, the indicator provides a continuous description of the traffic event and could therefore be analysed in a continuous way too. In the calculation of the indicator, an assumption about road users' projected paths is made. More specifically, the assumption of the projected path assumes an evasive braking manoeuvre, which is in fact used to weigh the nearness to a crash and the potential outcome severity together. The probabilistic framework proposed by Saunier & Sayed (2008) could be applied to this indicator as well in case the currently fixed assumptions about the road users' paths and evasive manoeuvres were to be replaced by a probability distribution that describes the revealed or hypothesised likelihood of the different options that the involved road users have.

In summary, it seems reasonable to conclude that the Extended Delta-V indicator shows a lot of potential, although further research is needed.

## 7.2 RQ2: How can site-based observations of road users' behaviour and interactions supplement or even replace surrogate safety measures, especially when severe events take place infrequently and/or dispersed?

It was hypothesized that in situations in which even the number of severe non-crash events is expected to be too low to draw reliable conclusions from surrogate safety measures, a supplementation or even replacement of surrogate safety measures by behavioural indicators could be useful. Three cases studies, with a varying emphasis between surrogate safety measures and behavioural indicators, have been conducted to investigate to what extent the observation of behavioural aspects can supplement or even replace surrogate safety measures.

One of the practical issues of studying road safety at road sections is that most surrogate safety measures are mostly suitable for assessing the severity of events involving road users with crossing courses. Additionally, severe events take place very dispersed over the network, while site-based observations can only cover small areas. The studies about bicyclists on bus lanes (Chapter 4) and the effects of wind turbines (Chapter 5) took place at road sections and therefore encountered these difficulties. In both studies, a different approach could be designed that allowed to draw some exploratory conclusions on road safety.

By using  $TTC_{min}$ , Time Gap and overtaking proximity in the study about bicyclists on bus lanes, we could describe the proximity in time of bicyclists and buses in individual interactions, hence measuring the severity of the situation in a meaningful (although in the case of Time Gap and overtaking proximity not formally validated) way. While it is a limitation of the study, the emphasis on these non-validated surrogate safety indicators was necessary to describe the severity of the traffic events in a meaningful way because most of the better validated indicators were in practice not considered sufficiently suitable to assess these same-direction interactions of which the most severe ones would take place too dispersed. Behavioural indicators such as lateral position, overtaking speed and

riding speed in this study led to additional insights in the way bicyclists and buses interact with each other. While this is useful information that contributes to a deeper understanding of the interaction process, in themselves they cannot sufficiently explain the potential risk of crashes in this study.

In the study about the effects of wind turbines, analyses of interactions of road users were not considered to be the most suitable unit of analysis, since a straight stretch of motorway generally involves relatively little interaction between road users. While interactions were taken into account through the observation of serious conflicts, a strong emphasis was put on behavioural indicators that describe the behaviour of the individual road user, more specifically the driving speed and lateral position. These behavioural indicators in themselves can insufficiently indicate the crash risk for individual situations (i.e. individual vehicles). Speed and lateral position (mostly mean speed and standard deviation of lane position) are behavioural indicators that have in non-site-based observations proven to be associated with crash risk and, in the case of speed, severity of the consequences. However, aggregated over a sufficiently large number of vehicles and in a quasi-experimental before-and-after setting, these behavioural indicators have allowed to suggest a first direction of effect. These behavioural data cannot be collected by human observers on site. In our study, we combine speed data from loop detectors with lateral position data measured from video cameras. All data could however be collected from video footage.

The study about vehicle interactions at priority-controlled and right-hand priority intersections (Chapter 6) has focused exclusively on observations of behavioural aspects by human observers, more specifically yielding behaviour and looking behaviour of the road users involved in the interaction. While leading to some interesting insights in road users' behaviour at such locations, the study does not allow to make a direct extrapolation towards crashes. The study cannot provide strong indications about the true safety performance of both types of infrastructure. The study shows that the number of priority violations among vehicles is higher at right-hand priority intersections than at priority-controlled intersections. While research suggests that failure to yield is one of the primary factors leading to crashes at unsignalised intersections (Lee et al., 2004; Parker et al., 1995), in itself, this does not necessarily mean that a higher number of violations directly corresponds with a higher risk of crashes. One observation that supports this statement is that right-hand priority intersections seem to be affected by an informal priority rule. Therefore, interactions that lead to a violation of the formal rule are not necessarily dangerous because they take place in a very controlled and anticipated way. As a result, no reliable inferences could be made on road safety based on the site-based observations of behavioural aspects by human observers alone.

When selecting behavioural indicators to assess road safety, the selection of the specific behavioural indicators therefore strongly defines to what extent inferences on road safety can be drawn from them. It is important to make use of behavioural indicators that have a proven, or at the very least strongly anticipated, direct correlation with the risk of (severe) crashes. Surrogate safety measures aim to describe the relationship between two road users in a traffic event for the purpose of quantifying the crash probability and/or crash severity in some meaningful way. As a result, they provide a more direct relationship to crashes than behavioural

indicators, which particularly relate to the individual behaviour and the process of interaction between road users without a direct assessment of the risk of the individual situation (Laureshyn, 2010). As a result, behavioural indicators are generally an even more indirect predictor of crash risk than surrogate safety measures, which are already an indirect predictor themselves. The stronger the emphasis of a study is on behavioural aspects the more important the relation of those selected behavioural indicators with crashes is in order to be able to draw reliable conclusions on road safety. From these case studies it seems that a stronger emphasis on surrogate safety measures still leads to stronger evidence of the expected safety effects. Generally it seems that behavioural aspects, when well selected and measured, could provide an indication of the direction of effect on safety in site-based observations in exploratory studies.

### 7.3 There is more than meets the eye – combining multiple techniques of road safety research

Site-based observations of surrogate safety measures and behavioural indicators definitely have merit as a stand-alone technique to investigate road safety, and can teach us valuable insights into the processes that lead to crashes. However, like any study method, site-based observation studies have their limitations (see section 1.3). Due to these limitations, site-based observations may not suffice to get the full picture clear. It is therefore highly recommended to combine the results from different study methods in order to supplement each other and to overcome the limitations of each individual method. For instance, one of the main goals of the H2020 project InDeV is to develop an integrated approach to VRU safety analysis based on behavioural observations, surrogate safety measures, police-reported crashes, in-depth crash investigations, self-reported crashes and naturalistic driving/riding data (InDeV, 2017).

As indicated, one of the studies included in this dissertation offered the opportunity to partly replicate a driving simulator experiment, hence allowing to combine the insights of site-based observations with those from driving simulator research (see Chapter 5). Our observations could largely confirm the results from the driving simulator experiment, but supplemented them with some additional insights, such as a more precise measurement of the impact on the driving speed and the influence of interactions with other road users. Another advantage of the site-based study were the large samples of records for the analyses of speed and lateral position. The driving simulator study on the other hand has offered unique insights into the looking behaviour of the drivers, and allowed to include another control condition in which the wind turbines were positioned further away from the roadway.

Similarly, I have contributed to a study in which we combined site-based observations and a driving simulator study to investigate drivers' behavioural responses to combined speed and red light cameras (SRLCs) (Polders et al., 2015). The study departed from the finding of a number of crash-based studies that SRLCs lead to a statistically significant increase in rear-end crashes (De Pauw et al., 2014; Høye, 2013), and tried to gain a deeper understanding of why and how this effect originates. The complementarity between the site-based observations and the driving simulator experiment was similar in this study. The findings from the site-based observations were largely in line with the results from

the driving simulator study. The site-based observations could show the revealed behaviour, and the relatively large samples of analysed vehicles could provide a more reliable insight into behavioural adaptations to the SRLCs, such as a shift in the dilemma zone for drivers when confronted with the yellow light (i.e., the dilemma zone moves closer towards the stop line when SRLCs are installed). The driving simulator experiment on the other hand provided a deeper insight into drivers' looking behaviour and has allowed to test another experimental condition, i.e. the presence of an advance warning sign.

While both examples relate to the complementary nature of site-based observation studies and driving simulator studies, other complements of site-based studies have shown potential as well. For instance, a study by van Nes et al. (2013) has shown that there are benefits in combining site-based observations with a naturalistic driving approach. To reveal underlying reasons why road users behave as observed, or to investigate whether specific behavioural adaptations are undertaken consciously or unconsciously, combining the observations with for instance questionnaires (as was done in the study about shared-use bus lanes – see Chapter 4) or focus groups can provide useful as well.

Sometimes, the behavioural changes one is interested in may be too subtle or the expected effect size too small to reliably be investigated using site-based observations, mostly due to the risk of confounding factors. In such instances, site-based observations might not be the best approach to investigate these potential behavioural adaptations. In such situations, an investigation of stated behaviour might provide an answer. During the course of this PhD, I encountered an interesting research question where this was the case. A few years ago, a right turn on red (RTOR) permission for bicyclists was introduced in Belgium. It provided road authorities with the option to allow RTOR for bicyclists at some intersections through the installation of a traffic sign. A recurring argument of opponents of the rule was that the rule could lead to a so-called "spillover effect", which implies that bicyclists might become more tended to make a RTOR at intersections where it is not allowed as well. It was initially considered to investigate this question by means of site-based observations, but due to timing a before-after study design (which would be preferred from a methodological perspective) was not feasible, the anticipated behavioural adaptations were not expected to be very pronounced and could not be targeted down to particular locations for observations. Therefore, it was decided to study the question by means of an experimental survey approach. The answers of an experimental group of participants who are triggered to have a higher awareness of the existence of the RTOR for bicyclists rule were compared to those of respondents from a control group. The results of the experiment showed that participants with an increased awareness of the existence of the RTOR rule turn right on red statistically significantly more often at intersections where RTOR for bicyclists is not allowed than respondents with a lower awareness of the existence of the rule (the control group). This finding suggests that the implementation of the rule could indeed lead to an increase in RTOR manoeuvres at locations where RTOR is not allowed. For more details about this study, the interested reader is referred to De Ceunynck et al. (2016).

## 7.4 Conclusions and implications for research and practice

The studies performed within the frame of this doctoral dissertation have led to a deeper insight into current practices as well as future challenges and opportunities within the field of surrogate safety measures and behavioural indicators in site-based observation studies. Applying surrogate safety measures can be especially useful when crash data, for various reasons, cannot provide a sufficient insight into a specific topic or measure. This can be the case, for instance, for analysing infrastructural or regulatory elements that have not been in place for a long time yet and/or at a low number of locations, or in case the expected numbers of crashes are anticipated to be low. The case studies that have been conducted within the frame of this PhD are of this nature. The case studies have led to safety-relevant insights into some topics that have rarely been addressed in scientific literature before.

A review of the applied surrogate safety measures in literature reveals an overwhelming variety and creativity in the field. A framework of unified methodologies and a generally accepted framework of best practices is needed. Key limitations in the field are the lack of a thorough validation of many surrogate safety measures and the fact that most measures fail to sufficiently include the outcome severity in case a crash would have taken place. A new indicator, Extended Delta-V, has been developed and tested to mitigate the latter limitation by taking into account both the proximity to a crash and the severity of its potential consequences. Despite promising first test results, further research is needed to further develop and validate the indicator. It is also recommended that observations of surrogate safety measures are supplemented with behavioural observations and/or data from other fields such as crash analyses, driving simulator data and data from naturalistic driving.

Even though further research on the studied case study topics is needed, this dissertation has been able to provide some valuable first insights into a number of policy-relevant road safety topics that have been scarcely researched to date by using a combination of observations of behavioural aspects and surrogate safety measures. It seems that a stronger emphasis on surrogate safety measures still leads to stronger evidence of the expected safety effects. However, generally it seems that behavioural aspects, when well selected and measured, could provide an indication of the direction of effect on road safety in site-based observations in exploratory studies.

The case study of bicyclists on bus lanes revealed that close interactions, with bus drivers keeping an insufficient Time Gap or lateral overtaking distance from bicyclists are relatively common. These close interactions are more common at the observed narrower bus lane than the wider bus lane. The case study about drivers' behavioural adaptations to wind turbines alongside motorways revealed that the presence of the wind turbines leads to observable behavioural adaptation effects related to driving speed and lateral position among passing drivers, but no substantial negative effect on road safety is believed to take place. The case study of right-hand priority intersections versus priority-controlled intersections gained interesting insights into the interaction process of road users but cannot provide strong indications of their relative safety performance.

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## Attachment: Curriculum Vitae

### Curriculum Vitae – Tim De Ceunynck (dd. 23/08/2017)

#### Personal details

Name: De Ceunynck  
First name: Tim  
Date of birth: 31/03/1987  
Address: Hengelhoefstraat 107, 3600 Genk, Belgium  
Telephone: +32 477 59 41 23  
E-mail: timdeceunynck@gmail.com  
Marital status: Married, no children

#### Working experience

Sep. 2016 – now *Belgian Road Safety Institute (BRSI)*  
Researcher: various studies around road safety and stimulating a modal shift towards active transport modes.

Sep. 2010 – Sep. 2016 *Hasselt University – Transportation Research Institute*  
PhD candidate/researcher: various studies in the frame of multiple projects (mostly road safety research), preparing a doctoral dissertation, project acquisition and management, teaching multiple courses in the Bachelor-Master programme in Transportation Sciences, coordinator of post academic road safety auditor course.

May 2014 – Dec. 2014 *Lund University (Sweden) – Transport & Roads, dpt. of Technology and Society, Faculty of Engineering LTH*  
Visiting researcher: various studies and analyses in the frame of my PhD, preparation of H2020 stage II proposal "InDeV".

#### Education

2010 – 2017 Double PhD:  
*Doctor in Transportation Sciences – Hasselt University, Belgium*  
*Doctor of Philosophy in Engineering – Lund University, Sweden*

2005-2010 *Bachelor & Master degree Transportation Sciences, major Mobility Management*  
Hasselt University, Belgium  
Degree: magna cum laude

2014 – 2015 *Crash reconstruction and in-depth analysis course (level HBO5)*  
Local Police of Antwerp, Belgium  
Degree: summa cum laude

2013 – 2014

*Post-academic course Road Safety Auditor*  
Hasselt University, Belgium  
Degree: cum laude

## **Languages**

Dutch: native proficiency  
English: full professional proficiency (CEFR level C1 degree)  
French: professional working proficiency  
Swedish: elementary proficiency

## **Software**

T-Analyst: excellent  
Statistical software (e.g. SPSS, SAS EG): good  
Microsoft Office: good  
PC-Crash: notes

## **Certifications**

Mar. 2017 – Mar. 2022 Certified road safety auditor by the Flemish Government

## **Reference projects**

### *SafetyCube*

Client: European Commission (Horizon 2020 programme)  
Duration and budget: 2015-2018, 5,790,000 euro (share BRSI: 610,000 euro)  
Function: Researcher

The objective of SafetyCube is to develop an innovative road safety Decision Support System that will enable policymakers and stakeholders to select and implement the most appropriate strategies, measures and cost-effective approaches to reduce casualties of all road user types and all severities. I am involved in the fifth work package about road infrastructure safety analysis.

### *ISAAC – Stimulating safe walking and cycling within a multimodal transport environment*

Client: CEDR Transnational Road Research Programme  
Duration and budget: 2016-2018, 294,000 euro (share BRSI: 60,000 euro)  
Function: Researcher

Developing an interactive tool to guide policy makers in selecting and implementing the most appropriate measures to promote active transport modes within the context of their city/region.

*InDeV – In-Depth understanding of accident causation for Vulnerable road users*

Client: European Commission (Horizon 2020 programme)  
Duration and budget: 2015 – 2018, 4,900,000 euro (share HU: 600,000 euro)  
Function: Project leader, member of the Executive Board and lead researcher at HU

Until my job change in September 2016, I was responsible for the organisation of all subtasks that HU was involved in. These included scoping reviews on surrogate safety measures and behavioural indicators, the start-up of short term and long term video observations in different partner countries and developing a handbook for practitioners about VRU safety diagnosis. I was strongly involved in preparing both stages of the project proposal as well.

*Policy Research Centre for Traffic Safety (Steunpunt Verkeersveiligheid)*

Client: Flemish Government (programme Research Centres for Policy Relevant Research)  
Duration and budget: 2012-2016, 2,300,000 euro  
Function: Secretary of the Executive Board and researcher

In the Policy Research Centre I supported the coordinator in the project management (a.o. drafting annual reports and plans, follow-up of the internal review procedures, organizing User Group meetings,...). As a researcher I was involved in several studies of the policy research centre (mostly around the use of surrogate safety measures and behavioural indicators for road infrastructure safety studies, and studies about media reporting of crashes and crash prediction models).

*The effect of wind turbines alongside motorways on drivers' behaviour*

Client: Rijkswaterstaat (The Netherlands)  
Duration and budget: 2014-2015, 50,000 euro  
Function: Project leader and lead researcher

In this project we investigated whether locating wind turbines alongside motorways leads to behavioural adaptations and/or serious traffic conflicts by means of a before-and-after site-based observation study.

**Miscellaneous:**

- Received the "Best Young Researcher Paper Award" at the 2012 ICTCT conference
- Member of the Nordic Traffic Safety Academy (since 2016)
- External Expert Transportation at the commissions for spatial planning in the Belgian cities Hasselt (since 2013) and Genk (since 2016)
- Co-founder and chairman of Mobilumni, the alumni association of the Bachelor-Master programme of Transportation Sciences at Hasselt University, Belgium
- Guest lecturer at the Mobility Academy organised by the Flemish Foundation for Traffic Knowledge (since 2011)

## List of 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. Submitted for publication to *European Journal of Transport and Infrastructure Research*, 17(3), 477-494. (impact factor: 0.818)

**De Ceunynck, T.,** Dorleman, B., Daniels, S., Lareshyn, A., Brijs, T., Hermans, E., & Wets, G. (2017). Sharing is (s)caring? Interactions between buses and bicyclists on bus lanes shared with bicyclists. *Transportation Research Part F: Traffic Psychology and Behaviour* 46, Part B, 301-315. (impact factor: 1.473)

Lareshyn, A., **De Ceunynck, T.,** Karlsson, C., Svensson, Å, & Daniels, S. (2017). In search of the severity dimension of traffic events: Delta-V as a traffic conflict indicator. Submitted for publication to *Accident Analysis & Prevention*, 98, 46-56. (impact factor: 2.070)

**De Ceunynck, T.,** Daniels, S., Vanderspikken, B., Brijs, K., Hermans, E., Brijs, T., & Wets, G. (2016). Is there a spillover effect of a right turn on red permission for bicyclists? *Transportation Research Part F: Traffic Psychology and Behaviour*, 36, 35-45. (impact factor: 1.473)

Polders, E., Cornu, J., **De Ceunynck, T.,** Daniels, S., Brijs, K., Brijs, T., Hermans, E., & Wets, G. (2015). Drivers' behavioural responses to combined speed and red light cameras. *Accident Analysis & Prevention*, 81, 153-166. (impact factor: 2.070)

**De Ceunynck, T.,** De Smedt, J., Daniels, S., Wouters, R., & Baets, M. (2015). "Crashing the gates" – selection criteria for television news reporting of traffic crashes. *Accident Analysis & Prevention*, 80, 142-152. (impact factor: 2.070)

**De Ceunynck, T.,** Ariën, C., Brijs, K., Brijs, T., Van Vlierden, K., Kuppens, J., Van Der Linden, M., & Wets, G. (2015). Proactive evaluation of traffic signs using a traffic sign simulator. *European Journal of Transport and Infrastructure Research*, 15(2), 184-204. (impact factor: 0.818)

**De Ceunynck, T.,** Kusumastuti, D., Hannes, E., Janssens, D., & Wets, G. (2013). Mapping leisure shopping trip decision making: validation of the CNET interview protocol. *Quality & Quantity*, 47(4), 1831-1849. (impact factor: 0.761)

**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 behavioral analysis of vehicle-vehicle interactions. *Transportation Research Record, Journal of the Transportation Research Board*, 2365, 39-48. (impact factor: 0.556)

Publications in international peer-reviewed scientific journals (in review)

**De Ceunynck, T.**, Johnsson, C., Laureshyn, A., Svensson, Å., de Goede, M., van der Horst, R., Saunier, N., Włodarek, P., & Daniels, S. (in review). The use of surrogate safety measures in site-based observations of road traffic: a scoping review. Submitted for publication to *Accident Analysis & Prevention*. (impact factor: 2.070)

**De Ceunynck, T.**, Sloomans, F., & Daniels, S. (in review). Characteristics and profiles of moped crashes in urban areas: an in-depth study. Submitted for publication to *Transportation Research Record: Journal of the Transportation Research Board*. (impact factor: 0.556)

Johnsson, C., Laureshyn, A., & **De Ceunynck, T.** (in review). In search of surrogate safety indicators for vulnerable road users, a review of surrogate safety indicators. Submitted for publication to *Transport Reviews*. (impact factor: 2.452)

van Haperen, W., Daniels, S., **De Ceunynck, T.**, Saunier, N., Brijs, T., & Wets, G. (in review). Yielding behavior and traffic conflicts at cyclist crossing facilities on channelized right-turn lanes. Submitted for publication to *Transportation Research Part F: Traffic Psychology and Behaviour*. (impact factor: 1.473)

Publications in national journals

**De Ceunynck, T.**, De Smedt, J., Daniels, S., Wouters, R., Baets, M., Van den Bulck, H., & Walgrave, S. (2015). Het ene ongeval is het andere niet... Analyse van de rapportering over verkeersongevallen in de media. *Verkeersspecialist*, 214, pp. 16-18.

Contributions to international conferences

**De Ceunynck, T.**, Sloomans, F., & Daniels, S. (forthcoming). Characteristics and profiles of moped crashes in urban areas: an in-depth study. In: *Proceedings of the 2017 Road Safety & Simulation conference*. Den Haag, The Netherlands.

van Haperen, W., Daniels, S., **De Ceunynck, T.**, Saunier, N., Brijs, T., & Wets, G. (2017). Yielding behavior and traffic conflicts at cyclist crossing facilities on channelized right-turn lanes. In: *Proceedings of the 96<sup>th</sup> Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

van Haperen, W., Daniels, S., **De Ceunynck, T.**, Saunier, N., Brijs, T., & Wets, G. (2016). Yielding behavior and traffic conflicts at cyclist crossing facilities on channelized right-turn lanes: cyclists or drivers first? In: *Proceedings of the 5<sup>th</sup> International Cycling Safety Conference*. Bologna, Italy.

**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 28<sup>th</sup> ICTCT workshop*. Lund, Sweden.

Laureshyn, A., Johnsson, C., **De Ceunynck, T.**, Svensson, Å., de Goede, M., van der Horst, R., Saunier, N., Włodarek, P., & Daniels, S. (2016). The use of surrogate

measures of safety in site-based observations of road traffic: a scoping review. In: *Proceedings of the 29<sup>th</sup> ICTCT workshop*. Lund, Sweden.

van Haperen, W., Riaz, M., **De Ceunynck, T.**, & Daniels, S. (2016). Observing observation of road user behaviour: a scoping review into current practices in scientific literature. In: *Proceedings of the 29<sup>th</sup> ICTCT workshop*. Lund, Sweden.

**De Ceunynck, T.**, Dorleman, B., Daniels, S., Laureshyn, A., Brijs, T., Hermans, E., & Wets, G. (2015). Sharing is (s)caring...? Interactions between buses and bicyclists on bus lanes shared with bicyclists. In: *Proceedings of the 28<sup>th</sup> ICTCT workshop*. Ashdod, Israel.

**De Ceunynck, T.**, Daniels, S., De Smet, M., Laureshyn, A., Brijs, T., Hermans, E., & Wets, G. (2015). VRU safety at signalized versus unsignalized crossings: an empirical analysis of crossing behaviour and conflict indicators. In: *Proceedings of the 28<sup>th</sup> ICTCT workshop*. Ashdod, Israel.

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 28<sup>th</sup> ICTCT workshop*. Ashdod, Israel.

Laureshyn, A., **De Ceunynck, T.**, Karlsson, C., & Svensson, Å (2014). Searching for the severity dimension of traffic events. In: *Proceedings of the 27<sup>th</sup> ICTCT workshop*. Karlsruhe, Germany.

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.

**De Ceunynck, T.**, Ariën, C., Brijs, K., Brijs, T., Van Vlierden, K., Kuppens, J., Van Der Linden, M., & Wets, G. (2014). Proactive evaluation of traffic signs using a traffic sign simulator. In: *Proceedings of the 93rd Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

**De Ceunynck, T.**, Daniels, S., Vanderspikken, B., Brijs, K., Hermans, E., Brijs, T., & Wets, G. (2014). Is there a spillover effect of a right turn on red permission for bicyclists? In: *Proceedings of the 93rd Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

**De Ceunynck, T.**, Daniels, S., Vanderspikken, B., Brijs, K., Hermans, E., Brijs, T., & Wets, G. (2013). Is there a spillover effect of a right turn on red permission for bicyclists? In: *Proceedings of the International Cycling Safety Conference 2013*. Helmond, The Netherlands.

**De Ceunynck, T.**, Daniels, S., Laureshyn, A., Hermans, E., Geussens, A., Brijs, T., & Wets, G. (2013). Analysis of right-turn merging conflicts on channelized right-turn lanes at signalized intersections. In: *Proceedings of the 26<sup>th</sup> ICTCT workshop*. Maribor, Slovenia.

**De Ceunynck, T.,** Daniels, S., Vanderspikken, B., Brijs, K., Hermans, E., Brijs, T., & Wets, G. (2013). Is there a spillover effect of a right turn on red permission for bicyclists? In: *Proceedings of the 26<sup>th</sup> ICTCT workshop*. Maribor, Slovenia.

**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 behavioral 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.

Langbroek, J., **De Ceunynck, T.,** Daniels, S., Svensson, Å, Laureshyn, A., Brijs, T., & Wets, G. (2012). Analyzing interactions between pedestrians and motor vehicles at two-phase signalized intersections – an explorative study combining traffic behaviour and traffic conflict observations in a cross-national context. In: *Proceedings of the 25th ICTCT workshop*. Hasselt, Belgium.

**De Ceunynck, T.,** Ariën, C., Brijs, K., Brijs, T., Van Vlieden, K., Kuppens, J., Van Der Linden, M., & Wets, G. (2012). Ex-ante evaluation of road signs and pavement markings using a traffic sign simulator. In: *Proceedings of the 25th ICTCT workshop*. Hasselt, Belgium.

**De Ceunynck, T.,** Daniels, S., Brijs, T., Hermans, E. & Wets, G. (2011). Explanatory models for crashes at high-risk locations. In: *Proceedings of the 24th ICTCT workshop*. Warsaw, Poland.

**De Ceunynck, T.,** Kusumastuti, D., Hannes, E., Janssens, D., & Wets, G. (2011). What Drives People? Analyzing Leisure-shopping Trip Decision Making. In *Proceedings of the 90th Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

#### Contributions to national conferences

**De Ceunynck, T.,** Dorleman, B., Daniels, S., Laureshyn, A., Brijs, T., Hermans, E., & Wets, G. (2016). Sharing is (s)caring...? Over de veiligheid van fietsers op busbanen met medegebruik door fietsers. In: *Jaarboek Verkeersveiligheid 2016*.

van Haperen, W., Daniels, S., & **De Ceunynck, T.** (2016). Voorrangsgedrag op bypasses: fietsers of automobilisten eerst? *Fietscongres 2016*.

**De Ceunynck, T.,** De Smedt, J., Daniels, S., Wouters, R., Baets, M., Van den Bulck, H., & Walgrave, S. (2015). Het ene ongeval is het andere niet... Analyse van de rapportering over verkeersongevallen in de media. In: *Jaarboek Verkeersveiligheid 2015*.

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

**De Ceunynck, T.**, Daniels, S., Vanderspikken, B., Brijs, K., Hermans, E., Brijs, T., & Wets, G. (2014). Leidt de maatregel "rechtsaf door rood voor fietsers" tot een toename van roodrijden elders? *Fietscongres 2014*.

**De Ceunynck, T.**, Daniels, S., Brijs, T., Hermans, E., & Wets, G. (2013). Geautomatiseerde conflictobservatie: stand van zaken en toekomstperspectieven. In: *Jaarboek Verkeersveiligheid 2013*.

Ariën, C., **De Ceunynck, T.**, Brijs, K., Brijs, T., Van Vlierden, K., Kuppens, J., Van Der Linden, M., & Wets, G. (2013). Ex-ante evaluatie van wegsignalisatie met een rijnsimulator. In: *Jaarboek Verkeersveiligheid 2013*.

#### Research reports

Laureshyn, A., Johnsson, C., **De Ceunynck, T.**, Svensson, Å, de Goede, M., van der Horst, R., Saunier, N., Włodarek, P., & Daniels, S. (2016). *Review of current study methods for VRU safety. Appendix 6 – Scoping review: surrogate measures of safety in site-based road traffic observations* (Report No. InDeV Deliverable 2.1 – part 4).

**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*.

van Haperen, W., Daniels, S., & **De Ceunynck, T.** (2016). Voorrangsgedrag en veiligheid op fietsoversteekplaatsen op bypasses – De invloed van de voorangsregeling. RA-2016-002. *Steunpunt Verkeersveiligheid*.

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

**De Ceunynck, T.**, De Smedt, J., Daniels, S., Wouters, R., Baets, M., Van den Bulck, H., & Walgrave, S. (2015). Verkeersongevallen in de media – Een analyse van de selectie en rapportering van verkeersongevallen in het Vlaamse nieuws. RA-2015-001. *Steunpunt Verkeersveiligheid*.

De Pauw, E., Daniels, S., Carpentier, A., Cornu, J., Declercq, K., Ariën, C., Brijs, K., **De Ceunynck, T.**, & Wets, G. (2015). Naar een nieuw verkeersveiligheidsplan voor Vlaanderen – Achtergrondrapport. *In opdracht van de Vlaamse Overheid*.

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