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DOI (link to publication from Publisher):
10.5278/vbn.phd.eng.00057

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

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DISSERTATION SUBMITTED 2018

AALBORG UNIVERSITY
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Dissertation submitted:	August 2018
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ISSN (online): 2446-1636
ISBN (online): 978-87-7210-246-7

Published by:
Aalborg University Press
Langagervej 2
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2018

PREFACE

This thesis was made based on research carried out in the Horizon 2020 project InDeV (In-Depth understanding of accident causation for Vulnerable road users), which received funding from the European Union's research and innovation programme under grant agreement no. 635895. The thesis consists of four papers:

Paper I: Madsen, T.K.O., & Lahrmann, H. Self-reported pedestrian and cyclist accidents and near-accidents – do they provide a different picture of safety than police records? *(Manuscript)*

Paper II: Madsen, T.K.O., Várhelyi, A. & Lahrmann, H. Detection of pedestrian and cyclist accidents using smartphone sensors – experiences and challenges. *(Manuscript)*

Paper III: Madsen, T.K.O., & Lahrmann, H. (2017). Comparison of five bicycle facility designs in signalized intersections using traffic conflict studies. *Transportation Research Part F*, vol. 46 (Part B), 438-450. http://dx.doi.org/10.1016/j.trf.2016.05.008

Paper IV: Madsen, T.K.O., Agerholm, N., Laureshyn, A. & Lahrmann, H. Conflict studies for road safety analyses – the use of video analysis as a watchdog for long-term analyses. Submitted to *Journal of Safety Research*, July 2018

During the PhD study, I got the chance to learn from experts within the fields of traffic safety and traffic conflict studies, and I would like to thank all InDeV partners for our collaboration during the past three years and the Transportation Research Institute (IMOB) at Hasselt University, Belgium, for welcoming me during my 3.5 months long research stay.

I would like to thank my supervisor Harry Lahrmann and my colleagues from the Division of Transportation Engineering at Aalborg University for our many inspiring discussions and for helping me throughout the project. Also, a special thanks to the Visual Analysis of People Group at Aalborg University, with whom I have worked with regarding the development of RUBA and all other tools used in the project. Without you, this project would not have been possible. Finally, I am grateful for all the contributions I have received from the road users and traffic safety professionals who participated in the studies.

Tanja Kidholm Osmann Madsen
Aalborg, August 2018

ENGLISH SUMMARY

Under-reporting of road traffic accidents in the official statistics, which are based on police records, is a big issue in both the general and in the site-based traffic safety work. Due to this under-reporting there is a bias in which types of accidents are registered, and the number of accidents registered at a particular location is often limited. The under-reporting is an issue for all types of road users, but is particularly extensive for cycling accidents and accidents with only less severe injuries. Furthermore, the use of police-recorded accidents implies that pedestrian single accidents are not included in the statistics since these accidents do not comply with the definition of an accident and accordingly are not included in the police records. These characteristics mean that the official accident statistics give incomplete insights into the safety of cyclists and pedestrians.

The purpose of this PhD project was to investigate the safety of cyclists and pedestrians as well as improve the methods for analysis and mapping of the safety of these road users. Two different approaches to traffic safety analyses were examined: 1) the use of self-reporting for non-site-based traffic safety analyses and 2) the use of video analysis for traffic conflict studies for site-based traffic safety work.

In the first part of the investigation, a self-reporting study was carried out among 1,434 cyclists and pedestrians who had volunteered to register their accidents and near-accidents on bicycle and on foot for a period of nine months. In total, the participants registered 202 accidents and 631 near-accidents. An analysis of these events showed that the characteristics of the self-reported events differed significantly from the patterns identified via the police records, especially with regard to the extent of single accidents and the most frequent accident types. The proportion of single cycling accidents was 39%, while 20% of the pedestrian accidents were single accidents. Furthermore, the results showed that particularly accidents between two light road users are under-reported in the police records and hence that e.g. rear-end collisions between two cyclists are less frequent in the police records compared to in the self-reported data.

One of the main points of criticism for self-reported data is that this method involves a risk that the information is false or that the participants deliberately or unknowingly omit to register specific types of events. To supplement the self-reported data with objective data, an algorithm was developed and tested in order to automatically detect accidents of pedestrians and cyclists based on smartphone motion sensors. The study showed that the algorithm detected all 14 accidents that were simulated by using a test dummy, but only 8 of 19 simulated accidents by a stuntman. In particular, the algorithm failed to detect simulated pedestrian fall accidents. Despite showing a potential of increasing the existing knowledge of accidents among cyclists and pedestrians, the study also concluded that there are

several challenges related to the detection of accidents automatically. These challenges must be solved before the method can be used in large-scale studies. As such, it is crucial that the system works across smartphone brands and models, and that it does not detect a high number of false positives, e.g. from using the phone during the day.

Another part of the project dealt with the development of software for video analysis. In that connection, the RUBA software for analysis of road user behaviour was developed, tested and used for a number of studies, particularly in relation to traffic safety analyses. RUBA uses a so-called watchdog approach in which the user marks field on top of the video to assess when there are changes inside the fields. If the changes are sufficiently large, they are registered by the software. RUBA can also be used to register interactions between two road users by combining two fields. If there are changes to both fields within a given time interval, RUBA will mark it as an event of interest which should be further reviewed and analysed manually. In this project, RUBA was used to assess the safety in a number of road intersections. The studies showed that RUBA reduced the amount of video to be further analysed remarkably. In one of the studies, RUBA reduced the video to less than 1% of its original length. In other cases, it reduced the video to 4-31% of the original length. This reduction makes it possible to analyse up to several weeks or months of video footage.

The analysis of a large amount of video footage is particularly important in the site-based traffic safety work. Often, only few accidents have been registered by the police at a particular location. Therefore, this PhD project focused on using traffic conflict studies, in which events that almost result in accidents are used as a surrogate for accidents. In the study, traffic conflicts were identified using the Delphi Method. Nine road safety engineers assessed 50 potential conflicts and classified them as conflicts and non-conflicts. The purpose was to assess whether or not the Delphi Method could be used to identify traffic conflicts instead of using the traditional traffic conflict techniques. Potentially, this could lead to the inclusion of other aspects than the time gap between two road users in the identification of traffic conflicts. In the study, four events were classified as serious conflicts and 19 were classified as less severe conflicts. For five events, the panel did not reach consensus regarding the final classification after three rounds of assessments. Further research is necessary to compare the results of the Delphi Method with well-established techniques in order to gain more knowledge on how they differ from each other. Furthermore, it is suggested to investigate which aspects the panellists of the Delphi study use to identify traffic conflicts, since this can potentially provide insights into the characteristics of traffic conflicts.

DANSK RESUME

Underrapportering af uheld i den officielle uheldsstatistik, som er baseret på politiets indberetninger, er et stort problem i både det generelle og i det stedbestemte trafiksikkerhedsarbejde. Denne underrapportering medfører, at der er en skævhed i, hvilke typer af uheld som registreres, og at antallet af uheld på en given lokalitet ofte er begrænset. Selv om underrapporteringen forekommer blandt alle trafikantgrupper, er problemet særligt stort for cykeluheld og uheld med mindre alvorlige skader. Anvendelsen af politiregistrerede uheld har tillige den ulempe, at faldulykker med fodgængere ikke indgår i statistikken. Det skyldes, at disse eneuheld jævnfør definitionen på et uheld ikke anerkendes som trafikuheld. Disse karakteristika medfører, at den officielle statistik giver et ufuldstændigt billede af sikkerheden blandt cyklister og fodgængere.

Formålet med dette ph.d.-projekt er derfor at undersøge trafiksikkerheden for cyklister og fodgængere samt at forbedre metoderne til analyse og kortlægning af disse trafikanters sikkerhed. To forskellige tilgange til trafiksikkerhedsanalyser blev undersøgt: 1) anvendelsen af selvrapportering i forbindelse med generelle trafiksikkerhedsanalyser, og 2) brugen af videoanalyse til trafikkonfliktstudier i forbindelse med det stedbestemte trafiksikkerhedsarbejde.

I forbindelse med den første del af undersøgelsen blev der gennemført en spørgeskemaundersøgelse blandt 1434 cyklister og fodgængere, som frivilligt havde meldt sig til at registrere deres uheld og næsten-uheld på cykel og til fods gennem en periode på ni måneder. I alt registrerede deltagerne 202 uheld og 631 næsten-uheld. En analyse af disse viste, at karakteristikaene for de selvrapporterede hændelser adskilte sig signifikant fra mønstrene i politiuheldene, ikke mindst i forhold til omfanget af eneuheld og de mest hyppige uheldstyper. Andelen af eneuheld blandt cyklister var 39 %, mens det samme gjaldt for 20 % af fodgængeruheldene. Resultaterne viste også, at især uheld mellem to lette trafikanter ikke registreres af politiet, og at eksempelvis bagendekollisioner blandt cyklister derfor ikke optræder så hyppigt i politiets registre som i de selvrapporterede data.

Et af de store kritikpunkter for selvrapporterede data er, at de indbefatter en risiko for, at oplysningerne er usande, eller at trafikanten bevidst eller ubevidst undlader at registrere nogle former for hændelser. For at supplere de selvrapporterede data med objektive data, blev der i projektet udviklet og testet en algoritme til automatisk detektering af uheld blandt fodgængere og cyklister på baggrund af data fra bevægelsessensorerne i en smartphone. Undersøgelsen viste, at algoritmen kunne detektere alle 14 simulerede uheld, som blev foretaget med en testdukke, men kun 8 ud af 19 simulerede uheld, som blev udført af en stuntman. Algoritmen havde især vanskeligt ved at detektere simulerede fodgængeruheld. Trods et potentiale for at øge den eksisterende viden om uheld blandt cyklister og fodgængere gennem

automatisk detektering af uheld, viste undersøgelsen dog også, at der fortsat er adskillige udfordringer forbundet med den automatiske uheldsdetektering, som skal løses, før metoden kan bruges i større undersøgelser. Konkret skal det sikres, at systemet virker på tværs af smartphone brands og -modeller, og at systemet ikke detekterer et stort antal falsk positive hændelser fra eksempelvis normal brug af telefonen.

I den anden del af projektet blev der arbejdet med udviklingen af et program til videoanalyse. I denne forbindelse blev programmet RUBA til analyse af trafikantadfærd udviklet, testet og anvendt i en række undersøgelser, hovedsageligt i forbindelse med trafiksikkerhedsanalyser. RUBA benytter en "vagthund"-tilgang, hvor man markerer felter på videobilledet for at undersøge, om der sker ændringer i disse felter. Hvis ændringerne er tilstrækkeligt store, bliver de registreret af programmet. Programmet kan også bruges til at registrere interaktioner mellem to trafikanter ved at sammenkoble to felter. Hvis der sker ændringer i begge felter indenfor et givet tidsrum, udpeger RUBA det som en interessant hændelse, som herefter skal analyseres manuelt. I dette projekt blev RUBA anvendt til at analysere sikkerheden i forskellige vejkryds. Undersøgelserne viste, at RUBA kan reducere mængden af video, der skal studeres manuelt, markant. I et enkelt tilfælde blev videoen reduceret til mindre end 1 % af videoens originale længde, mens den i andre tilfælde reducerede videoen til 4-31 % af den oprindelige længde afhængig af trafikmængden i krydsene. Dette gør det muligt at analysere op til adskillige uger eller måneders videooptagelser.

Muligheden for at analysere en stor mængde video er især vigtigt i det stedbestemte trafiksikkerhedsarbejde. Da der ofte kun er registreret få uheld på en given lokalitet, fokuserede ph.d.-projektet på brugen af konfliktstudier, hvor hændelser, som næsten resulterer i uheld, bliver benyttet som surrogat for uheld. I projektet blev trafikkonflikter udpeget ved hjælp af Delphi-metoden. I Delphi-studiet vurderede ni trafiksikkerhedsingeniører 50 potentielle trafikkonflikter for at klassificere dem som henholdsvis konflikter og ikke-konflikter. Formålet med dette var at undersøge, om Delphi-metoden kunne bruges til at udpege trafikkonflikter på en anden måde end ved brug af de traditionelle teknikker for herigennem at kunne inkludere andre aspekter end tidsafstanden mellem trafikanterne. I undersøgelsen blev fire situationer klassificeret som alvorlige konflikter, mens 19 blev klassificeret som mindre alvorlige konflikter. I fem tilfælde nåede panelet ikke til enighed omkring en endelig klassificering efter tre runder. Yderligere undersøgelser bør foretages for at sammenligne Delphi-metoden med de veletablerede trafikkonfliktteknikker med henblik på at undersøge, hvordan metoderne adskiller sig fra hinanden. Ligeledes bør det undersøges, hvilke aspekter der ligger til grund for udpegningen af trafikkonflikter i Delphi-studiet, da dette potentielt kan give større indsigt i, hvilke aspekter der kendetegner trafikkonflikterne.

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CHAPTER 1. INTRODUCTION

Cycling and walking are often mentioned as two transportation modes which potentially can improve public health (Lumsdon & Mitchell, 1999; Oja *et al.*, 2011) and reduce congestion in urban areas (Koska & Rudolph, 2016). Therefore, these two modes have been promoted frequently in an attempt to reach a shift from cars towards cycling and walking (Ogilvie *et al.*, 2004). The number of trips carried out on bicycle and on foot is already high in some cities across Europe. For instance, the bicycle shares are 29% in Copenhagen (City of Copenhagen, 2017) and 32% in Amsterdam (Dixon *et al*. 2018), while 46% and 47% of the trips in Barcelona and Paris are carried out on foot (EPOMM, 2018).

However, walking and cycling are also among the most unsafe modes of transport. Statistics from Denmark show that the risk of fatalities or severe injuries is respectively 14 and 17 times higher per kilometre for pedestrians and cyclists compared to when travelling by car (Christiansen & Warneke, 2018). Therefore, the analysis and improvement of vulnerable road users' safety is an important issue in road traffic safety work.

The analysis of road users' safety can be divided into two types of assessments depending on the purpose with the analysis: 1) Non-site-based traffic safety analyses and 2) site-based traffic safety analyses. The non-site-based safety analyses typically focus on identifying general traffic safety patterns, e.g. with regard to which road user types are mostly at risk, to dangerous road types or traffic situations and to contributory factors (e.g. drink-driving, fatigue, inattentiveness) that influence the risk of accidents. This type of analysis can be used to tailor the initiatives of improving road traffic safety in general (e.g. via campaigns or traffic enforcement) towards specific types of road users and situations. Conversely, site-based traffic safety analyses aim at assessing the safety at specific locations, e.g. at black spots, in order to identify characteristics that influence the safety level at the particular site. For instance, safety issues at a specific location could be related to the design of the road infrastructure, to the presence of trees and buildings that impair the sight distance or to attributes of the surroundings which increases the risk of accidents. The outcome of such an analysis can therefore be used to change the site-specific characteristics that involve a risk to the safety of road users.

Both non-site-based and site-based road traffic safety analyses have traditionally been based on police-recorded accidents. However, these records have a large degree of under-reporting, in particular for accidents involving cyclists (Elvik & Mysen, 1999). This under-reporting increases gradually as the accident severity decreases (Ahmed *et al.*, 2017; Elvik & Mysen, 1999). Janstrup *et al*. (2016) found that the Danish police registered respectively 7% and 14% of the cycling accidents with slight and severe injuries by comparing accident records from a hospital and the police. Although the police reporting rates were higher for pedestrians, they still only captured 23% of the slight injuries and 62% of the severe injuries (Janstrup *et al.*, 2016). In addition to this, the definition of an accident specifies that at least one of the road users involved must be on wheel (ITF, 2011). Pedestrian single accidents are thus usually not included in the accident statistics, since they are not considered as road traffic accidents. Consequently, traffic safety analyses based on police-recorded accidents might provide incomplete and biased insights into the safety of vulnerable road users, which underlines the need of improving the knowledge of the safety of vulnerable road users.

Other data sources such as hospital records, insurance claims and self-reported accidents have been used as an alternative or a supplement to police-recorded accidents in order to provide better and more complete insights into the safety of vulnerable road users (see e.g. Broughton *et al.*, 2010; Isaksson-Hellman & Werneke, 2017; Lahrmann *et al.*, 2018b). In addition to these sources, surrogate safety measures are used as a means to conducting traffic safety analyses based on non-accident data that can be related to the traffic safety. For instance, these analyses can be conducted using observations of safety-related features, identification of traffic conflicts or self-reporting of near-accidents (see e.g. van Haperen, 2016; Laureshyn *et al.*, 2017; Aldred & Goodman, 2018). The applicability of these sources varies depending on the type of analysis. In the following, the data sources for non-site-based and site-based traffic safety analyses are presented.

1.1. NON-SITE-BASED TRAFFIC SAFETY WORK

Non-site-based traffic safety analyses based on police-recorded accidents often suffer from having a bias in what is reported due to the large degree of under-reporting in the police records and the fact that only accidents with specific characteristics must be registered by the police. For instance, the Danish police is not obliged to register an accident unless it involves casualties or has material damages worth more than a certain value (approx. 6,700 € per vehicle, or 670 € for other material damages) (Danish Road Directorate, 2017b). Hence, only the most severe accidents are registered. The Danish Road Traffic Accident Investigation Board (AIB, 2015) compared cycling accidents registered at an emergency room and by the police and found that the data source had a great influence on which types of accidents were registered. The study showed that the number of single cycling accidents was much higher than reflected by the police records and that rear-end collisions, right-hook accidents, accidents with road users from perpendicular roads and accidents involving parked vehicles, pedestrians or animals also occurred more frequently when using data from the emergency room. Surprisingly, left-hook cycling accidents seemed to be under-reported among accidents registered at the emergency room compared to the number of accidents registered by the police.

Hospital records have been suggested as a means to increase the degree of reporting compared to police records (see e.g. Broughton *et al.*, 2010; Fredlund & Frank, 2016). In this way, data will be included from all road users who received treatment from the hospital/emergency room. However, not all road users seek medical treatment at the hospital or emergency room after a road traffic accident, and hospital data will therefore still suffer from under-reporting. According to Lauritsen (1987), only half of all personal injury accidents are captured when using hospital records. However, the missing accidents generally involve less severe injuries than those registered by the police or at the hospital (Larsen *et al.*, 1995). In addition, the level of details of registered accidents is remarkably lower than in police records. For instance they typically lack information on where it occurred. There are, however, differences in the level of details depending on where the road user sought medical treatment. For instance, a research group at one of the Danish emergency rooms conducts an extended registration of road traffic casualties (Accident Analysis Group, 2018) and hence have more information regarding each road traffic injured admitted to the emergency room. However, this is not general practice at all Danish emergency rooms.

Insurance claims can similarly be used as an alternative or a supplement to police records. For instance, Isaksson-Hellman & Werneke (2017) used insurance claims to study bicycle-car collisions in order to include accidents on all severity levels in the analysis. They concluded that insurance data could be used to gain a deeper understanding of collisions between cyclists and cars. Short & Caulfield (2016) linked police records, hospital records and insurance claims to assess how much they overlapped each other. They found that the use of insurance claims identified a large number of accidents that were not captured when using police or hospital data. Despite the higher number of accidents, the use of insurance data may still be biased, since it only includes accidents that are reported to the insurance company. Depending on the extent of injuries and damages, the road user may decide not to report it to the insurance company, particularly if the excess is higher than the costs of replacing the damaged belongings. Furthermore, some road users may not even have insurance. This may increase the risk of under-reporting of the less severe accidents in which the damages and injuries are limited. Furthermore, it can potentially be difficult to get access to the data from the insurance company, as they are not available in official registers like police and medical records. Therefore, data should be retrieved separately from each insurance company.

Self-reporting can be used as a supplement to police records or medical records by letting the road users register their accidents themselves (Arthur *et al.*, 2005; Lahrmann *et al.*, 2018b; Shinar *et al.*, 2018). In this way, a larger proportion of the accidents can be registered compared to police and hospital data, since all types of accidents can be included independently of the damages and injuries sustained in the accident. This can increase the sample size and may potentially lead to a less biased sample. For instance, the results from a self-reporting study on cycling accidents showed that only 4% of the respondents answered that they were in contact with the police, 26% that they sought treatment at the emergency room and 23% that they had contacted their insurance company (Lahrmann *et al.*, 2018b).

Furthermore, self-reporting can be used to register near-accidents (Aldred & Goodman, 2018; Poulos *et al.*, 2017). The use of self-reported near-accidents implies that we do not have to wait for a sufficient amount of accidents before conducting the traffic safety analyses. Instead, the analysis is based on situations which almost result in accidents. Studies have shown, that participants may encounter several near-accidents each month (Aldred & Goodman, 2018; Poulos *et al.*, 2017), whereas approx. 8-12% of the participants will be involved in an accident within one year (Lahrmann *et al.*, 2018b; J.C.O. Madsen *et al.*, 2013; Møller *et al.*, 2017). Despite these advantages of using self-reported data, the use of self-reported information also implies a risk that the registered information is incorrect, that road users deliberately omit to register certain types of accidents or that they simply forget to register that they were involved in an accident or a near-accident (af Wåhlberg, 2009; af Wåhlberg *et al.*, 2010; Boufous *et al.*, 2010; Lajunen & Özkan, 2011). Many self-reporting studies use recall periods of e.g. one year, and in some cases the recall periods are up to five years to ensure that enough accidents are registered (af Wåhlberg, 2009; Andersen *et al.*, 2016). To accommodate this, some studies have sent out questionnaires for self-reporting of accidents monthly (Lahrmann *et al.*, 2018b) or weekly (Aertsens *et al.*, 2010) in order to reduce the risk of forgetting the accidents. For the collection of near-accidents, the risk of forgetting the incident may be present even few weeks after it occurred (Chapman & Underwood, 2000).

Table 1 summarizes the characteristics of the four data sources for non-site-based traffic safety analyses.

Table 1: Characteristics of data sources for non-site-based traffic safety analyses.

Data source	Characteristics
Police	- Large degree of under-reporting, particularly for cyclists - Bias related to the which types of accidents are registered - Only casualties and accidents with property damage above a certain value are included - Pedestrian single accidents are not registered
Hospital	- Higher reporting rate than police records - Only accidents that urged the road user to seek medical treatment at the hospital or emergency room are included - Do not contain information of the location of the accident
Insurance claims	- Higher reporting rate than police and hospital data - Involves a risk that accidents are not reported if the excess is higher than the damages - Data should be retrieved from each insurance company separately - Potentially difficult to get access to data
Self-reporting	- Both accidents and non-accident data (e.g. near-accidents) can be registered to increase the amount of data - Accidents are registered independently of severity - Risk that the information is incorrect - Risk of road users forgetting or omitting to register the incidents

1.1.1. POTENTIAL AND IMPROVEMENT OPPORTUNITIES OF SELF-REPORTING

As indicated above, self-reporting seems to be suitable for contributing to better non-site-based traffic safety analyses since it may potentially have a lower degree of under-reporting than police records, hospital records and insurance data. However, it is likely that self-reported accidents and near-accidents differ from police records with regard to the most frequent types of events and other characteristics. Differences between the two data sources may potentially lead to other results from the safety analyses and hence provide a different view on the safety of vulnerable road users. Therefore, a part of this project aims at comparing self-reports with police records in order to gain more knowledge and better insights into the safety of vulnerable road users than by using police records only.

While self-reported accidents and near-accidents can be a means to overcome some of the issues with under-reporting of accidents in police records, the main issues with self-reported accidents and near-accidents are that the information may be incorrect and that some events may not be registered because the road user deliberately omit to register them or simply forget that they happened. Therefore, it is important that incidents can easily be registered, preferably soon after it occurred to reduce the risk of details being forgotten. A study by Kaplan *et al*. (2017) suggests that the majority of the respondents (72.8-81.2%) would be encouraged to self-report their cycling accidents if they can do it either via a smartphone app or on a website. However, even in case of providing systems to facilitate the self-reporting, it is likely that some incidents will still contain incorrect information or be missing. Therefore, as much information as possible should preferably be registered automatically. This requires that the road users are monitored continuously, since accidents and near-accidents can occur at any time and at any place. So far, only few studies have been conducted with the aim of detecting accidents or near-accidents from cyclists (Candefjord *et al.*, 2014; Dozza & Werneke, 2014) and no studies have been found that specifically detect pedestrian falls based on naturalistic data. Candefjord *et al*. (2014) successfully detected cycling accidents based on data from smartphone motion sensors, while Dozza and Werneke (2014) concluded that there were a lot of false positives when detecting safety-critical events in naturalistic cycling data. Therefore, another part of this project focuses on the potential in registering accidents automatically based on smartphone sensors.

1.2. SITE-BASED TRAFFIC SAFETY ANALYSES

The purpose of site-based traffic safety analyses is to locate specific sites in the road network with a higher number of accidents than expected. These sites are then analysed in order to identify site-specific characteristics of the accidents and make changes in order to improve the safety. For this purpose, police records are commonly used as the main data source. However, accidents are rare events, and the number of accidents in the police records has generally decreased over time (ITF, 2018), partly due to an improvement of the safety level over the years, partly due to the under-reporting in the police records (Elvik & Mysen, 1999). Therefore, it is not uncommon that the occurrence of accidents at a particular site on average is one or less accidents per year (Danish Road Directorate, 2017a). Consequently, it requires several years of accident data from police records for the analysis of a particular site. Even from many years of data (e.g. 5-10 years), the search for common characteristics that may explain the occurrence of accidents can be difficult. As a result of the high degree of under-reporting, these issues often means that only few registered accidents with vulnerable road users are registered at a single location.

Similar to when used for non-site-based traffic safety analyses, self-reported accidents or near-accidents can be used to increase the number of events registered at a specific location and thereby potentially provide better insights into the prevalent safety issues at that location. This requires that registrations include information on where the incidents occurred. In a study on cycling safety, Lahrmann *et al*. (2018a) asked the participants to locate the accident site at a map and copy the coordinates into the questionnaire. Their findings indicated that nearly all participants could locate the accident on a map. On the other hand, there is – equivalently to when used for non-site-based traffic safety analyses – a risk that the road users provide incorrect information, omit certain events or forget to register events.

Even when using self-reported accidents, it is likely that only few events will be registered at a specific site unless data are collected over a long period of time, e.g. several years or from a large number of road users. A potential approach to overcome the implications of having only few events per site is the use of surrogate safety measures. In that respect, observational studies can be conducted to observe specific behaviour or characteristics such as red light running, speed behaviour, pedestrians' behaviour when crossing the road, etc. that may influence the occurrence or severity of an accident at the particular site (van Haperen, 2016). However, some behavioural aspects may be difficult to link to the safety of road users if there is no direct connection between the studied road user behaviour and the risk of accidents. Therefore, it can be difficult to use in e.g. before-after studies to make firm conclusions regarding how a particular safety measure has improved the safety of the road users.

Another example of a surrogate safety measure is the traffic conflict technique, in which the number of traffic conflicts is observed and used as surrogate for accidents. A traffic conflict is defined as a situation in which two or more road users are sufficiently close to each other in time and space that they would collide if they continue with the same speed and direction (Kraay, 1982). It is assumed that traffic conflicts are similar to accidents apart from the fact that at least one of the road users makes an evasive manoeuvre (brake, swerve, accelerate) in time to avoid the collision. Since these events occur much more frequently than accidents, it is possible to get a larger sample of safety-related data and collect data faster compared to a traditional accident analysis (Hydén, 1987). Throughout the years, a large number of techniques for the identification of traffic conflicts have been developed and applied (Johnsson *et al.*, 2018). However, most of the techniques were tailored to car traffic and thus not directly transferable to vulnerable road users (Johnsson *et al.*, 2018).

One of the most commonly used traffic conflict study methods in Scandinavia is the Swedish Traffic Conflict Technique (Hydén, 1987). Originally, this method used trained observers to register the number of serious conflicts. Given that the approach requires special training, tends to be very time consuming and implies a risk that the observers miss or misjudge conflicts (Hydén, 1987), many later traffic conflict studies have replaced the observers in the field with video recordings. However, it often takes up to ten times as long to perform a manual video analysis compared to the length of the video (Laureshyn, 2005). In many studies, the analyses are thus based on small video samples, which are limited to e.g. 3-28 hours of data each (Buch & Jensen, 2017; Phillips *et al.*, 2011; van der Horst, 2013). Experiences from Scandinavia have shown that traffic conflicts typically occur only a few times per day at a single location (Fyhri *et al.*, 2017; Lahrmann *et al.*, 2018c; Linderholm, 1992; T.K.O. Madsen & Lahrmann, 2017; Sakshaug *et al.*, 2010). The number of traffic conflicts may therefore be low, which makes it difficult to draw any conclusions from the analysis, unless it is based on several weeks or months of data (Laureshyn *et al.*, 2017).

As a result of the need of long-term recordings for traffic conflict studies, one direction in the recent research within traffic conflict studies is the development of systems to process traffic video using computer vision techniques for an automated identification of traffic conflicts. In these systems, video recordings are usually processed frame by frame to extract trajectories of the road users and calculate time-based indicators from the trajectories in order to identify the situations in which two road users are close to each other in time and space. A few examples of such systems are 1) the 'Traffic Intelligence' project (Jackson *et al.*, 2013), which is an open source tool for detection of road users and extraction of their trajectories, and 2) the automated video analysis system from the German Aerospace Center (DLR) (Saul *et al.*, 2017), which detects, classify and track road users. Although there is a large potential for automated traffic conflict studies using video analysis, there are also some challenges involved in the use of automatic video analysis systems for identification of traffic conflicts. For instance, these systems often use some kind of time-based indicator for the identification of traffic conflicts, although other aspects than the temporal distance may be relevant including as indicators, e.g. the age of the vulnerable road users, the use of gestures or the presence of head turning or other indications of the awareness towards other road users. According to Johnsson *et al*. (2018), none of the existing indicators have yet been able to capture all relevant aspects of traffic conflicts. Furthermore, Laureshyn *et al*. (2017) argued that the automated systems produce a lot of false positives due to inaccurate tracking of road users and that data therefore should be checked manually in any case.

Table 2 summarizes the characteristics of the four data sources for site-based traffic safety analyses.

Table 2: Characteristics of data sources for site-based traffic safety analyses.

Data source	Characteristics
Police	- Very few accidents at the specific location - Accidents from a long period of time needed (e.g. 5-10 years)
Self-reporting	- Accidents and non-accident data (e.g. near-accidents) can increase the amount of data and make it easier to identify safety issues - Respondents must register the location - Long registration period may be necessary to avoid having only few incidents from each site
Observational studies	- Based on non-accident data - Can be difficult to link directly to the risk of accidents
Traffic conflict studies	- Based on non-accident data - More safety-related data is collected in shorter time - The method is very time consuming when conducted manually - Automatic video analysis tools can be used to process more data but tend to be inaccurate - Most techniques are tailored to car traffic and thus not directly transferable to vulnerable road users - No existing traffic conflict indicator has been able to capture all relevant aspects that characterise traffic conflicts

1.2.1. POTENTIAL AND IMPROVEMENT OPPORTUNITIES OF TRAFFIC CONFLICT STUDIES

Traffic conflict studies may be the best option to obtain a sufficiently large data sample for the analysis of the traffic safety at a single location. One of the main issues when conducting traffic conflict studies for site-based traffic safety analyses is, as previously mentioned, that one may need several weeks or even months of data in order to get enough traffic conflicts for a traffic safety analysis. Due to inaccuracies of extracting road user trajectories in the available automated video analysis systems, a high number of false positives should often be removed manually after the analysis. Therefore, one can alternatively use a so-called watchdog approach for the analysis of traffic video to identify traffic conflicts. The basic idea of a watchdog approach is to use a fast and simple video analysis tool that is designed for being used as a first step to process large amounts of video in order to remove irrelevant parts before conducting a manual analysis. As such, the watchdog could potentially reduce the amount of video to something manageable for a manual processing. Therefore, this project deals with the development and testing of such a watchdog video analysis tool.

Most traffic conflict techniques were made with car traffic in mind. The indicators used for identifying traffic conflicts are therefore not directly transferable to vulnerable road users, whose behaviour differ considerably from car traffic. For instance, many techniques use time-based indicators (Johnsson *et al.*, 2018), and while car traffic typically have braking times in the order of seconds, pedestrians can stop or change direction almost immediately. In addition, none of the previously used traffic conflict indicators have been able to capture all relevant aspects that characterise traffic conflicts (Johnsson *et al.*, 2018). Hence, there is a need of new indicators or other approaches for the identification of traffic conflicts, in particular with regard to vulnerable road users. This project therefore uses other methods to identify traffic conflicts.

1.3. RESEARCH AIM AND OBJECTIVES

The overall aim of this PhD project is to investigate the safety of vulnerable road users, in particular cyclists and pedestrians, and improve the methods for the analysis and mapping of the safety of these road users by developing, testing and applying tools for traffic safety analyses. In line with the objectives and premises of the InDeV project, in which this project was made, the project therefore investigates two approaches for traffic safety analyses which may have a high potential to overcome the existing issues with under-reporting of police records: 1) the use of self-reporting for non-site-based analyses and 2) the use of video analysis for traffic conflict studies in site-based analyses.

The research questions are as follows:

- What are the implications of using self-reported accidents and near-accidents as opposed to police records for the analysis of the safety of vulnerable road users?
- What is the potential of detecting accidents of pedestrians and cyclists automatically based on motion data?
- How can a watchdog video analysis tool be designed and used to become a useful tool for traffic safety analyses?
- How can traffic conflicts be identified so that it includes other aspects than the time distance between the two road users?

In order to answer these questions, the PhD project consists of four studies, which are presented in the four papers of this thesis. In the following chapters, the conducted studies and applied methods for each of the two approaches are described briefly. Further information is provided in the attached papers.

CHAPTER 2. SELF-REPORTING OF ACCIDENTS AND NEAR-ACCIDENTS

Two studies were carried out with the purpose of investigating self-reporting as a method for conducting non-site-based traffic safety analyses of vulnerable road users. Firstly, a self-reporting study was carried out among a group of pedestrians and cyclists in order to assess the implications of using self-reported safety data instead of police records (Paper I). Secondly, to facilitate the self-reporting, the potential of using smartphone motion sensors for detection of walking and cycling accidents was examined through the development and testing of an algorithm for automatic accident detection (Paper II). This app was developed in cooperation with researchers from the Visual Analysis Group at Aalborg University.

2.1. SELF-REPORTING VIA APP AND WEB QUESTIONNAIRES

With the aim of gaining more knowledge about the safety of vulnerable road users, a study was carried out to collect self-reported accidents and near-accidents. The study was carried out as part of the InDeV project and hence collected data from four countries: Denmark, Belgium, Sweden and Spain. In this project, the responses from the Danish part of the survey were used for an investigation of the implications of using self-reported safety data instead of police records.

Study participants were recruited via social media (Facebook, LinkedIn), interest organisations for vulnerable road users (e.g. the national federations of cyclists and pedestrians), participants from previous studies, etc. Only road users aged 18 years or older were eligible for participating in the study. In total, 1,434 participants signed up for the Danish part of the study. Characteristics of the self-reported cycling and walking accidents and near-accidents that were registered during a period of nine months (01.09.2016-31.05.2017) are presented in a separate report by T.K.O. Madsen *et al*. (2018).

For the study, a questionnaire for self-reporting of accidents and near-accidents was developed for two platforms (Figure 1): 1) an app for Android smartphones and 2) an online questionnaire. The purpose with this was to make the registration as simple as possible for the respondent in order to get as much registered as possible. Both methods were mentioned by Kaplan *et al*. (2017) as options that would encourage the road users to register their incidents. To reduce the risk of forgetting to register events, app participants could register accidents and near-accidents whenever they wanted. Those who had enabled notifications on their smartphone would receive a notification at the beginning of each month with a reminder to register their accidents and near-accidents. Similar to the approach by Lahrmann *et* *al.* (2018b), respondents who participated via the online questionnaire received an e-mail with a link to the questionnaire at the beginning of each month and were asked to register their accidents and near-accidents from the past month.

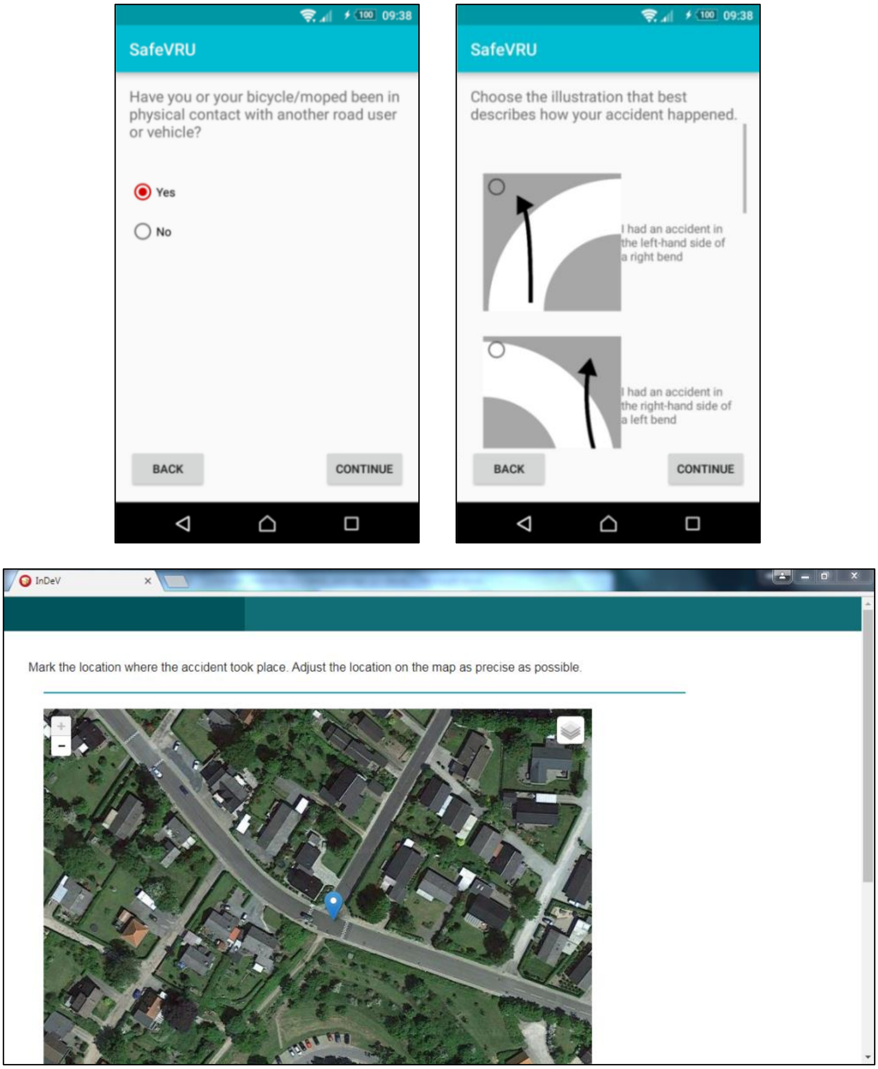

Figure 1: Android smartphone app for immediate registration of near-accidents and accidents (top) and interface of online questionnaire for monthly registration of near-accidents and accidents (bottom). Map background: Google Maps.

The questionnaire consisted of questions to cover the same information as usually included in police records (Danish Road Directorate, 2017b), such as:

- Time and location
- Mode of transportation
- Description of what happened
- Accident type (e.g. rear-end collision, accidents involving pedestrians)
- Other involved road users and their mode of transportation
- Road type (e.g. intersection, curve, bridge)
- Injuries
- Helmet use
- Weather conditions
- Road surface conditions
- Potential contributory factors (e.g. being influenced by alcohol/drugs/medicine)

In addition, more contributory factors were included in the questionnaire than in typical police records, e.g. fatigue, listening to music, using the phone for talking or texting, inattentiveness, etc. to gain more knowledge of the accidents. Furthermore, the questionnaire asked the participants whether they had been in contact with the police, hospital/emergency room, general practitioner or insurance company.

Results from a previous study indicated that some participants registered events that were not supposed to be registered, e.g. near-accidents if only accidents should be registered or events that were neither accidents nor near-accidents (Lahrmann *et al.*, 2018b). Therefore, in addition to registering which type of event they had experienced (accident, near-accident, unsure), the participants were presented to four yes/no questions in the beginning of the questionnaire to automatically classify whether the participant had been involved in an accident, a near-accident or neither:

1. Have you or your means of transport been in <u>physical contact</u> with another road user or vehicle?
2. Did you <u>crash/fall/get hurt/damage some of your personal belongings</u>?
3. Were you so <u>close to collide</u> with another road user that it <u>felt uncomfortable</u>?
4. Did you or the other road user make an <u>evasive manoeuvre</u> (e.g. brake, accelerate, change direction) in order to avoid a collision?

An event was classified as an accident if the respondent answered ‘yes’ to at least one of the questions 1 and 2. If the respondent answered ‘yes’ to questions 3 and/or 4, the event was classified as a near-accident. A ‘no’ to all four questions meant that the event was classified as neither an accident nor a near-accident. Based on this classification, the questionnaire would contain a varying number of questions to be answered; the level of details was high for accidents and lower for near-accidents. Although a high level of details was desirable also for near-accidents, the decision of reducing it for near-accidents was made as a compromise to reduce the time spent on answering the questionnaire, given that the participants could potentially experience several near-accidents per month (Aldred & Goodman, 2018; Poulos *et al.*, 2017). Having a high number of questions for each near-accident could thus lead to participants omitting to register the near-accidents in the questionnaire.

In total, 833 incidents were used for the analysis: 631 near-accidents and 202 accidents. For the analysis, all responses were reviewed manually to identify the type of the incident (e.g. rear-end, road user from opposite directions turning in front of each other, single accidents) based on the participants' descriptions of what happened in the incident. This information was, together with other characteristics from the questionnaire, compared to police records from the official accident statistics (Danish Road Directorate, 2017a)

2.2. DETECTION OF ACCIDENTS VIA SMARTPHONE SENSORS

A supplementary study was carried out as part of the InDeV project to examine the potential of detecting cycling and walking accidents automatically based on motion data. The intention with this approach was to register as much information as possible, e.g. the time and location of the accident, in order to obtain objective data and hence reduce the risk of incorrect information on accidents and avoid that accidents were missed. Ideally, this could be used in combination with the use of a questionnaire for self-reporting in order to collect information regarding other aspects than those described by the objective data.

In this study, the basic idea was to use motion data to monitor the road user in order to detect if the road user was involved in an accident when travelling as pedestrian or cyclist. In addition to information regarding the time and location, motion data should be saved from the period before, during and after the accident.

For the collection of motion data, built-in smartphone sensors were chosen as the most suitable sensor type for monitoring of pedestrians and cyclists, since this approach did not require any additional sensors to be carried around and hence did not add additional costs to the data collection. To support this choice, a small study by Candefjord *et al*. (2014) indicated that the use of smartphone sensors was suitable for the detection of accidents from cyclists.

In order to detect accidents from motion data, a rule-based algorithm based on kinematic triggers (acceleration, jerk, rotation) and the occurrence of changes of the state of the screen (turned on/off) was applied (Figure 2). The intention with the latter was to discard motion from using the phone. The thresholds used in the algorithm to distinguish accidents from normal motion behaviour were based on a survey of the literature and an analysis of collected data from normal cycling and walking behaviour. The acceleration threshold was chosen to 8 m/s^2, since the values in the literature ranged from 4.9 m/s^2 (Boubezoul *et al.*, 2013) to 15 m/s^2 (Mulcahy & Kurkovsky, 2015). Boubezoul *et al*. (2013) additionally used a rotation threshold of 2 rad/s to identify motorcycle falls, and thus the same threshold was applied in our algorithm. Finally, the jerk threshold was set empirically based on a sample of cycling and walking data that was collected in the study. Based on this data, the threshold value was set to 14.7 m/s^3 for the absolute jerk value, as this value seemed to be sufficiently above the values from normal behaviour. A full description of the algorithm is provided in Paper II.

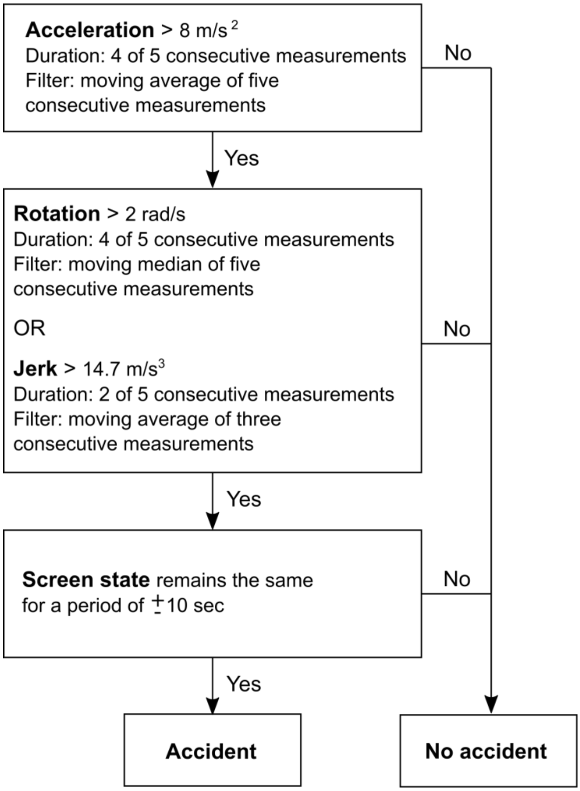

Figure 2: The rule-based algorithm used to assess the potential of identifying accidents automatically based on the built-in sensors in smartphones (Paper II).

No real accidents were available for testing of the algorithm. Therefore, to test the potential of identifying accidents via the algorithm, simulated accidents were performed using two different simulation methods: 1) Simulated accidents by a stuntman and 2) simulated accidents by using a test dummy, which was made specifically for the InDeV project by researchers from Lund University (2016). The two simulation methods are illustrated in Figure 3 (stuntman) and Figure 4 (test dummy).

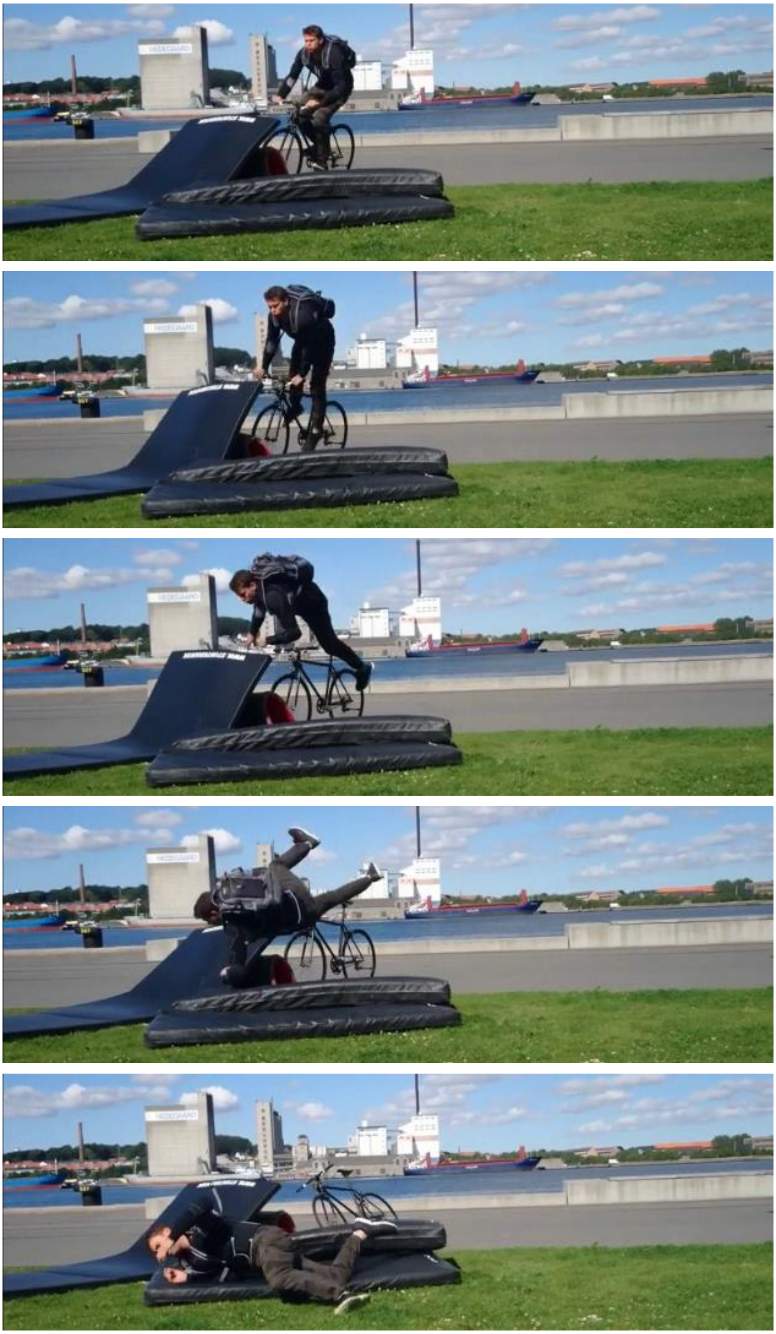

Figure 3: Example of simulated cycling accident by stuntman, illustrated by still images from video. Link to video: https://youtu.be/avT7ce02ymE

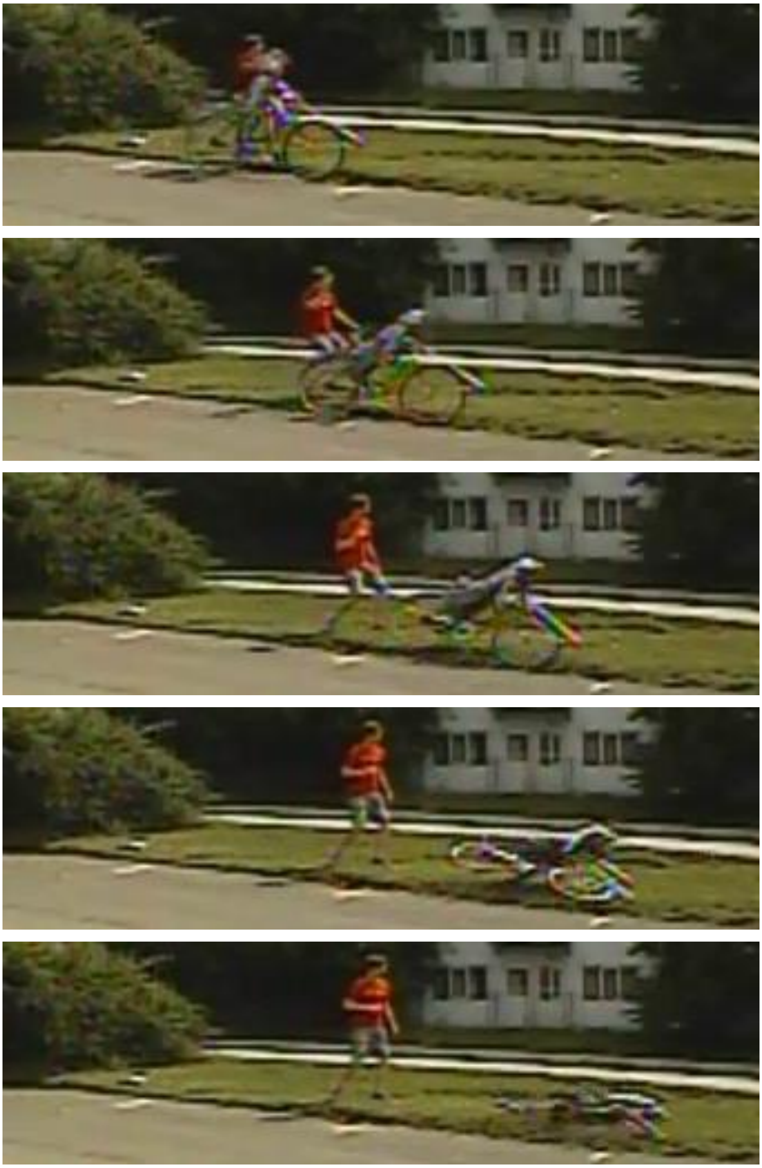

Figure 4: Example of simulated cycling accident by using a test dummy, illustrated by still images from video. Link to video: https://youtu.be/8UTxi34E3Fg (Lund University, 2016)

CHAPTER 3. WATCHDOG VIDEO ANALYSIS TOOL FOR TRAFFIC CONFLICT STUDIES

In relation to site-based traffic safety work, the PhD project focused on the development, testing and application of a watchdog video analysis tool. During this work, the watchdog video analysis tool RUBA was developed in cooperation with researchers from the Visual Analysis Group at Aalborg University (Bahnsen *et al.*, 2018). Based on a number of different analyses related to the safety of road users, this watchdog was tested and applied in order to examine its potential to facilitate the analysis of the safety of road users, particularly when carrying out traffic conflict studies. In relation to this, different approaches to the identification of traffic conflicts were assessed in order to address the issues with the current indicators when used for vulnerable road users. The two studies described in Paper III and Paper IV illustrate the development of the watchdog video analysis tool and the different techniques tested for identification of traffic conflicts.

3.1. THE RUBA WATCHDOG VIDEO ANALYSIS TOOL

The video analysis software RUBA (abbr. of 'Road User Behaviour Analysis') was developed to facilitate the analysis of traffic video in studies of road user behaviour. RUBA uses a watchdog approach in which the aim is to reduce large amounts of video to a number of timestamped events of specific interest for the analysis. These events should then be further analysed manually or using other software.

When conducting an analysis in RUBA, the user imports videos into the software and marks areas ('detectors') of specific interest for the analysis in order to analyse colour changes on a pixel level in these areas. Depending on the purpose with the analysis, the user of the tool can choose between four types of detectors (illustrated in Figure 5) with different characteristics for the analysis: presence detector, movement detector, stationary detector and traffic light detector. Detailed information on how to conduct analyses in RUBA is available in a user guide that we made in addition to the development of RUBA (Bahnsen *et al.*, 2018).

The presence detector can be used to register changes inside the detector and is particularly suitable for detection of road users in areas where only the road users of interest travel, e.g. on designated paths, road lanes or pavements. The movement detector registers motion inside the detector for a specific, predefined direction and is therefore suitable for detection of road users in areas where road users from different directions pass the detector, e.g. in intersections. The stationary detector registers when there are changes inside the detector but that the object moves slowly through the detector area or does not move, i.e. objects standing still. This detector is particularly applicable for registration of road users who stop in the middle of the road or wait next to the road before crossing.

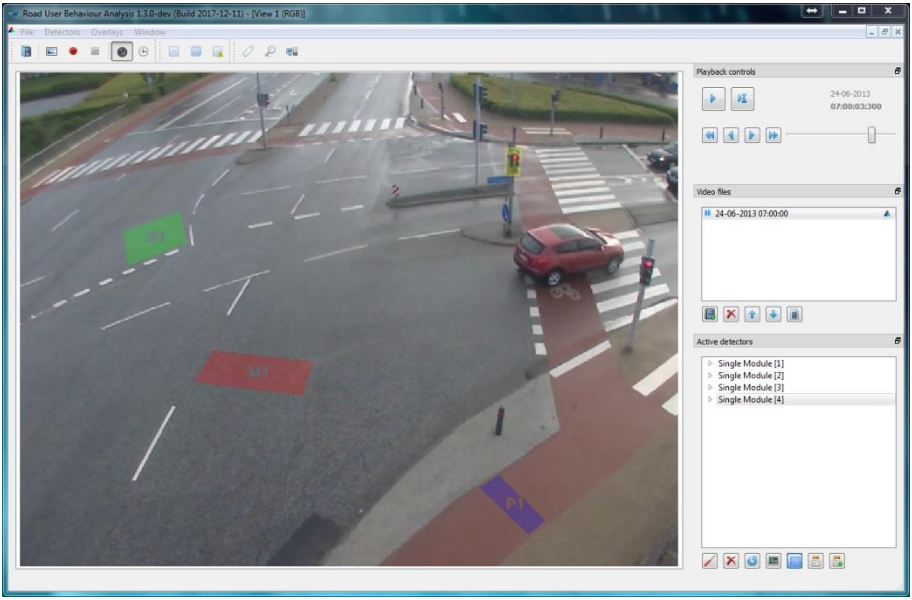

Figure 5: RUBA interface. The user creates detectors on top of the video to register changes inside the detector. Three different types of detectors can be used to register road users: the presence detector (blue) detects changes inside the detector independently of direction; the movement detector (red) detects motion in a specific direction; the stationary detector (green) detects when something is standing still or moves slowly through the detector. In addition, a traffic light detector (yellow) can be used to register the colour of the traffic light.

RUBA detects changes independently of whether they originate from road users or from "noise" (shadows, shaking leaves and branches, birds, etc.). Therefore, the detectors should be calibrated manually on a range of parameter settings in the tool in order to register only the road users. After this, RUBA will analyse the video footage and register the time of when the detector was triggered. RUBA outputs a list of timestamps for the detections, a screenshot of the detection and a list with the number of detections aggregated on a predefined interval (e.g. 15 minutes), which can for instance be used as a measure of exposure.

Depending on how the detectors are placed, different types of analyses can be made and various types of road user behaviour can be identified for further analysis. For instance, RUBA can be used to register pedestrians crossing the road, cyclists or vehicles travelling in the wrong direction, etc. Two detectors can also be combined for more advanced analyses to detect when both detectors have been triggered within a given time interval. For instance, this can be used to register interactions or potential traffic conflicts between two road users, detection of red light running, etc. So far, the tool has mainly been used for traffic conflict studies to register potential traffic conflicts between two road users by detecting situations in which two road users are close to each other in time and/or space (e.g. Lahrmann *et al.*, 2018c; T.K.O. Madsen & Lahrmann, 2017) but also occasionally for behavioural studies (Øhlenschlæger *et al.*, 2018).

RUBA has a number of different functions and is compatible with other tools developed in the InDeV project with the aim of facilitating the whole analysis process. A typical analysis of traffic conflicts may be conducted as follows:

- Detection of potential conflicts in RUBA.
- Manual sorting of events to remove false positives.
- Review of video clips of the remaining events via RUBA.
- Extraction of small video clips via RUBA.
- Further analysis to identify traffic conflicts.

3.2. DEVELOPMENT OF RUBA

The overall scope with the developed tool for video analysis of road user behaviour was that it should be easy to use and able to reduce the video footage to an extent that makes it manageable to process further manually. Therefore, the development of the RUBA watchdog video analysis tool for analysis of road user behaviour was conducted in an iterative process in which the tool was applied on various projects, rigorously tested and modified based on the results to implement new functions to allow for a broader range of analyses and to improve the functionality towards making it faster and more user-friendly.

In the first version of the watchdog video analysis tool (named 'TrafficDetector'), tools were developed with the aim of facilitating the analysis of video in a traffic conflict study which compared the safety of cyclists in signalised intersections with different types of bicycle facilities (Paper III). The basic idea of the tool was that road users should be detected using a simplified version of tracking of the road users. This approach was based on detection of motion in a series of individual detector fields that were combined into modules. If the detectors were triggered in the right order, corresponding to the path a road user would travel through the intersection (e.g. to make a right turn), it was detected as a road user.

For the study described in Paper III, three types of modules were developed to detect left-turning vehicles, right-turning vehicles and cyclists passing through an intersection. Figure 6 illustrates the modules for right-turning vehicles and cyclists passing through the intersection. To be detected as a right-turning vehicle, the blue presence detector in front of the stop line should first be triggered to indicate that something is present in the area. Logically, a right-turning vehicle would then move forward in a direction towards the right – which will trigger the movement detector (large red field) – or stop to yield for cyclists before completing the right turn – which will firstly trigger the green stationary detector and later the movement detector when the vehicle completes the right turn. The time of the turn is registered when passing the small presence detector (blue rectangular field). In order to avoid false positives from road users from the opposite direction or from the left, another movement detector was created to disable the other detectors from being triggered if something passed through this detector in a direction towards the right side.

Equivalently, cyclists crossing the intersection would be detected only if the four detector fields (two blue, one red and another blue) were triggered in the right order shortly after each other to indicate that something had moved in the correct direction. The time of the cyclist's crossing of the intersection would be registered at the entrance of the last field.

The intention with this approach was that specific manoeuvres (e.g. right turns) could be registered with high accuracy and few false positives, and that the time gap between two road users who crossed each other's paths in the intersection similarly could be estimated with high accuracy. The time gap was measured based on the timestamps from the last detector in the modules and used as an indicator of the proximity of the road users. Hence, situations in which the road users were close to each other could be extracted for further analysis to assess whether they were traffic conflicts or normal interactions.

Based on the experiences from the first study and other later projects, the tool was continuously improved with new features, different analysis methods and modifications to make the tool faster and more user-friendly to use. For instance, the detection of road users were changed from using the complex modules tailored to a specific road user group and manoeuvre (Figure 6) to using a more simple and flexible approach in which only one detector was typically used for detection of each road user type (Figure 7). In this way, less time should be spent on adjusting the detector settings due to the lower number of detector fields.

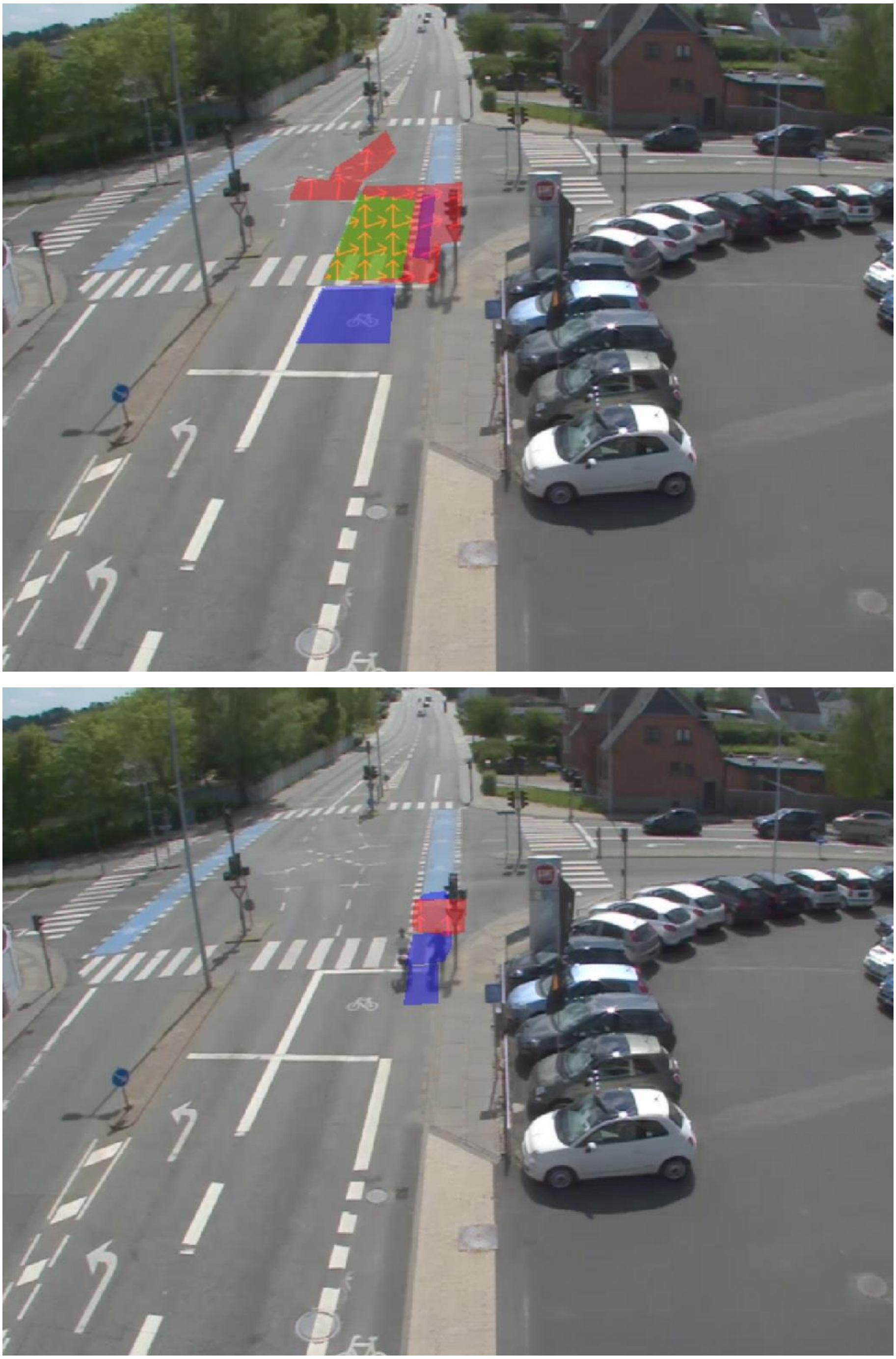

Figure 6: First version of the developed watchdog video analysis tool (“TrafficDetector”).

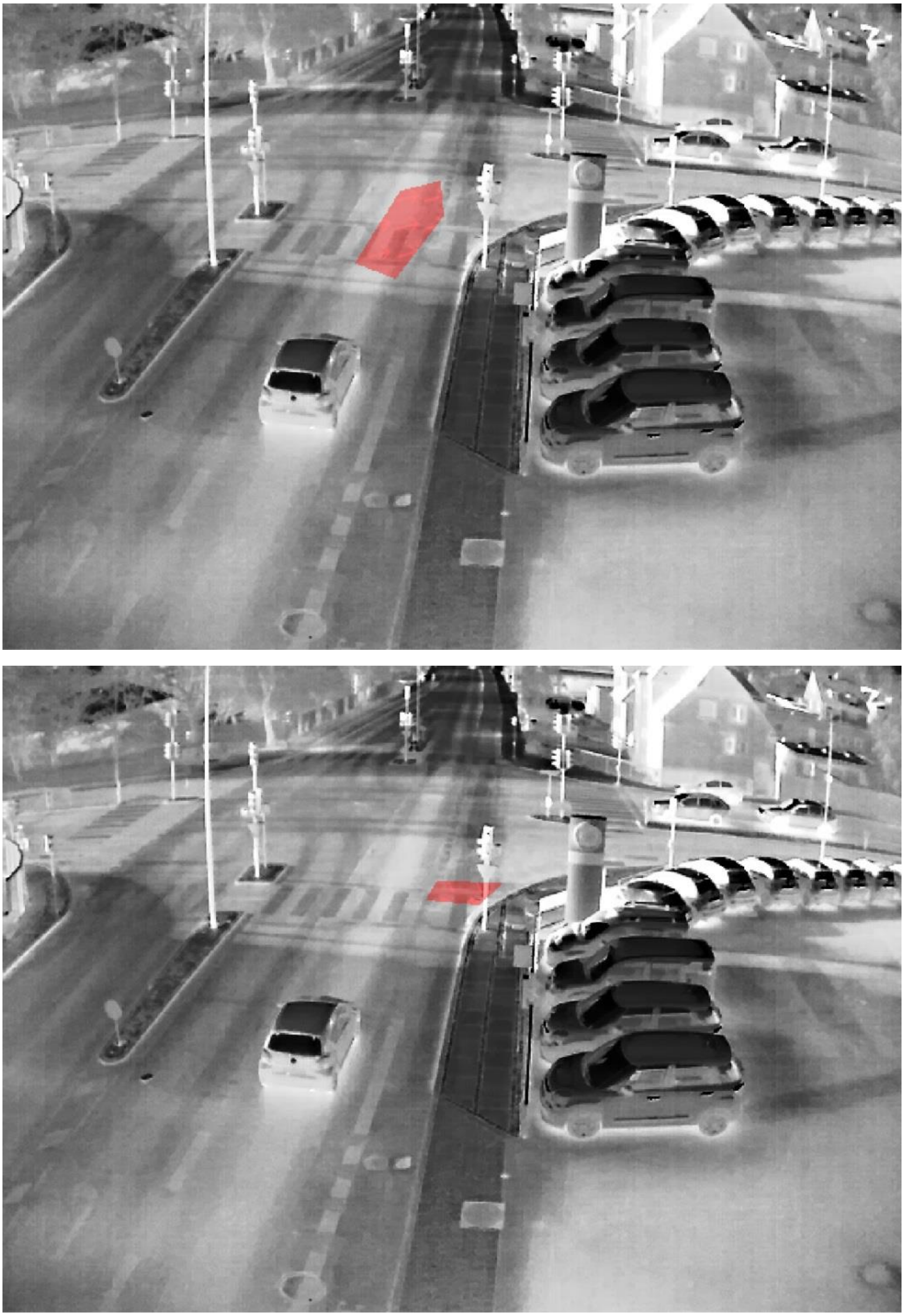

Figure 7: Final version of the developed watchdog video analysis tool ("RUBA").

3.3. IDENTIFICATION OF TRAFFIC CONFLICTS

In the two studies of using the watchdog video analysis tool for traffic conflict studies, two different approaches for identification of traffic conflicts were applied with the aim of including other aspects than covered by time-based indicators. In the first study (Paper III), conflicts between cyclists and turning vehicles were identified using both a time-based indicator and a reaction-based indicator that identified traffic conflicts based on a visible reaction to the situation from at least one of the road users. In the second study (Paper IV), an elaboration on the basic ideas behind the reaction-based indicator was made through the completion of a Delphi study for identification of traffic conflicts.

3.3.1. TIME-BASED VS. REACTION-BASED INDICATORS

Time-based traffic conflict indicators identify traffic conflicts based on the temporal distance between two road users. Throughout the years, a large number of time-based indicators have been proposed (Johnsson *et al.*, 2018). Some of the most commonly used are the 'time to collision' (TTC) and the 'post-encroachment time' (PET) (Laureshyn *et al.*, 2016). The PET value describes the temporal distance from the first road user leaves the conflict zone (i.e. the overlapping area of the trajectories of two road users who cross each other's paths) until the second road user enters the conflict zone. Hence, this measure gives an indication of how close the road users are to each other when they are both near the area of the conflict zone. The TTC indicates the time remaining before a collision will occur if the road users continue with the same speed and direction. If the minimum value is above zero, the road users did not collide. (Johnsson *et al.*, 2018). The TTC can be calculated only as long as the two road users are on collision course. However, even if the road users are not on collision course, there can be situations in which a small change in speed or direction will bring the road users on a collision course. These situations may similarly involve a high collision potential. Laureshyn (2010) therefore suggested using the T_2 value. This indicator describes the time that remains for the second road user to avoid a collision if they get on a collision course.

In the study in Paper III, traffic conflicts were in the time-based conflict indicator defined as situations with a minimum TTC $\leq$ 2.0 seconds or a minimum T_2 value $\leq$ 0.5 seconds. For each potential traffic conflicts, trajectories were made in T-Analyst (Laureshyn, 2015) to estimate the minimum values of TTC and T_2.

The reaction-based indicator used in Paper III was based on the principle of using the evasive manoeuvre similar to the approaches in the Swedish Traffic Conflict Technique (Hydén, 1987) and the Dutch traffic conflict technique DOCTOR (van der Horst & Kraay, 1986). The evasive manoeuvre indicates that at least one of the road users felt that a collision was imminent to a degree that they would not voluntarily expose oneself to (Hydén, 1987). In the reaction-based indicator used in this study, a traffic conflict was hence defined as a situation in which a least one of the road users clearly indicated that the event was too dangerous and as a result reacts on it near the conflict zone, e.g. by using gestures or performing an evasive manoeuvre (braking, accelerating or swerving). Conflicts were in this study identified by the PhD student and her supervisor who both assessed the potential traffic conflicts individually. In case of disagreement with regard to whether or not a situation should be characterised as a traffic conflict, the situation was reviewed and discussed jointly until a decision could be made.

3.3.2. THE DELPHI METHOD

In another study (Paper IV), traffic conflicts were identified using the Delphi method in order to examine the potential of using this method to identify traffic conflicts by potentially including other aspects than covered via time-based traffic conflict indicators. For instance, the assessment can include factors such as age, head turning to look for other road users, the use of gestures, etc.

The idea of conducting a Delphi study is to ask a group of panellists with specialised knowledge on a specific topic to give their opinion on the topic to be studied (Hsu & Sandford, 2007; von der Gracht, 2012). The Delphi study is conducted in multiple rounds in which the panellists answer the same set of questions. After each round, the answers from the panellists are summarized, and the distribution of answers and a summary of comments are included in the next round in order to let the panellist know what the group as a whole has answered. Based on this information, the panellists assess the questions again. Ideally, the study continues in this way until the group has reached consensus regarding an answer which reflects the opinion of the group and until their answers from one round to the next does not change anymore. (Hsu & Sandford, 2007)

Nine traffic safety professionals with experience in conducting traffic safety analyses in practice participated in the Delphi study. The qualifications within the group varied to ensure diversity in the panel, and some therefore had experience with using traffic conflict techniques, while others were road safety auditors.

50 situations were classified into one of three categories: 'no conflict', 'less severe conflict' and 'serious conflict'. The situations had all been preselected in a screening of the RUBA detections of potential traffic conflicts. Although the panellists should ideally go through all potential detections, the study was limited to 50 situations in order to reduce the workload and the risk of dropout, as the use of multiple rounds make Delphi studies a very time-consuming method which require a lot of commitment (Yousuf, 2007). The study was conducted via an online questionnaire made in Google Forms (Figure 8). Each situation showed an illustration of the road users involved and their manoeuvres. Furthermore, a video of the situation was embedded into the questionnaire. After having seen the video one or multiple times,

the panellists would classify the situation into the three groups and potentially leave a description with additional explanation of why they classified it the way they did or what made them insecure about their classification.

Figure 8: Delphi study questionnaire. The panellists were presented to an illustration of the situation in question, a video of the situation and fields to classify the situation as 'no conflict', 'less severe conflict' or 'serious conflict' and to describe their choice.

The process of the Delphi study is illustrated in Figure 9. In total, the study consisted of three rounds in an attempt to reach consensus regarding how each situation should be classified. After each round, the answers were checked for two aspects as specified by von der Gracht (2012): 1) consensus and 2) stability. Consensus was in this study reached, if at least two thirds (i.e. 6 of 9 panellists) agreed on whether a given situation should be classified as a conflict (less severe or serious) or as no conflict. If classified as a conflict, the severity was chosen based on the majority's classification. The stability was assessed by comparing the group opinion between two consecutive rounds. If the group opinion remained the same (i.e. 'conflict' or 'no conflict'), the opinion of the group was said to be stable. Only situations that did not meet both criteria were included in the next round.

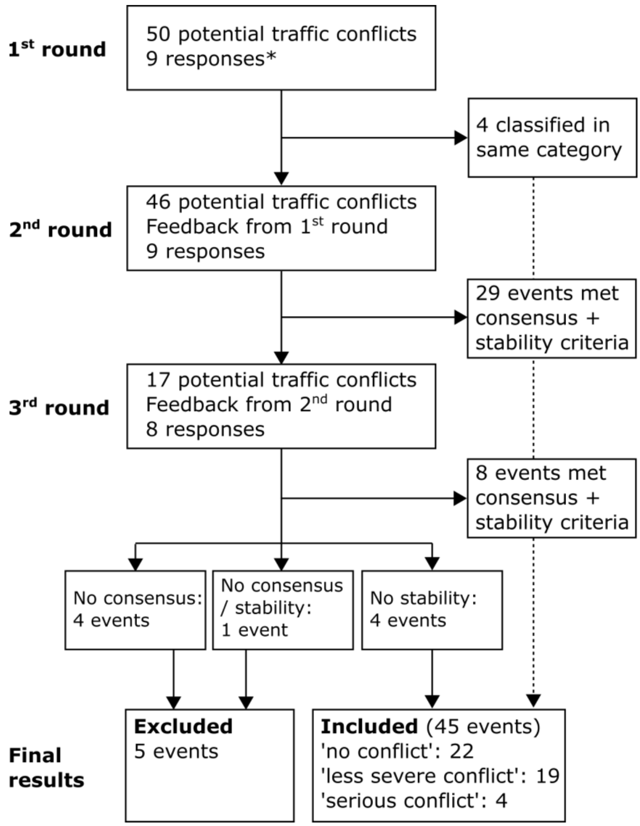

*Figure 9: Process of the Delphi study. *One panellist responded after the second round had begun. The responses from this panellist were therefore neither included in the feedback for the second round, nor in the assessment of which situations to include in the second round.*

CHAPTER 4. SUMMARY OF FINDINGS

The study described in **Paper I** investigated the implications of using self-reported accidents and near-accidents compared to using police-recorded accidents for the analysis of the safety of pedestrians and cyclists. The results indicated that self-reported data on several points differs from police records. Firstly, there was a high number of single accidents with both pedestrians (20% of the walking accidents) and cyclists (39% of the cycling accidents). In comparison, single cycling accidents accounted for only 4% of the police-recorded cycling accidents, while pedestrian single accidents are non-existent in police records because they are not regarded as traffic accidents. This means that analyses based on police records not sufficiently acknowledge single accidents for their large contribution to the general safety level of pedestrians and cyclists and thus not identify the issues related to these accidents, e.g. slippery roads, potholes, uneven pavement, obstacles, etc. Secondly, the study found that particularly incidents with another light road user occurred more frequently in the self-reported data than in the police records. Thirdly, the most prevalent accident types in multiparty accidents differed significantly between police records and the two types of self-reported date. In particular, there was a higher proportion of rear-end collisions in the self-reported cycling accidents and more cycling near-accidents involving turning vehicles than among the police-recorded cycling accidents. Although only few pedestrian accidents and near-accidents were registered by the participants, the data indicated that these also differed from police records. Concretely, most of the respondents' multiparty near-accidents occurred at intersections, whereas an analysis based on police records concludes that pedestrians are mainly at risk for being run over by another road user at road sections. Overall, the main message of this study thus is that the use of self-reported data for traffic safety analyses influences the conclusions drawn based on the analysis and hence the suggested efforts for improvement of the general safety of vulnerable road users. Consequently, using self-reported data may provide better insights into the safety of pedestrians and cyclists.

One of the main concerns of using self-reported data for traffic safety studies is whether or not the registered information is correct and complete, since participants may deliberately omit some information that they do not want to admit or because they accidentally forget to register an event. Therefore, as a supplement to the use of self-reporting for registration of information regarding accidents in Paper I, **Paper II** studied the potential of using motion data from smartphone built-in sensors to detect accidents of pedestrians and cyclists automatically in order to collect as much information as possible regarding the accidents. Hence, the basic idea was that this information should be used in combination with a questionnaire in which the road users provide additional information about the accident. The results showed that all cycling accidents (14 in total) that were simulated using a test dummy, were detected by the developed algorithm, but that only 8 of 19 simulated cycling and walking accidents simulated by a stuntman were detected. Although the study thus indicated that accidents of cyclists and pedestrians could potentially be detected automatically, the study also illustrated that it is a complex task to develop such a system. Therefore, we only made a proof of concept, and there are still several challenges that must be addressed before such a system can be used for detection of accidents among vulnerable road users in a real-world setting. Concretely, improvements should be made with regard to the functionality across different smartphone brands and models, and that it can detect accidents without too many false positives, e.g. due to handling of the phone when in use.

Paper III used the first version of the developed watchdog video analysis tool (TrafficDetector) in order to compare five different designs of bicycle paths through signalized intersections in order to gain knowledge about which design was safer for the cyclists. A traffic conflict study was carried out on 80 hours of video from five sites using TrafficDetector to detect potential conflicts between cyclists and turning vehicles. The results from the study showed that TrafficDetector reduced the total amount of video to 16% of its original length, which corresponded 64 hours of video that had to be further analysed manually. However, there were large differences in the performance across the five studied sites. The video footage from the intersection with the lowest traffic volumes was reduced to three hours (4%), whereas the video footage from the intersection with the highest complexity was only reduced to 25 hours (31%). The identification of traffic conflicts with respectively time-based and reaction-based indicators showed that the time-based indicator generally included more conflicts than the reaction-based indicator. A further analysis indicated that one major difference between the two approaches was that the time-based indicator included merging events in which the cyclist and the vehicle drove close to each other in a seemingly controlled manner. These events were not included as conflicts in the reaction-based indicator because they were here considered as normal behaviour.

Based on the experiences from Paper III, the study in **Paper IV** analysed two intersections (one rural mainly with motorised traffic and one urban with pedestrians, cyclists and motorised traffic) with a refined version of the watchdog video analysis tool (RUBA). The amount of video was in this study increased to 476 and 610 hours due to the low number of conflicts that were identified with the reaction-based indicator in the previous study. RUBA reduced the original video to 99 hours (16%) in the urban intersection and to 3.5 hours (< 1%) in the rural intersection, which had a low traffic volume and mainly consisted of motorised traffic. Instead of identifying traffic conflicts ourselves as in the previous study, this study conducted a Delphi study among nine traffic safety professionals who were asked to assess 50 potential conflicts in three rounds. After three rounds, nine situations did not meet the consensus and/or stability criteria. However, it was decided from the beginning to stop after three rounds to reduce the workload on the panellists. Furthermore, only eight of the nine panellists completed the third round.

The panel did not reach consensus for five of the 50 situations and these were thus not included in the analysis of the safety in the two studied intersections. The other 45 situations were successfully classified into three categories: ‘no conflict’ (22 events), ‘less severe conflicts’ (19 events) and ‘serious conflicts’ (4 events) and used to assess the safety in the two studied intersections. In comparison, the police records only contained information from three accidents in total from the two intersections even though ten years of data were used. Overall, this study indicated that the use of RUBA in combination with the Delphi Method was a useful tool for identification of traffic conflicts based on other aspects than when using a time-based indicator.

CHAPTER 5. DISCUSSION

5.1. ASSESSMENT OF THE SAFETY OF VULNERABLE ROAD USERS VIA SELF-REPORTING

One purpose of this PhD project was to investigate the safety of vulnerable road users through the examination and further development of tools to support the analysis using other methods than police-recorded accidents. As such, a part of this PhD project focused on the collection of self-reported data to compare it with police records. Overall, the results indicated that the use of self-reported accidents and near-accidents can be used as a means to overcoming the issues with under-reporting in police records in the non-site-based traffic safety work. Similar to other studies using either self-reported or hospital-recorded accidents (e.g. Lahrmann *et al*., 2018b; Janstrup *et al*. 2016), this study confirmed that it is possible to capture a considerably larger proportion of the accidents than by police records. In particular, the findings showed that the occurrence of single accidents is underestimated in the police records: the proportion of single cycling accidents was 39% in our study compared to 4% in the police records, and 20% of the registered pedestrian accidents were likewise single accidents. This pattern is similar to the results from other studies of cycling accidents (AIB, 2015; Schepers *et al*., 2015) and pedestrian accidents (Öberg *et al*. 1996) which all found that the number of single accidents is considerably higher than reflected by police records.

Despite the obvious advantages of getting more complete data for traffic safety analyses, self-reporting is often criticised for the fact that the data are registered by the road users themselves and thus may be incorrect, incomplete and biased (af Wåhlberg, 2009; Boufous *et al*., 2010; Lajunen & Özkan, 2011). However, some measures can be used to accommodate these issues. For instance, the study carried out in this project (Paper I) and several other studies (Lahrmann *et al*., 2018b; Aertsens *et al*., 2010) have sent out a series of questionnaire instead of using only one questionnaire in order to reduce the recall period. In addition, this PhD project used an app to give the road users opportunity to register their accidents or near-accidents at any time. Hence, they could register immediately after the incident occurred and thereby reduce the risk of forgetting details. However, despite these efforts to improve the quality and completeness of the collected data, it is unlikely that the data registered in this self-reporting study – and self-reporting studies in general – is complete. This may potentially lead to biased conclusions, although not as distinct as when using police records.

5.2. APP AND WEB QUESTIONNAIRES

In the self-reporting study (Paper I), the questionnaire could be accessed via two platforms (Android smartphone app and online questionnaire) to make it as easy as possible for the participants to register their accidents. Both methods were mentioned by Kaplan *et al*. (2017) as a means to encourage road users to register their accidents. A further analysis of the responses shows that the monthly response rate to the questionnaire differed remarkably between the two platforms used in the study (Table 3). Participants who received monthly emails with a link to the online questionnaire had a response rate of 94-96% each month, whereas only 9-42% of the app users answered the questionnaire each month.

Table 3: Monthly response rate to the questionnaire via an app and via a web questionnaire.

	App	Web
September 2016	42%	96%
October 2016	11%	94%
November 2016	9%	94%
December 2016	34%	95%
January 2017	30%	95%
February 2017	26%	95%
March 2017	25%	94%
April 2017	20%	94%
May 2017	28%	94%

The large difference in the response rates for participants using the app and web questionnaires may be explained by the way the questionnaires worked for each of the two platforms. Whereas the web participants received a monthly questionnaire via e-mail and reminders in case they did not respond within one week, not all app users received reminders from the study since it required that they had enabled notifications to be shown. Therefore, they had to remember to register their accidents and near-accidents in the app. Unlike the web participants, they were also not encouraged to register on a monthly basis independently of whether or not they had been involved in an incidents within the past month. It is therefore likely that the app participants mainly have registered in the app when they have had something to register and the web participants have answered the questionnaire in any case every month.

The missing reminders on the app may have increased the risk of forgetting to register accidents and near-accidents throughout the study. At worst they may even have forgotten that they have signed up for the study. On the other hand, the option to register incidents immediately via the app could potentially have increased the chance of registering an event, because the app users did not have to wait for up to one month before the next questionnaire was sent out. Since participants tend to forget near-accidents even after few weeks (Chapman & Underwood, 2000), it is likely that web participants may have forgotten details about their near-accidents or that it happened. For instance, some participants noted that they could remember that they had been involved in a near-accident but did not remember any details about the incident. To investigate this further, the responses from the app and from the online questionnaire have been compared. This analysis showed that the app participants registered significantly fewer near-accidents than the web participants, which suggests that they have forgotten to register more of their incidents than the web participants. However, to gain more knowledge of the strengths and weaknesses of each registration method, the implications of how it affects the responses and how to improve the quality of the self-reported information via the design of the questionnaire, further research is needed.

5.3. AUTOMATIC ACCIDENT DETECTION AS SUPPLEMENT TO SELF-REPORTS

In this project, it was also attempted to improve the quality of self-reported accidents through the development of an app for automatic accident detection (Paper II). Initially, the intention with this was that the accident detection app and self-reporting should be used in combination: 1) an accident detection app should monitor the movements of the road user and register the time, location and motion pattern before, during and after the road user had been involved in an accident. 2) In case that the app had detected an accident, the road user should receive a questionnaire on the smartphone in order to provide additional information regarding the accident, e.g. who were involved and a description of what happened. The advantage of this approach is that some information (e.g. time and location) potentially can be collected directly. Ideally, this can lead to more accurate data and accommodate some of the issues with self-reporting of incidents, such as the risk of forgetting to register the events.

In order to create such a system for automatic collection of accidents of pedestrians and cyclists, it requires that all of the following premises are fulfilled: 1) all pedestrian and cyclist accidents should be detected automatically, 2) there should be no or very few false positive detections of accidents, 3) the system should work all the time and preferably not involve substantial inconveniences for the road users, e.g. in terms of heavy equipment to be carried around or battery drain on their smartphone and 4) if an accident is detected, the system should automatically save as much information as possible and send a questionnaire to the road user to register additional information via self-reporting.

Particularly the automatic accident detection proved to be a challenging task. Therefore, in the end, the two studies were made separately. This decision was made to make it easier during the development and testing phases in order to ensure that the two parts were fully functional individually before combining them into one.

However, due to challenges during this development, the accident detection algorithm was only made as a proof of concept. Hence, it was neither tested in combination with self-reporting nor on a larger scale. Nevertheless, the study showed some issues that should be addressed before a system for automatic accident detection and registration of additional information via self-reporting can be used in large-scale studies.

The accident detection algorithm consisted of a simple rule-based algorithm based on kinematic triggers (acceleration, jerk, rotation) and changes in the screen state (i.e. turning it on/off). The threshold values used in the study were mainly based on values found in literature. These values were then tested for their applicability to detect accidents of pedestrians and cyclists. With this approach, 22 of the 33 accidents – which had been simulated by using a test dummy (14 cycling accidents) and by a stuntman (10 cycling accidents and 9 walking accidents) – could be detected. In this study, the algorithm detected some but not all of the simulated accidents that were carried out for the test (Paper II). In particular, it failed to detect the pedestrian fall accidents that were carried out. Furthermore, the algorithm detected a relatively large number of false positive accidents when tested on a sample of continuous data: three false positive accidents were detected from 22 hours of data, because the algorithm erroneously identified normal use of the smartphone (e.g. phone conversations, texting or handling of the phone) as accidents.

In order to detect all simulated accidents, the thresholds should have been adjusted to other values than the ones used in this study. However, this will most likely result in the detection of more false positive accidents. To accommodate this, annotated motion data could have been used to set the threshold values in order to ensure that all simulated accidents could be detected. However, to detect all accidents and avoid false positives, this approach would require that a large number of (simulated) accidents are annotated and used in order to ensure that the algorithm can detect accidents of different types. Due to errors during the data collection from the simulated accidents, only a limited number and types of situations could be used. As such, further studies should be made to collect more accidents and improve the algorithm.

For testing of the potential of detecting accidents automatically, a series of simulated accidents were carried out using a stuntman and a test dummy. Both methods have previously been used for testing of other algorithms for detection of accidents among vulnerable road users. For instance, Candefjord *et al*. (2014) used a test dummy for simulation of cycling accidents, and Attal *et al*. (2014) used a stuntman for simulation of motorcycle accidents. However, our study showed that there was a large difference in the performance depending on the simulation method. It is likely that the motion pattern of a real accident will be somewhere in-between the two approaches used in the study: the test dummy on one side and the stuntman simulations on the other. However, further investigations into the motion patterns of real accidents and the ability of the algorithm to detect these accidents are necessary in order to fully examine the potential of detecting cycling and walking accidents automatically via smartphone sensors.

To avoid additional costs and weight of external equipment for monitoring of the road users' movements, this study used the built-in sensors of smartphones for the detection. Candefjord *et al*. (2014) used a similar approach and concluded that it was indeed possible to detect cycling accidents via smartphone sensors. In this study, the development of the two apps for self-reporting and automatic detection of accidents focused on Android smartphones. If the method should be used broadly, the system should also be developed to work on iPhones. This may possess some challenges, in particular for the development of the system for automatic accident detection, since it may be more difficult to get access to the sensor readings from iPhones compared to Android smartphones. In addition, the developed algorithm was only tested on three Android smartphones, and it is thus unknown how it will work if other smartphones were used for the data collection, e.g. if they have sensors with a different sampling frequency. To address these issues, the app could for instance be improved in the following ways: 1) To avoid a large number of false positives from handling of the phone when using it, the algorithm could be modified so that it only monitors the road user when travelling as pedestrian or cyclist, and 2) it should be ensured that the accident detection algorithm works across smartphone brands and models independently of the type of sensors in the smartphone, which may for instance have varying sampling frequencies. Alternatively, separate sensors could be used to collect motion data in order to limit the number of different sensor types.

5.4. IDENTIFICATION OF SITES FOR FURTHER ANALYSIS

An important factor not covered in this PhD project is the choice of which locations to analyse further in the site-based traffic safety work. In the studies from Paper III and Paper IV, most locations were chosen because they had a relatively high number of police-recorded accidents. However, as pointed out previously, the under-reporting in this data source is high for vulnerable road users, and one may therefore not identify the locations with a high safety risk for vulnerable road users. Instead, sites of interest for a traffic conflict study can e.g. be chosen based on observations from the road administration and local residents. As an example, the rural intersection from Paper IV was analysed because statements from local residents indicated that the number of accidents was higher than the two that were registered by the police within a period of ten years.

In Paper I, self-reported accidents and near-accidents were collected and used for a non-site-based analysis of the safety of pedestrians and cyclists. In theory, this method could also be used for identification of sites to be further analysed. However, the number of respondents will generally be too low to achieve a sufficient amount of data for identification of specific sites for further analyses because it is unlikely that the method can be used to collect data from all road users. Typically, only a small sample of road users will be used in a self-reporting study. For instance, Paper I was based on a sample of 1,434 participants who registered their accidents and near-accidents. The participants were spread geographically across Denmark and so were the registered accidents and near-accidents, as illustrated in Figure 10. Even in cities with a relatively high agglomeration of participants, the number of registered events was low when zooming in at a single intersection. While this sample was sufficient for analyzing general safety patterns, a much larger sample of participants is needed in order to identify locations that should be further analysed. As such, self-reported data may be more useful for studies in smaller areas, e.g. in cities, to get a better overview of the major traffic safety issues, than it is for identification of black spots. Instead, the use of hospital data can be considered as a better alternative than police records for overcoming the issues with under-reporting that makes it difficult to identify black spots. However, accidents from hospital records generally do not contain any information on where the accident occurred, and it will thus require a change in the registration procedures to include information of the accident location in the hospital records. Therefore, further research could look into how hospital data can be improved in order to become a useful data source for the identification of black spots.

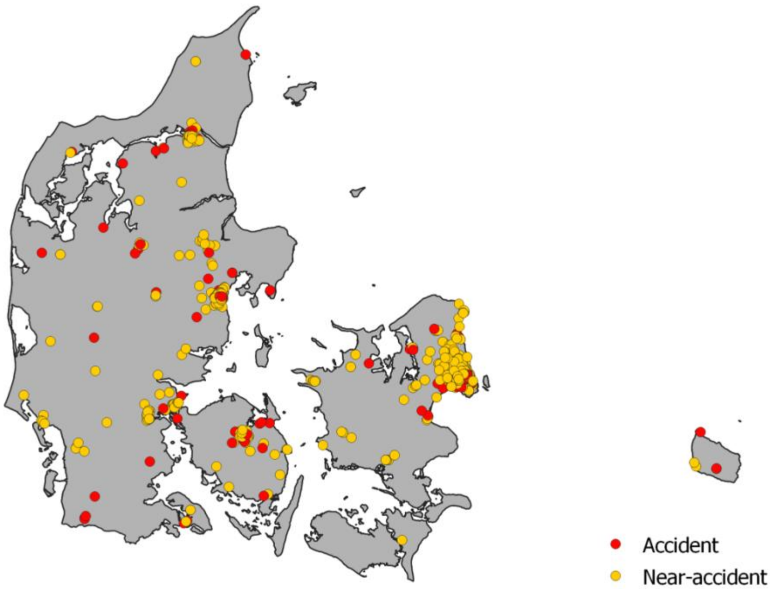

Figure 10: Geographical distribution of the self-reported accidents and near-accidents.

5.5. VIDEO ANALYSIS AND THE DELPHI METHOD FOR TRAFFIC CONFLICT STUDIES

A part of this PhD project focused on the development and use of the watchdog video analysis tool RUBA for site-based traffic safety analyses. RUBA was developed as an alternative to the two most prevalent ways of conducting traffic conflict studies: 1) manual analysis and 2) automated video analysis. Both of these methods have significant disadvantages: while the manual analysis is very time-consuming and restricts the amount of data that can be analysed, automated systems are inaccurate when extracting road user trajectories (Laureshyn *et al*., 2017) and hence require that the output is checked manually. Therefore, the scope was to provide a solution which takes into account that traffic conflicts cannot, at the moment, be identified automatically. RUBA thus uses computer vision techniques to process video footage but with the main purpose of reducing the video so that further processing can be handled manually.

In addition, the project focused on how to identify traffic conflicts involving vulnerable road users. Often, time-based indicators are used to measure how close two road users have been on colliding with each other (Laureshyn *et al*., 2016). However, the major disadvantage of this approach is that important aspects are not considered when analysing whether or not a specific situation can be considered to be a traffic conflict. According to Johnsson *et al*. (2018), none of the existing indicators can capture all relevant aspects of traffic conflicts. Furthermore, the time proximity may not be a suitable indicator for the risk of collisions in traffic conflicts between a motorized vehicle and a vulnerable road user – or between two vulnerable road users. The reason for this is that vulnerable road users, and in particular pedestrians, can stop or change direction almost immediately. Therefore the Delphi Method was used to identify traffic conflicts based on other aspects than the temporal distance between the road users (Paper IV). The results showed that this method seemed useful for traffic conflict studies and that it can potentially be an alternative to the traditional traffic conflict techniques, which are not directly transferable to studies of vulnerable road users (Johnsson *et al*., 2018).

However, the use of the Delphi Method also showed some weaknesses. Out of 50 potential conflicts that were assessed by nine traffic safety professionals, five situations did not meet the consensus criterion after three rounds and hence had to be excluded from further analysis. A deeper investigation of the results of these situations shows that the responses are spread relatively evenly between the categories ‘no conflict’ and ‘less severe conflict’. More rounds could potentially be carried out in an attempt to reach consensus for the remaining five events. On the other hand, one of the panellists dropped out before completing the third round and it is likely that even more panellists would have dropped out if using more than the three rounds, as the Delphi method is very time-consuming. Therefore, an option could be to pay the panellists for their time, although it would add to the costs of conducting traffic conflict studies. It should also be noted that this study did not compare the results from the Delphi study with the results from well-established traffic conflict techniques. Therefore, further research is recommended to assess how the Delphi study differs from other techniques.

Ideally, traffic conflict studies should be conducted using fully automated systems that identify all traffic conflicts and without any false positives. At the moment, this is not possible, since it requires that research within computer vision make significant progress with regard to improving the accuracy of extracted trajectories independently of weather and light conditions, etc. that can influence the accuracy. Furthermore, it requires that a wide range of parameters are used to identify traffic conflicts instead of using only the time distance between the two road users. For this, deep learning techniques or similar advanced techniques should probably be used in order to catch all aspects that characterise traffic conflicts. Therefore, a large amount of traffic conflicts must first be identified manually. Potentially, the Delphi Method can be used for this in order to include all relevant aspects.

CHAPTER 6. CONCLUSIONS

The overall aim with this PhD study was to investigate the safety of vulnerable road users with a particular focus on cyclists and pedestrians and to improve the methods for analysis and mapping of their safety by developing, testing and applying tools for facilitating traffic safety analyses.

A part of the project focused on the use of self-reporting of accidents and near-accidents for non-site-based traffic safety analyses by addressing the following two research questions:

- What are the implications of using self-reported accidents and near-accidents as opposed to police records for the analysis of the safety of vulnerable road users?
- What is the potential of detecting accidents of pedestrians and cyclists automatically based on motion data?

To answer these questions, a self-reporting study was carried out, and an algorithm was developed for automatic detection of accidents based on motion data from smartphone sensors. The results showed that the use of self-reported data influences the conclusions drawn based on the analysis and hence the suggested initiatives to improve the general safety of pedestrians and cyclists. This can lead to better insights into the safety of vulnerable road users. Concretely, the study found that the prevalence of single accidents for cyclists and pedestrians is substantial and should not be ignored. Furthermore, the study indicated that more focus should be directed to accidents between two light road users, as these are more common than indicated in police records.

The development and testing of an accident detection algorithm showed that it is possible to detect cycling and walking accidents in motion data collected with smartphone sensors. However, the study also showed that this is a complex task with a number of challenges that must be solved before it can be used widely for large-scale studies of vulnerable road users' safety. With the used approach, not all simulated accidents were detected, and handling of the phone during daily use lead to a relatively high number of false detections. If accidents should be detected automatically, further development of the algorithm is necessary, e.g. to ensure that it works for all smartphone brands and models independently of the characteristics of the sensors.

Another part of the project focused on the use of video analysis for traffic conflict studies in site-based traffic safety analyses via the following two research questions:

- How can a watchdog video analysis tool be designed and used to become a useful tool for traffic safety analyses?
- How can traffic conflicts be identified so that it includes other aspects than the time distance between the two road users?

In the project, the watchdog video analysis tool RUBA was developed and used for traffic conflict studies. The basic idea with RUBA is that it can analyse video footage and identify situations of interest for further analysis. The ultimate scope was that RUBA potentially could become a useful tool for assisting researchers and traffic safety professionals when conducting road user behavioural analyses based on video footage. Therefore, RUBA uses a simple approach in which the user draws fields on top of the video and adjusts them via a few settings to detect road users passing through the fields. The results showed that RUBA can reduce the amount of video significantly, particularly in areas with limited traffic. Therefore, RUBA can for instance be used to conduct traffic safety analyses such as traffic conflict studies, which often require the use of long-term video footage. In a long-term perspective, such analyses are potentially conducted using fully automated video analysis software. However, until advances in the development of video analysis tools have made this possible, RUBA can be used to facilitate the manual analysis to identify traffic conflicts.

The results of a traffic conflict study using the Delphi Method showed that out of 50 assessed situations, the panel of nine traffic safety professionals classified four events as serious conflicts and 19 events as less severe events. Consequently, the use of the Delphi Method increased the amount of data significantly compared to when using police records, in which only 3 accidents were registered in total within a period of ten years. The study demonstrated that the Delphi Method seems to be useful for traffic conflict studies because the method in theory can include all kinds of aspects that characterise traffic conflicts and not only the time gap, which is the most common indicator of traffic conflicts in the current traffic conflict techniques. The advantage of using the Delphi Method is that bases the identification on the experience and observations of the panellists, who in this case had a broad and long experience with traffic safety analyses. As such, this method can also be useful for the further development of automated video analysis systems for automatic detection of traffic conflicts, since it requires that a large number of traffic conflicts are identified manually before systems can be developed to perform this identification automatically.

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ISSN (online): 2446-1636
ISBN (online): 978-87-7210-246-7

AALBORG UNIVERSITY PRESS