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On the Analysis of Naturalistic Driving Data

Development and Evaluation of Methods for Analysis of Naturalistic Driving Data from a Variety of Data Sources

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Abstract

In the last several years, the focus of traffic safety research has shifted from injury prevention during a crash to measures taken before a crash, in order to mitigate its effects or avoid it completely. Measures include advanced driver assistance systems, safety aspects of autonomous driving and infrastructure design, behavior-based safety (driver training), and policy-making. All of these pre-crash measures require an understanding of driver behavior.

As a result of this need, naturalistic driving data (NDD) has emerged as a crucial data source with high ecological validity. NDD enable not only the real-world assessment of driver behavior, but also that of road infrastructure and pre-crash safety measures. However, NDD's great potential is hindered by its complexity. Consequently, new methods to analyze NDD are greatly needed.

This thesis presents a novel framework for traffic safety research using NDD and discusses the framework's benefits and drawbacks. Furthermore it presents novel methods for analyzing NDD. The first paper presents a robust method to reduce bias in the analysis of time-series NDD. The second paper ports the DREAM method, used in traditional on-scene crash investigations, to vehicle-to-pedestrian incidents in NDD with video data. The third paper analyzes NDD with a novel method based on expert judgment. This method, inspired by DREAM, is currently applied to commercially collected and event-based, real-world crashes with driver and forward video. Finally, the fourth paper presents a new, pragmatic method to extracting range, range rate and optical parameters (e.g. looming) from the forward video in commercially collected lead-vehicle NDD.

In summary, the methods developed and presented in this thesis use quantitative and qualitative analyses of time-series and video data from naturalistic driving to augment our understanding of driver behavior. Pre-crash safety measures will be further advanced not only by these insights, but also by future applications of the methods developed in this thesis.

Keywords: naturalistic driving data, naturalistic driving studies, analysis, methods, driver behavior, safety measures, ADAS, behavior-based safety, legislation, infrastructure design, crash causation

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List of papers

Paper I Dozza, M., Bärgman, J., & Lee, J. D. (2013). Chunking: A procedure to improve naturalistic data analysis. *Accident Analysis & Prevention, 58*, 309-317. doi: 10.1016/j.aap.2012.03.020

Contribution: Dozza and Bärgman developed the method and jointly authored the paper, with support by Lee.

Paper II Habibovic, A., Tivesten, E., Uchida, N., Bärgman, J., & Ljung Aust, M. (2013). Driver behavior in car-to-pedestrian incidents: An application of the Driving Reliability and Error Analysis Method (DREAM). *Accident Analysis & Prevention, 50*, 554–565. doi: 10.1016/j.aap.2012.05.034

Contribution: Bärgman contributed to the modification of DREAM for application to naturalistic driving data, the initial study design, the analysis plan and authoring the method section.

Paper III Engström, J., Werneke, J., Bärgman, J., Nguyen, N., & Cook, B. (2013). *Analysis of the role of inattention in road crashes based on naturalistic on-board safety monitoring data*. Proceedings of the 3rd International Conference on Driver Distraction & Inattention. Göteborg, Sweden

Contribution: Bärgman contributed to the iterative development of the analysis plan and the qualitative coding schema applied to the data. Bärgman also contributed to the data processing, interpretation of aggregated coding schemas, and authoring the method section, with primary responsibility for the quantitative data section.

Paper IV Bärgman, J., Werneke, J., Boda, C.-N., Engström, J., & Smith, K. (2013). *Using manual measurements on event recorder video and image processing algorithms to extract optical parameters and range.* Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, (pp. 177-183). Bolton Landing, N.Y.

Contribution: Bärgman developed the method and was primary author. The study design and application of the method were performed jointly with co-authors.

Contents

1 Introduction

1.1 Background

Crashes in traffic accounted for over 1.24 million fatalities world-wide in 2010. They stand out as the ninth leading cause of death, and the first for men between 15 and 29 (WHO, 2013).

Several studies have shown that driver behavior is a main contributing factor to traffic crashes. In a comprehensive review of U.S. crashes, Treat et al. (1977) concluded: “Thus, conservatively stated, the study indicates human errors and deficiencies were the cause in at least 64% of crashes, and were the probable cause in about 90-93% of crashes investigated” (Treat et al., 1977, p. 28). More recent work has focused on identifying the exact nature of the driver behavior that ends in crashes.

1.1.1 Approaches to studying driver behavior

In the literature on traffic safety, at least three fundamentally different approaches have been used to address the research question: What are the driver behaviors that end up in crashes? In the first, experimental studies of driver behavior in specific situations typically aim to establish causal driver behavior-crash relationships. This highly controlled approach often uses driving simulators (Engström et al., 2005; Wortelen et al., 2013), laboratory settings (Hancock et al., 1991; Caird et al., 1994), or test-track experiments (Summala et al., 2012; Bärgman et al., 2014). Experimental studies require a priori specification of the scenario and the driver behavior to be studied (for example, a specific behavior hypothesized to contribute to crashes). Once scenario and behavior are defined, experimental studies facilitate the testing of hypothesized causal relationships among scenarios, driver behavior, the infrastructure and other road users.

In the second approach, traditional collection and analysis of on-scene in-depth crash investigation data primarily address questions related to injury outcome (Otte et al., 2003; Seeck et al., 2009; Fagerlind et al., 2010). In recent years, these data have typically included variables that document vehicle kinematics, together with driver and witness accounts of the event (Paulsson, 2005; Sandin et al., 2007; Seeck et al., 2009). The kinematics are retrieved through reconstruction based on, for example, tire tracks and vehicle deformations (Niehoff et al., 2006). The data collected through crash investigations can be used as input into epidemiological studies of injuries (Kullgren, 2008) and provide a basis for simulations of vehicle kinematics in crashes. The driver and witness accounts, collected through interviews and questionnaires, provide information about driver state (e.g., fatigue). Understanding the influence of driver state on the occurrence of crashes contributes to driver behavior causation research. However, this approach cannot provide in-depth (time-series) understanding of actual driver behavior in the few seconds before the crash.

Finally, in the last several years a third approach has been developed. The collection and analysis of naturalistic driving data (NDD) has emerged as a useful tool for observing and understanding driver behavior in real traffic (see e.g., Hickman et al., 2010a; Victor et al., 2010). The data is unobtrusively acquired, and includes information about the driver, the vehicle and (often) the driving environment, including other road users. The data is collected from sensors ranging from accelerometers (provided by the vehicle's electronic bus system, e.g. CAN (ISO_11898, 2003)) to GPS and radar, including video of the driver, the vehicle, and the surrounding traffic environment. The main drawback to the naturalistic approach is that, because it uses the observation-without-interfering paradigm, great care needs to be taken if a researcher aims to establish casual relationships (Rothman, 2012). However, associations can be established, as discussed in Carsten et al. (2013).

1.1.2 Aim of the thesis

- The foremost aim of this thesis is to contribute to the mitigation of crashes and critical events in real traffic by developing and demonstrating new methods for analyzing naturalistic driving data (NDD). These methods should be able to facilitate the design and evaluation of new and improved safety measures (e.g., infrastructure design, advanced driver assistance systems, behavior-based safety services (driver training), and legislation).
- A secondarily aim is to create a framework that organizes methods and data used for the analysis of NDD in traffic safety research. The framework and its taxonomy should help researchers link appropriate methods and data.

1.2 Informing the design and evaluation of traffic safety solutions

There are many ways to address traffic safety: infrastructure design, legislation and policy-making, advanced driver assistance systems (ADASs), and other pre-crash safety measures to avoid crashes or reduce their severity. Elvik et al. (2009) have reviewed 128 safety measures which include all these components. This thesis focuses on aspects of traffic safety that influence the way the crash occurs (that is, what happens before it becomes a crash). This section briefly describes five different means of addressing traffic safety with this pre-crash focus.

1.2.1 Infrastructure design

The "Self-Explaining Road" (Theeuwes et al., 1995; Andersson et al., 2005; Charman et al., 2010) is a key concept in the design of roadways. Theeuwes et al. (1995, p. 217) define it as "a traffic environment which elicits safe behavior simply by its design". Infrastructure designers need to know how the infrastructure shapes drivers' expectations and how mismatches between expectations and events lead to crashes and safety critical events (Papers II & III). Pre-crash safety can also be improved by designs that make specific maneuvers impossible to perform. For example, implementing 2+1 roads, which alternate between one and two lanes in each direction every few kilometers, would reduce the incidence of head-on collisions because drivers traveling in opposite directions are less likely to be passing (overtaking) in a lane with opposing traffic (Carlsson, 2009)). The addition of wire barriers between opposing lanes in this scenario would make it physically impossible for drivers to pass in a way that risks a crash with oncoming traffic.

Infrastructure design includes specifications for the details of the actual roadway (e.g., lane widths and curve design), instructions on how the roadside should be designed to mitigate the consequences of a crash, and guidelines (e.g., cost/benefit tradeoffs) for choosing design solutions (Trafikverket, 2000; Andersson et al., 2005).

1.2.2 Legislation and policy-making

Informed legislation and policy-making should be based on empirically rigorous research. The methods presented in this thesis support traffic safety research based on real-world on-road data and are, accordingly, relevant to legislators and other framers of the rules of the road.

Formal rules of the road have been in place since before motorized vehicles arrived on our streets (Clapton, 2004). These rules are the basis for road-users’ interactions with each other and the infrastructure, at least in most developed countries. That is, the rules themselves are not barriers in the same way that a guard rail or a wire fence on a 2+1 road is (Carlsson, 2009). For the rules to be effective, road users must heed them. In some countries, however, rules are frequently ignored. As an example, in the World report on traffic injury prevention 2002 (WHO, 2002) Phan Van Khai, Prime Minister of the Socialist Republic of Viet Nam, stated that in Viet Nam, “Nearly half of the motorcycle riders are not licensed and three quarters don’t comply with traffic laws.”

Many of the laws and regulations that constitute the rules of the road have been in place for a long time and are common across regions. Others are new, differing between regions and/or developed based on the emergence of new phenomena in traffic. An example of the latter is the recent focus on the use of electronic devices while driving. In Sweden, legislation on the use of electronic devices was first explicitly addressed when the government requested a scientific review of the topic (Kircher et al., 2011). As a result, in early 2013 the Swedish government presented a proposal on the wording of a new regulation on the use of electronic devices in vehicles, requesting white papers that comment on the proposed regulation. One example of such a white paper is Bärgman et al. (2013b). Finally, on December 1st 2013 the regulation was made an active part of Swedish legislation, with the following wording:

> When traveling on the road with a motor vehicle, the driver may engage in activities such as the use of mobile phones and other communication equipment only if it does not adversely affect the performance of the vehicle. (Vid färd på väg med ett motordrivet fordon får föraren ägna sig åt aktiviteter såsom användande av mobiltelefon och annan kommunikationsutrustning, endast om det inte inverkar menligt på framförandet av fordonet; Näringsdepartementet, 2014)

The wording of this regulation reflects informed decision-making based, at least in part, on scientific analysis of the impacts of mobile device use on driver and vehicle performance.

1.2.3 Advanced Driver Assistance Systems

The development of Advanced Driver Assistance Systems (ADASs), a major focus for the automotive industry in the last 20 years (Floudas et al., 2004), requires information about the pre-crash phase of crashes. Components of the pre-crash phase include driver behavior, driver expectation, and interaction with infrastructure and other road-users. To develop new ADASs and improve current systems, we need to improve our understanding of driver behavior in real traffic (Lee, 2008; Carsten et al., 2013). In the literature there are only a few methods that use NDD to design and evaluate ADASs (Carsten et al., 2008; McLaughlin et al., 2008; Ljung Aust et al., 2011). The method presented in Paper I supplements current methods.

ADASs can be categorized in two ways: (a) those intended to avoid crashes, and (b) those intended mitigate their consequences. The two categories are often treated as complementary, since the ideal outcome is avoidance, but when that is impossible mitigation is better than nothing (LeBlanc et al., 2006; Brännstrom et al., 2008; Jermakian, 2011). In this thesis, references to ADAS always refer to systems with a traffic safety focus.

A second way to categorize ADASs focuses on how they interact with the driver. ADAS can either (a) inform the driver about a future threat (warning-ADAS) or (b) apply some physical intervention to the vehicle (intervention-ADAS). The former only inform the driver about a condition that may end up in a crash, while the latter intervenes by, for example, braking or steering. Interventions can be continuous, i.e. adaptive cruise control (ACC), which automatically keeps a set headway to the vehicle in front (Labuhn et al., 1995; Marsden et al., 2001). In contrast, many intervention-ADASs intervene only when a crash is imminent, i.e. automatic emergency braking (AEB), which automatically brakes or steers the vehicle to avoid a crash or mitigate its consequences (Kuehn et al., 2011).

Other examples of ADAS currently on the market are: (a) *forward collision warning* (FCW), a system that warns drivers if they are about to collide with another vehicle (euroFOT-consortium, 2009); (b) *lane departure warning* (LDW), a system that warns drivers when they are leaving their lane (euroFOT-consortium, 2009; Gordon et al., 2010); (c) *lane keep support*, a system that intervenes by helping drivers keep the vehicle in the current lane (Kawazoe et al., 2001; Braeuchle et al., 2010); and (d) *driver alert*, a system that tells drivers either that they seem to be tired or that they are not paying insufficient attention to the driving task (Victor, 2005; VCG, 2014).

Cooperative driver assistance systems focused on safety (Meinecke et al., 2009; Roessler et al., 2009) have the same aim as ADASs, but are based on technology that communicates with other road users (e.g., cars or trucks) or the infrastructure (e.g., intersections). The communication technology enables additional functionality, i.e. removing the need for line-of-sight for in-vehicle sensors. Although these cooperative systems are not traditionally categorized as ADASs, I will henceforth include them in the acronym ADAS.

ADAS can be used as a foundation to facilitate what is called autonomous (or different levels of automated) driving (AD). A single, commonly accepted definition of AD has yet to emerge. However, all definitions take the driver out of the driving loop for at least a period of time. NHTSA (2013) has proposed five levels of vehicle automation, ranging from level 0 (*no-automation*), in which “The driver is in complete and sole control of the primary vehicle controls at all times” to level 4 (*full self-driving automation*), in which “The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip” (NHTSA, 2013, p. 4). Two aspects of driver acceptance are important at all levels of automation: (a) acceptance of AD in general, and (b) acceptance of the specific behavior of the AD systems in each situation. To facilitate both types of acceptance, we do want autonomous cars on our roads to behave as if they were being driven by a person (Li et al., 2003; Markoff, 2010).

1.2.4 **Driver education and behavior-based safety**

To improve the efficacy of driver education, the links between driver behavior and context need to be made clear to students. Research on NDD can document these links, supporting more efficient driver training. The methods in Papers II-IV address the identification of factors that contribute to the occurrence of crashes and other safety critical events and that can be a be included in driver education and training.

Traditionally, driver education has been seen as the training and information that new drivers receive. Research on driver education often includes comparisons to other safety measures (Tronsmoen, 2010), before/after studies (Carstensen, 2002), or both. Some research suggests that one-time driver education is not an effective safety measure, at least not in the long term (Watson, 1997; Mayhew et al., 2002). In contrast, Carstensen (2002) reported a decrease in multiple-vehicle crashes (but not single-vehicle crashes) during the first year after a major change to driving education in Denmark.

New practices for novice drivers are topics constantly being investigated. Examples of novel practices include simulator-based training (Ivancic et al., 2000), and training utilizing feedback, either with (McGehee et al., 2007a; McGehee et al., 2007b) or without (Lotan et al., 2005; Musicant et al., 2013) video recording in the vehicle. This type of feedback training, known as *behavior-based safety* (Paper III), has spawned a new type of driver education in the last decade – behavior-based safety in the commercial vehicle domain (Papers III & IV). Commercial vehicle companies (e.g., transport fleets and emergency vehicle fleets) can purchase the services of behavior-based safety companies such as www.lytx.com to reduce the cost of both crashes and maintenance.

Papers III of this thesis utilized data provided by Lytx, Inc (former DriveCam, Inc). Lytx is a company that provides behavior-based safety services. The methods developed in this thesis may be used to further enhance behavior-based services.

1.2.5 Safety ratings for consumers

Consumers about to purchase a new car have access to a variety of regional New Car Assessment Programs (NCAP; e.g., Hershman, 2001; Miller et al., 2014) providing information that can be used to choose the “safest” vehicle. Although the programs have been criticized for pushing car manufacturers to sub-optimize designs, this practice has been found to be of less of a problem then some expected (Lie et al., 2002). The NCAP organizations continue to refine their rating schemata; recently, they have started taking the pre-crash phase into consideration (Miller et al., 2014).

A different rating schema is the EuroRAP (http://www.eurorap.org), in which a large set of European roads have been rated with respect to safety. This helps consumers (including commercial fleets) choose the safest route when driving.

These safety rating programs need to know what to rate: analysis of both normal driving and safety-critical events (SCEs) in NDD can give them this information. In particular, Paper I supports the robust, safety-benefit evaluation of ADASs, while Papers II and III can be used to identify the most important factors for improving traffic safety, from both vehicle and infrastructure perspectives.

1.3 Naturalistic driving data (NDD)

Until recently there have been only two sources of NDD, *naturalistic field operational tests* (NFOTs) and *naturalistic driving studies* (NDSs).

NFOTs are projects that evaluate some form of safety countermeasure, for example one or more ADASs (LeBlanc et al., 2006; Carsten et al., 2008; Sayer et al., 2008; Benmimoun et al., 2011; Carsten et al., 2013). These tests are often empirically rigorous, with both treatment and baseline phases to enable statistical comparison. Many NFOTs include sections with descriptive statistics of normal everyday driving (LeBlanc et al., 2006). One drawback of the NFOTs of production ADASs is that ADASs are often sold in bundles. (For example, forward collision warning is bundled with adaptive cruise control.) As a result, disentangling the effect of the different systems on safety is not always easy (Ljung Aust et al., 2011). On the bright side, NFOTs are one of the few methods that provide an appropriate approach to the evaluation of early-to-market and pre-production ADASs (LeBlanc et al., 2006; Sayer et al., 2008; Benmimoun et al., 2011).

NDS projects collect data for the purpose of understanding specific situations, traffic events and driver behavior. Unlike NFOTs, these studies are strictly observational (Carsten et al., 2013); they do not contrast treatment and baseline conditions as part of the study design. As a result, one downside is that the data do not directly support the inference of causality (Carsten et al., 2013). Two of the most common foci of NDS are normal everyday driving (Neale et al., 2005; Boyle et al., 2009; Victor et al., 2010; Othman et al., 2012) and *safety-critical events* (SCEs), events hypothesized to pose an increased level of risk of a crash (Fancher et al., 1998; LeBlanc et al., 2006; Victor et al., 2010; Ljung Aust et al., 2011; Liang et al., 2012; Paper II; Paper III). These foci are the topic of section 5.4.

It should be noted that it is possible to base an observational study on conveniently-acquired experimental data from an NFOT. However, care must then to be taken to address the potentially confounding effects of, for example, prototype ADASs, or interaction effects between different ADASs (Ljung Aust et al., 2011; Carsten et al., 2013).

One important aspect of driver behavior in relation to traffic safety is that, in most cases, a particular behavior in itself is not enough for a situation to develop into a crash (Paper III). A driver may drive very fast, look away from the roadway for several seconds and drive through a red traffic light– all without crashing. This is, however, true only as long as there are no other road users present to encroach on the path of the inattentive driver's vehicle. More generally, for most traffic crashes, there has to be a mismatch between the driver's actions and the situation (other road users' actions and/or the environment) for a crash to occur (Paper III; Victor et al., 2014).

The two traditional approaches to studying driver behavior, experiments and crash investigation, provide only limited information for identifying and understanding this mismatch (Sandin et al., 2007; Paper II; Paper III). However, once the mismatches are identified, experimental studies can be used to investigate causality, and traditional crash investigations can facilitate human observations (interviews) and kinematics reconstruction (Paulsson, 2005; Seeck et al., 2009; Fagerlind et al., 2010).

NDD can provide detailed data on both the context (scenario) and driver behavior in an ecologically valid setting. This approach facilitates an understanding of the mismatch between driver's actions and on-road scenarios, both in normal everyday driving and in conflict situations (Neale et al., 2005; Paper III; Othman et al., 2012).

In this thesis *data* refers to information collected as part of either a quasi-experimental study (NFOT) or an observational study (NDS). This usage of the word is in line with Victor et al. (2010) and averts the need to coin an acronym.

In their review of the three major categories of on-road studies for traffic safety research (i.e., controlled observations, field operational tests and naturalistic driving studies), Carsten et al. (2013) discuss their benefits, drawbacks and complementary nature. In discussing NDD, they conclude: "Even though the increase in information density is promising, it is necessary to put effort into developing suitable methods, both for data extraction and data analysis" (Carsten et al., 2013, p. 172).

2 Motivation for the thesis

There are four major motivations for writing this thesis. All four focus on methods for improving traffic safety using NDD.

The first motivation concerns legislation. Legislators and other policy-makers in the traffic safety domain need a solid foundation in research to make effective laws and policies. In recent years, analysis of NDD has provided novel information about the prevalence of inattention and distraction, pointing to these as major factors contributing to crashes and near-crashes (Klauer et al., 2006; Hickman et al., 2010b; Victor et al., 2014). In the U.S., legislators and policy-makers have been using NDD for a long time to support the writing of safety regulations. It seem plausible that, in the future, regulations will be increasingly based on the results of analysis of NDD (Victor et al., 2014), rather than on more subjective evaluation or studies with less ecological validity. For example, driving while using cellphones and other nomadic devices is regulated in many countries, although recent studies indicate that some aspects of the use of these devices (talking) may not be as risky as was initially feared, at least under specific circumstances. By revealing how these devices are actually used and how it affects safety, naturalistic driving analysis could provide new ideas for the development of acceptable and effective regulations (Hickman et al., 2010b; Liang et al., 2012; Tivesten et al., 2014a, 2014b; Victor et al., 2014).

The second motivation is education and training based on NDD. To improve safety on our roads, educators can either use NDD directly or just use the results of the analyses. NDD can be integrated into driver education by, for example, providing post-drive performance feedback to novice teen drivers (Lotan et al., 2005; McGehee et al., 2007a; Musicant et al., 2013), in a behavior-based safety approach. The commercial driving industry has found another benefit: appropriate behavior-based coaching (training) can produce substantial savings through the reduction of the cost of both crashes and maintenance (Hickman et al., 2010a; Wege et al., 2013).

The third motivation is the application of NDD to the design of road infrastructure. The data can be used to evaluate driver behavior related to infrastructure solutions intended to improve safety. One such solution is replacing two-lane roads (a single lane in each direction) with 2+1 roads, to facilitate safer overtaking (Carlsson, 2009). A naturalistic driving study could be specifically designed to collect and analyze driver behavior data before and after implementation of a solution on a specific piece of road. Alternatively, analysis may be performed post-hoc (on already available NDS data) by analyzing driver behavior differences on similar stretches of road that differ primarily by having, or not having the infrastructure solution (Hallmark et al., 2013, pp. 9-14). Drivers' behavioral adaptation to new infrastructure designs can also be evaluated more generally. For example, Othman et al. (2012) and Hallmark et al. (2013) have investigated how drivers negotiate curves with different radii.

The fourth and final motivation is to document how NDD can support the development and deployment of ADASs and AD vehicles. More specifically, NDD can contribute to answering the following questions: Which ADASs should the automotive industry focus on developing in order to provide the greatest safety impact in real traffic? How should ADASs be designed to have the greatest safety impact in real traffic? ADAS development has been the focus of the majority of naturalistic driving studies worldwide (General_Motors, 2005; LeBlanc et al., 2006; Reagan et al., 2006; Alkim et al., 2007; Sayer et al., 2008; Smith et al., 2009a; Dozza, 2010).
There are at least three different ways NDD can play a role in the development and deployment of ADAS and AD. First, NFOTs can be used to evaluate both prototype (General_Motors, 2005; LeBlanc et al., 2006; Carsten et al., 2008; VCG, 2013) and on-market (commercially available to consumers;Benmimoun et al., 2011) ADASs/ADs with respect to, for example, system efficiency, driver adoption and driver acceptance. Second, promising areas for future ADAS/AD development (Dozza, 2013; Papers II-III) can be identified, using NDD from studies with and without system evaluation (Neale et al., 2005; Paper III; TRB, 2014b; Utesch et al., 2014). Third, NDD can be analyzed to improve our understanding of drivers' everyday driving, facilitating the quantification of drivers' safety margins in different parameterizations for use in ADAS/AD algorithm tuning (Smith et al., 2009b; Bärgman et al., 2014). Quantifying safety margins is likely to support development that aims to increase ADAS/AD system acceptance.

3 Review and categorization of research on driver behavior based on NDD

This section summarizes my review of driver behavior research that uses NDD, presenting a framework for categorizing the data and their sources (Table 1). The framework is intended to help researchers link their data to appropriate analysis methods, and to contribute to a taxonomy for methods and NDD. Papers I to IV, included in this thesis, illustrate the use of the framework while demonstrating the utility of the various methods.

All NDD are collected in real traffic and share methods of data collection. However, the data can (a) have different origins (e.g., collected for commercial or research purposes), (b) come from different locations (e.g. site-based or in-vehicle) and (c) have different foci for analysis (e.g., normal driving vs. safety-critical events). These three dimensions form the meta-analytic framework for categorizing data and analysis foci (Table 1). The details are presented in the following sections.

Table 1: Categorization framework for traffic safety research based on NDD

Location of data collection	Analysis focus	Data origin	
		Commercial	Research
Vehicle-based	Normal driving		Paper I
	Safety critical events	Paper III, Paper IV	Paper II
Site-based	Normal driving		
	Safety critical events		

The existing literature does not focus on the benefits and drawbacks of the categories comprising the dimensions of the framework, other than the differences between naturalistic observation and experimental data (Carsten et al., 2013). Accordingly, discussion of benefits and drawbacks is reserved for the discussion (Section 4).

3.1 Data collection location: Vehicle-based vs. site-based

NDD has primarily been collected in two types of locations, in-vehicle and site-based. They form the first column of Table 1. The discussion of site-based data is included to fill out the framework with respect to the literature, even though there are no site-based papers included in the thesis, because site-based studies are beyond its scope.

3.1.1 Vehicle-based

Vehicle-based data are collected by acquisition systems installed in vehicles, and stored, at least temporarily, in the moving vehicle. The vehicles are typically driven around as part of the everyday lives of the participants (drivers). The data collected may include GPS, the vehicle bus system (e.g. CAN), accelerometers, radar, and video cameras. The video may be directed toward the cabin, the driver’s face and feet, and forward into surrounding traffic (LeBlanc et al., 2006; Victor et al., 2010; Selpi et al., 2012). Thus vehicle-based data may include data about the driver and/or the vehicle and/or the surrounding environment. It constitutes the most common type of naturalistic driving study to date; in fact, several prominent studies have used this approach. Among them are the 100-car NDS (Neale et al., 2005), the euroFOT (Benmimoun et al., 2011), and the SHRP2 study that is currently (as of 2014) in progress (TRB, 2012; Victor et al., 2014).

3.1.2 Site-based

Data can also be collected at a specific fixed location, for example, an intersection or a specific stretch of road (Saunier et al., 2003; Smith et al., 2009a; Laureshyn et al., 2010; Gordon et al., 2012). I call this *site-based* data collection. Studies using site-based data collection typically do not focus on an individual driver's behavior, but on the aggregate (or exceptional) driving behavior of a population of drivers. For example, by instrumenting intersections with static cameras, researchers can extract vehicle trajectories using image-processing technology. The trajectory data can then be used to summarize driver behavior in aggregate, but it cannot address individual drivers or individual differences across drivers.

Site-based data collection can focus on capturing normal driving and quantifying normal driver behavior (as inferred from observable vehicle kinematics) for specific locations (Smith et al., 2009a; Gordon et al., 2012; van Nes et al., 2013). Alternatively, it can focus on safety-critical events (e.g., crashes and near-crashes) occurring at specific locations. One way the data can be used is to improve enforcement of red-light running regulations. In a study by Aoude et al. (2011), a set of driver models that classify red-light violations were successfully validated using NDD.

Triggered site-based data collection methods are available, storing data only when certain criteria have been fulfilled, i.e. when time-to-collision between two interacting vehicles becomes small or when there is a crash (Yong-Kul et al., 2007). Further, the availability of automated license plate readers (Anagnostopoulos et al., 2006) can facilitate studying individual vehicle trajectories.

3.2 Analysis foci: Normal driving vs. safety-critical events

This section describes the two foci of data analysis. They constitute the second row in Table 1.

3.2.1 Normal driving

Most time spent driving is uneventful from a safety perspective. Drivers quickly learn to adapt to the vehicle kinematics, other road users, and the environment, in order to travel safely and comfortably. I call this *normal driving*. Understanding normal driving (e.g., drivers' comfort zone boundaries; Summala, 2007) is important for infrastructure design, legislation and policy-making, driver education, and the development of ADASs. Normal driving data from NFOT or NDS, together with appropriate methods of analysis (e.g., Paper I), facilitate such understanding.

During normal driving, drivers continuously adapt their behavior to match the ever-changing demands of the traffic situation, by means of both anticipatory and compensatory control (Hollnagel et al., 2005; Engström, 2011). Anticipatory control involves anticipating how the situation will unfold and performing actions such as steering, braking or accelerating to shape it (Neisser, 1976; Summala, 1988; Hulst, 1999; Fuller, 2005; Land, 2006; Lehtonen et al., 2014). Relative distances and velocities between the vehicle, other road users, and the infrastructure are constantly adjusted to maintain the field of safe travel (Gibson et al., 1938).

In contrast, compensatory control consists of actions performed in response to other road users' behavior, kinematics of the driver's own vehicle, or failure to anticipate the unfolding of events (Summala, 1988; Salvucci et al., 2004; Lehtonen et al., 2014). During normal driving, these actions are part of what the experienced driver expects to have to do (for example accelerating or decelerating to accommodate a merging vehicle). As such, compensatory control is generally a routine part of normal driving, shaped by the driver's expectations and observations as events unfold.

To understand normal driving, we need to understand the interplay of anticipatory and compensatory control (Hollnagel et al., 2005; Summala, 2007). Collecting and analyzing NDD allows us to learn more about driver actions and reactions, as well as the resulting interactions between road users and the infrastructure (Lehtonen et al., 2014).

Several different NDD collection strategies can be used for the analysis of normal driving. One such strategy is the collection of continuous data, for example from the time the vehicle is started until it is turned off (LeBlanc et al., 2006; Victor et al., 2010). Another strategy is more selective, capturing only short segments of data throughout the drive, according to some sampling criteria, such as the acquisition of random segments (e.g. 20 s) of in-vehicle data (Aksan et al., 2013), or the acquisition of data within a fixed distance (e.g. 50 m) of a specific intersection (Smith et al., 2009b).

Note that location-based data can be extracted post-hoc from continuous data. That is, data can be extracted around specific locations, for example intersections or curves (Nobukawa, 2011; Othman et al., 2012; Hallmark et al., 2013). If the research focuses on driving maneuvers, i.e. overtaking, lane changes, or car following, data segments before, after, and during these events can be extracted from the continuous data (Sayer et al., 2003).

3.2.2 Safety-critical events

Crashes are rare. This is the reason why the focus of much crash causation research has been crash surrogates, such as near-crashes. The logic to this approach is a hypothesized relationship between the non-crashes and crashes. Hydén (1987) and

Guo et al. (2013) support the existence of this relationship. However, there is a lot of variation in the way non-crashes (e.g., near-crashes and incidents) are defined and categorized. For example, conflict theory researchers primarily classify events based on human estimates of *time-to-accident* (Hydén, 1987; Svensson, 1998): "Time-to-Accident is the time that remains to an accident from the moment one of the road users takes evasive action calculated assuming that they otherwise had continued with unchanged speeds and directions" (Svensson, 1998, p. i). In contrast, most naturalistic driving studies, including the 100-car study (Klauer et al., 2011), the SHPR2 study (SHRP2, 2010), and the ongoing UDrive (www.udrive.eu) study, use a two-stage process to extract what I call *safety-critical events* (SCEs; Utesch et al., 2014). The first stage is automated identification of potential conflicts (SCE candidates) using sensor data, and the second is a visual review of videos of the situation according to a set coding schema. The SCE candidates are classified by whether they are relevant for traffic safety or not (see Section 5.4). This process extracts a set of safety-relevant events consisting of crashes and non-crashes, with the latter used as proxies or surrogates for crashes. There are still major ongoing discussions on how to define crashes and non-crashes in SCEs; or for the latter, the *traffic events that are not crashes but are still safety-relevant* (FOTnet-consortium, 2014; Utesch et al., 2014). This is further discussed in Section 5.4.

3.2.3 On Normal driving vs. safety-critical events

In this thesis I categorize all research that explores SCEs as SCE research, even if normal driving segments are used as baseline data (Hallmark et al., 2013; Victor et al., 2014). Further, I also include research aimed at identifying SCE triggers (Victor et al., 2010) or relationships between event severity and certain driver behaviors like eyes-on-road (Victor et al., 2014).

The difference between normal driving and SCEs may seem obvious. However, as driving is a dynamic and continuous process, both in terms of kinematics and the behavior and state of the driver, the distinction is often murky (Källhammer et al., 2013). Much of the research on normal driving does not exclude SCEs from the analysis of large amounts of continuous NDD, i.e. in the evaluation of ADASs (Benmimoun et al., 2011). Instead, the base rate of SCEs is considered so small in comparison to that of true normal driving that it is assumed to have a negligible effect on the aggregated analysis of normal driving (Källhammer et al., 2013). In this thesis I distinguish between normal driving and SCEs, with the underlying assumption that SCEs are rare in everyday normal driving.

3.3 Data origins: Commercial vs. research data

This section describes and defines the two rightmost columns in Table 1.

In this thesis I distinguish between commercial and research data. In the former, the main aim is typically not to study driver behavior, but to pursue a business model. In contrast, most research studies are aimed at answering a set of empirically falsifiable questions and interpreting the results with respect to issues of traffic safety, i.e., development of an active safety system, design of infrastructure, or policy-making. In this thesis I use the terms *commercial data* and *research data* to identify the origin of the data and the purpose of its collection. The reason for this distinction is pragmatic. The data source (a) determines the rules governing access to the data, (b) defines the selection of both drivers and vehicles, and (c) defines the SCE identification and extraction process.

3.3.1 Commercial data

Commercial NDD is emerging as an important source for understanding why SCEs occur. To date it has received only limited attention (McGehee et al., 2007a; papers II-IV). Preventing or mitigating the consequences of SCEs is a goal of infrastructure design, legislation and policy-making, driver education, and ADAS development.

The business model for a company that conducts commercial data collection is based on one or both of the following two incentives. First, data are collected if and only if drivers (the end users) perceive that they stand to benefit from the data collection (Arai, 2007; Victor et al., 2010; Lich et al., 2012). Examples of incentives for drivers include (a) cheaper vehicle insurance if an event recorder is installed (Toledo et al., 2008; Azzopardi et al., 2013); (b) the belief that recording will lead to exoneration if a crash were to occur, including avoiding lawsuits for causing injuries (Mueller, 2006; Victor et al., 2010); and (c) the potential for leverage against corrupt government officials in some countries (claimed in TV/media in Sweden, 2013).

Second, data are collected when the market provides commercial incentives for both a product/service provider and a buyer (for example, a trucking firm). The buyer’s incentive is typically to (a) have an objective means of proving innocence and reducing legal costs, in the event of a crash; (b) reduce the fleet’s stand-still costs by reducing the number of crashes; (c) reduce the actual repair costs for crashes; and (d) reduce vehicle maintenance costs by diminishing wear-and-tear (for example, on brakes and tires) (DriveCam, 2012; Paper III).

Data collected for commercial purposes are often refined and distilled by the provider. The distilled data is then provided back to the buyer, either as actual data (e.g., video clips and corresponding safety classification), or as a training service for individual drivers working for the buyer (DriveCam, 2012).

3.3.2 Research data

The collection of NDD with a research origin is largely governed by the financing body’s incentives. To date, funding bodies have overwhelmingly been government agencies, at the federal (e.g., European Union or US.. Department of Transportation) or regional (national funding in Europe or state funding in the U.S.) levels. The financing is often motivated by the opportunity to improve traffic safety by (a) identifying traffic safety concerns (Boyle et al., 2009; Uchida et al., 2010; UDrive-consortium, 2014); (b) specifying relationships between safety and a specific factor, for example, a driver, vehicle or environmental condition (Boyle et al., 2009; Hallmark et al., 2013); or (c) addressing known traffic safety concerns, by means of ADAS product development or evaluation (LeBlanc et al., 2006; Sayer et al., 2008; Benmimoun et al., 2011).

3.4 The variety of naturalistic driving data

This section describes the data collected in the various naturalistic studies included in this thesis. Video is an important component in most of the research covered in this thesis. Data without video is beyond the scope of this thesis.

The videos are used to understand the driving behavior of individual drivers, as well as the interaction between drivers and their surroundings. Most naturalistic studies with video are vehicle-based. For site-based data collection, the video is usually collected from cameras on nearby road infrastructure or buildings (Smith et al., 2009a; Laureshyn, 2010), or from mobile towers put in place specifically for the purpose of the study (Gordon et al., 2012).

Most vehicle-based studies with video include at least one camera facing forward and one focused on the driver's face and/or body to identify actions and reactions. However, in some studies only the forward video was available (Lich et al., 2011; Lich et al., 2012). Additional camera views may include (a) a close-up of the driver's face to capture eyes and facial expressions, (b) a view of the driver's feet to capture brake readiness and reaction times, (c) a rear-facing camera to study the effect of trailing vehicles on driver behavior, and (d) side views to capture road users' actions in complex environments such as intersections.
In addition to video, vehicle-based NDD often include records from the vehicle's internal communication bus (CAN; ISO_11898, 2003). This information may include, but is not limited to, the list shown in Table 2.

The availability of the various types of CAN data varies appreciably between projects. Access to CAN data is typically controlled by the vehicle manufacturers and their suppliers, since they all want to avoid reverse engineering and other commercial intellectual property leakage. Practically, data that include proprietary ADASs or derivatives thereof are usually only available to the vehicle manufacturer, the suppliers of the ADAS, and trusted research organizations (Victor et al., 2010).

Table 2: Examples of data that may be available from CAN in naturalistic driving studies

3-axis acceleration	angular rates	steering angle
Brake pedal position	throttle pedal position	use of the clutch
gear selected	turn signal use	windshield wiper status
Ambient temperature	cabin temperature	ambient lighting condition
use of headlights	belt usage	ADAS active (individual)
ADAS settings (e.g. adaptive cruise control headway settings)	ADAS warnings (e.g. lane-departure or forward-collision warnings)	ADAS interventions (e.g. ESP or automatic emergency braking)
button operation (e.g. radio, temperature, built-in phone etc.)	Vehicle speed	

Additional in- or on-vehicle sensors are often added to provide specific information about key features of the interaction between the driver, vehicle and environment, for example: (a) radar for range and range rate to other road users, (b) accelerometers and yaw rate sensors to study drivers' braking, acceleration and steering behavior, (c) GPS to capture the vehicle's position, and (d) traffic sign recognition. Eye-trackers have been used in NDD collection, but it has proven difficult to achieve sufficient quality in the capture of driver's gaze-direction in naturalistic settings (Victor et al., 2010; Victor et al., 2014). Additional range and range-rate add-on sensors are often also added, because vehicle manufacturers and their suppliers may not be willing to share the CAN data from radar, even when they are available.

For commercially-based collection, data are usually limited to a maximum of two cameras (one forward and one on the driver), two or three accelerometers, and GPS. Research data is often collected at 10Hz or higher, while commercially-collected data usually has a lower sample frequency, such as 4Hz.

In research studies, questionnaires are often administered to participating drivers to complement in-vehicle sensing. In addition to standard questionnaires collecting background information about the drivers (e.g., demographics), commonly used questionnaires include (a) the Driving Style Questionnaire, DSQ (French et al., 1993), and (b) the Manchester Driving Behavior Questionnaire, DBQ (Lajunen et al., 2003).

For site-based collection, radar can be used to ascertain approach speeds and relative positions of multiple vehicles (Chan, 2006). It is also possible to collect NDD without video by capturing only the vehicle speed and position (e.g. GPS; Mononen et al., 2012).

Finally, NDD are often complemented by data from external sources, i.e. map data attributes (e.g., road type and number of lanes) via map matching through GPS positions, or compared with crash databases with respect to location (LeBlanc et al., 2006; Victor et al., 2010).

4 Summary of papers

This chapter summarizes the papers appended to the thesis.

4.1 Paper I

Objective: Paper I developed and presented a method, *chunking*, that facilitates robust and comparable results in the analysis of continuous NDD.
Background: NDD have been available for only a limited time and to only a few researchers. Methods to facilitate appropriate analysis are needed now that NDD are beginning to be more readily available, because traditional methods neglect the impact of segment length and its potential to significantly bias results. Segment length is the section of continuous data upon which an operator is applied to extract a performance indicator (e.g. standard deviation of lane position). The chunking method corrects this source of bias and is appropriate both for basic driver behavior research and for the development and evaluation of Advanced Driver Assistance Systems.
Method: The chunking method is designed to be used when the aim of analysis is to create aggregate measures of continuous NDD across trips or entire conditions (for example). Chunking divides the datasets into equivalent subsets of data (called chunks) before other calculations are applied. The main benefit of the method is the robust and consistent calculation of parameters when analyzing continuous NDD, although care has to be taken to account for sample dependencies and auto-correlation. Examples of the application of chunking are presented, and results are compared with traditional methods of analysis.
Results: Results show large biases in statistical results with traditional methods, , which were reduced using the chunking approach. As an example, in a set containing 399 driving hours of NDD, 75% <u>of the data</u> were in segments longer than 100 s although 75% <u>of the segments</u> were shorter than 100 s. The choice of appropriate chunk size was a key to robust results.
Conclusion: Prior to this paper, very little research had been aimed specifically at addressing the methodological issues of analyzing continuous NDD. The results show that neglecting chunking can introduce large biases in statistical results. Using chunking is advisable in many cases, but the effects of auto-correlation and sample dependencies must be still be considered.
Application: Chunking is appropriate wherever aggregation across segments in NDD is being considered, particularly when extracting an indicator (e.g. standard deviation) that is sensitive to segment length.

4.2 Paper II

Objective: Paper II had two aims. The first was to develop a method to use NDD with video to improve understanding of the pre-crash phase of incidents, near-crashes and crashes. The second was to apply the method to car-to-pedestrian incidents and identify the implications of the aggregated causation patterns for ADAS design.
Background: Development of appropriate countermeasures to pedestrian crashes requires an understanding of which factors contribute to the occurrence of crashes. Naturalistic driving studies provide detailed information about observable driver behavior that traditional crash data collection methods cannot provide. To my knowledge, this is one of very few papers published to date (2014) that uses expert-assessment of video data of naturalistic driving to investigate crash-contributing factors.
Method: Data were collected in Japan during business trips by a fleet of 60 company-owned cars in more than 16 urban areas. The data were analyzed using a modified version of the Driving Reliability and Error Analysis Method (DREAM) (Sandin et al., 2007; Wallén-Warner et al., 2008). The inclusion of video and time-series data called for modifications to the method, chief among them being: a contributing factor was added for pure surprise events, descriptions were changed to clarify interpretation when video and time-series were available, and examples and guidelines for the application of DREAM to pedestrian conflicts were added. The time-series data of the involved road users' actions were annotated for each event, using the forward and driver video. A text narrative of the event was also created. Events were divided into three distinct scenarios: (a) the driver of the instrumented car was going straight through an intersection, (b) the driver was turning (left or right) in an intersection, and (c) the driver was going straight along a road with no intersection. DREAM aggregation charts were created for each scenario.
Results: For the first scenario, misdirected attention was cited in 26 events. In eight of these, the drivers were engaged in activities irrelevant for safe driving, such as using a mobile phone. For both the first and second scenarios, the most common critical event (17 of 36 and 17 of 20, respectively) consisted of the driver braking hard to avoid a collision. For the second scenario, the conflicting pedestrian was not seen by the driver early enough to avoid the need for an evasive maneuver in 16 instances. In seven of these, the pedestrian was occluded. Finally, for the third scenario, in 19 of 31 events the driver began the turn before the intersection was clear. In 27 events, the driver was deemed to have misjudged the situation; a conflict pedestrian, occluded by vehicles or other pedestrians, was involved in 24 of them. In only one event in this scenario was the driver looking at something inside of the car (irrelevant for safe driving).
Conclusion: This paper successfully applied a modified DREAM method to incidents with video. The analysis showed that a majority of drivers misunderstood the pre-crash situation, due to attention allocation towards something other than the conflict.
Application: The results in this paper are directly applicable to the design of ADASs. They could also be used to guide infrastructure design, such as intersection layout and traffic control.

4.3 Paper III

Objective: Paper III investigated the role of driver inattention in crossing-path intersection crashes and rear-end crashes.

Background: The contribution of drivers' inattention to traffic crashes is not well understood. Data from traditional methods do not have the requisite fidelity in the pre-crash phase to allow detailed analysis of driver inattention. NDD (e.g., time-series data with video) have emerged as a promising method for studying the unfolding of pre-crash events. However, most naturalistic driving studies record only a few crashes, if any. In contrast, commercial on-board safety management systems (OBSM) record quite a few actual crashes. OBSM devices are typically mounted in commercial-fleet vehicles and collect accelerometer data, video of the forward roadway and often also video of the driver, for a period of time around crashes and other safety-critical events. These data can provide a lot of detailed information for the study of which factors contribute to the occurrence of crashes (e.g. inattention or occlusion).

Method: A total of 133 real-traffic crash events involving vehicles instrumented with the DriveCam (now Lytx) OBSM system were analyzed. The events were drawn from two scenarios: 70 rear-end crashes where the OBSM-instrumented vehicle was the striking vehicle, and 63 crossing-path intersection crashes where the instrumented vehicle intended to drive straight through the intersection. Annotation of the 133 video sequences included (a) driver actions and visual behavior, (b) whether there was occlusion of the other (conflicting) vehicle, and (c) reconstruction of optical parameters (distance and relative speed between the two vehicles) in the rear-end events (as described in Paper IV). An event-coding scheme was developed for qualitative expert assessment of factors contributing to the crashes. The scheme was partly based on work by Habibovic et al. (2013) (Paper II) and by the EU-US inattention taxonomy group presented in Engström et al. (In preparation). The experts who applied the coding scheme used both qualitative information about the event (e.g. video and narratives) and quantitative data extracted from accelerometers, GPS and video annotation. When all events for rear-end and intersection crashes had been coded, all codings were aggregated.

Results: Inattention, especially in terms of taking the eyes off the forward roadway, was identified as a primary contributing factor to rear-end crashes. For intersection crashes (where the study vehicle was going straight), inattention was not as prevalent. Instead, occlusion of the conflicting vehicle and insufficient safety margins were identified as key factors.

Conclusion: Commercially collected event-based data (with video) can provide an unprecedented, detailed view of the unfolding of the few seconds before a crash, giving us new information about pre-crash behavior. The role of inattention as a factor contributing to crashes strongly depends on the scenario and crash type.

Application: A deeper understanding of the role of inattention in crashes could improve legislation, as well as the design of behavior-based safety systems and other safety measures.

4.4 Paper IV

Objective: Paper IV presents a method for extracting optical parameters related to a lead vehicle, from the following vehicle driver's perspective. The method is applied to video collected using event-based NDD.

Background: Traditionally, research into crash causation has primarily focused on post-crash reconstruction: interviews and controlled follow-up experiments have been used to study suspected causation mechanisms. Commercially-collected NDD collection of crashes with video are now slowly becoming available to researchers, providing a database for time-series analysis of the pre-crash phase of actual crashes. Analyses of these data will likely facilitate further understanding, both qualitative and quantitative, of the mechanisms or factors contributing to crashes. This paper describes an annotation method that consists of using manual measurements taken from the video screen to reconstruct optical parameters and range to a lead vehicle, from a the perspective of the driver of the following vehicle.

Method: Video data of the rear of a stationary passenger car of known width were collected for a set of 14 different ranges, by means of the forward-looking camera of a DriveCam (2012) system. The optical parameters of the camera were extracted, and a model was created that rectifies the intrinsic distortion in the image. For method validation, twenty participants manually measured the on-screen size of the vehicle, and the errors between coders for different distances were analyzed. The model was used to predict the distance between the cars and the results were compared to the actual range data.

Results: The results indicate that the method is useful when the distance between the two vehicles is relatively short: when they are less than 10m apart, the range estimate is within 10cm of the actual distance. However, incorrect estimation of the lead-vehicle width contributes significantly to range estimation errors. For optical parameters, on the other hand, optical rectification errors are likely to be the main source of error.

Conclusion: Parameter estimates using the proposed method are good for short distances between the two vehicles. At longer distances it should be used with care. The method is relevant for event-based NDD with video when image processing competence and tools are not available, and could be used as validation material for other methods.

Application: This method can play an important role in research exploring why lead-vehicle conflicts occur, and thus in the development of safety measures to reduce the number of and severity of crashes.

5 Discussion

As naturalistic driving studies have emerged, their data have become available to a larger community of researchers, and new data collection and analysis methods have had to be developed to exploit this wealth of information. It is important that these tools are made available through scientific publications. This thesis describes approaches to overcoming some specific methodological challenges, the benefits och these approaches, and some of the obstacles that remain. These descriptions are put in the context of the framework described in Table 1.

This chapter discusses the benefits and trade-offs associated with the analytic framework in Table 1. The framework addresses three dimensions of naturalistic driving: (a) data collection location, (b) analysis focus, and (c) data origin. This review relates each dimension to the analysis of NDD and to the papers included in this thesis. The chapter concludes with brief discussions of the implications of my research on sustainable development.

5.1 Data collection location: Vehicle-based

The collection and analysis of vehicle-based NDD have boomed in the last few decades. A wide variety of methods have been applied in the analysis of this data, in an ongoing effort to improve the design and evaluation of the different safety measures described in Section 1.2. A sampling of methods can be found in Klauer et al. (2006), (McGehee et al., 2007a), McLaughlin et al. (2008), Hickman et al. (2010b), Nobukawa (2011), Othman et al. (2012), and Victor et al. (2014).

The detailed analysis of vehicle-based NDD is relatively new, and there are relatively few documented methods available. A review of the literature suggests that the framework presented in Section 3 (Table 1) may be the first published attempt to categorize the variety of methods for analyzing and collecting NDD.

Table 1 categorizes the papers included in this thesis. Papers I and III introduce novel methods, while Papers II and IV apply existing methods that had not previously been applied to vehicle-based NDD. The following sections briefly describe the four papers.

Paper I presents a procedure for reduction of bias in the results from the analysis of normal everyday driving using vehicle-based NDD. In previous studies, it is often unclear how performance metrics such as standard deviation of lane position (SDLP) have been calculated for segments of NDD of different lengths (LeBlanc et al., 2006). Moreover, the segments for which SDLP is calculated are shorter than the length that Paper I argues is optimal for robust analysis (Peng et al., 2013). In both instances, the method developed in the paper to optimize chunk duration would likely facilitate more transparent and robust results.

The methods presented in Papers II to IV address the identification of factors that may be associated with crash causation. Like the data in Paper I, the data used in Papers II to IV are collected by sensors inside the vehicle. However, unlike the data in Paper I, the data in Papers II to IV are not samples of normal everyday driving data but rare events classified as SCEs, collected from inside the vehicle. Further discussion on SCEs can be found in Section 3.2.2.

The methods presented in Papers II and III support the identification of both the driver behaviors and the factors in the traffic environment that contribute to the occurrence of crashes and other SCEs. For example, a review of the literature found that previous studies seeking to explore the role of visual occlusion in crashes had to rely on involved road users' memories of the event as obtained through interviews (Sandin, 2009; Seeck et al., 2009), due to a lack of "objective" data of the event. The methods in both Paper II and III, however, address visual occlusion in relation to SCE occurrence from a perspective similar to that of the driver of the instrumented vehicle by facilitating the detailed study of how an SCE unfolds. Another example of the usefulness of these methods concerns the influence of the mere presence of other road users on the occurrence of SCEs. Traditional crash databases and in-depth crash studies do not have sufficient data to identify when or how other road users' presence may be contributing to crashes (Van Elslande et al., 2007; Chalmers, 2014; NHTSA, 2014). In contrast, vehicle-based NDD with video provide a detailed (frame-by-frame) visualization of 1) when and for how long the driver looks towards other road users, and 2) how other road users may occlude the principle other vehicle (Paper III). Thus, all papers in this thesis highlight some of the potential of NDD, when appropriate methods are applied.

Traditional traffic safety data from real roads, such as in-depth crash investigations and crash statistics, lack the detailed record of the unfolding of the crashes (and other SCEs) that vehicle-based NDD can provide. Thus, I believe there is a wealth of information hidden in the datasets of vehicle-based NDD that has yet to be fully realized, due to a limited understanding of the data's potential and which methods to use.

5.1.1 Benefits and drawbacks

Vehicle-based data collection facilitates detailed studies of individual drivers' behavior. Possible research areas include, for example, driver actions and reactions, between and within subject studies, driver behavior over a wide variety of everyday scenarios, and drivers' interactions with the infrastructure and other road users from the drivers' perspective.

There are three main drawbacks of vehicle-based collection. First, installation of the data acquisition and sensoring equipment can be quite expensive. Often, budgets permit only a limited number of vehicles to be studied. As a result, there are few crashes available for analysis, with a somewhat larger (but not large) set of non-crash SCEs (e.g., near-crashes). Even when data from the SHRP 2 (TRB, 2013) study is used, in which over 1000 crashes were collected, after the crashes are stratified into specific crash scenarios, the number of crashes in each group is still small. To address this deficit of data, I advocate the use of data from an untraditional source: commercially collected data (see section 3.3.1 and 5.5). Although their use only allows convenience sampling, and the datasets may include only a limited amount of data (which have a relatively low sample frequency), the large number of crashes facilitates detailed analysis of the pre-crash phase of real crashes, including stratifying them into specific crash scenarios (Paper III). The small number of crashes in research-based NDD typically makes stratification unfeasible.

The second drawback is that, when using near-crashes as surrogates for crashes, care has to be taken to avoid selection bias. The potential for bias increases with the use of commercially collected data, because the researcher has no control over the sampling of the SCEs (safety-critical events, see Section 3.2.2). The literature review revealed only a peripheral discussion on how SCE selection bias affects the generalizability of results (Wu et al., 2012; Jonasson et al., 2014). The discussion in Paper III on research control is important for future research using commercially collected data.

Finally, due to the large amounts of data, quality assurance and data validation are difficult and consume relatively large portions of the available funding. Range and range rate data from radar deserve special attention with respect to data quality in naturalistic driving studies. Although radar has been available in several NDS studies, the quality of range and range rate data has been quietly debated in the research community. In the Victor et al. (2014) study of SHRP2 data, the radar data was considered so poor that the method presented here in Paper IV was used to extract range and range rate data instead.

5.2 Data collection location: Site-based

Site-based NDD collection has received less attention than in-vehicle data collection in the research community, and none of the papers included in this thesis analyzed site-based NDD. However, the site-based approach is promising, especially for understanding how changes to infrastructure design impact traffic safety. The deployment of mobile site-based data collection units provides an opportunity to analyze behavior patterns and SCE occurrences before and after a design change. The designs can then be refined as necessary and properly implemented (Gordon et al., 2012). In addition, future research (for example, that of Laureshyn (2010)) aims to study and document road-user behaviors in a naturalistic setting for the purpose of traffic safety research

It should be noted that red-light-running cameras store not only violations and license plates, but also information such as speed and traffic density; this, too, is site-based NDD. 'Although this presents a possibly useful source of traffic safety information for future research.

5.2.1 Benefits and drawbacks

There are three main benefits of site-based data collection. First, a large number of vehicle trajectories can be collected for a specific data collection site, allowing for detailed aggregate driver behavior (as can be observed by vehicle kinematics) at that site. Second, with a limited instrumentation effort, triggered site-based collection has the potential to collect large amounts of safety-critical events at sites identified as risky. This information could lead to the design of appropriate countermeasures for that site (as well as for similar sites).Third, site-based collection can efficiently evaluate individual infrastructure designs or other safety countermeasures, either across sites or at a single site with a before-after study design.

The main drawbacks of site-based data collection are also threefold. First, an individual driver's behavior inside the vehicle cannot be studied. Second, the data quality has been generally very low, leading to challenges due to insufficient resolution and precision. For example, it is very difficult to calculate road-user trajectories from the site-based video because of poor resolution. To date, hardware requirements and tracking algorithms have limited the feasibility of conducting academically sound research with site-based NDD. Nevertheless, some studies (e.g. Gordon et al. (2012)) show promising results. A third disadvantage is that the base rate of SCEs is very low (as it is for vehicle-based NDD); thus, false positives from tracking and data quality issues can easily overwhelm the analysis. Improved vehicle-tracking algorithms and data verification procedures are sorely needed, if site-based collection is to be used extensively for research on driver behavior.

5.3 Analysis foci: Normal driving

Research questions addressing normal driving from the perspective of traffic safety are highly diverse. Examples from the UDrive project (UDrive-consortium, 2014) include: (a) What driver characteristics (e.g., age, gender, annual mileage, and personality factors) influence speed choice? (b) What driver characteristics influence car-following behavior and reaction time to the lead vehicle? and (c) To what extent are driver assistance systems and seat belts used? (Utesch et al., 2014). Other questions require the classification of different driver errors according to some coding schema (Stanton et al., 2009). Most of these questions need actual driving data, while other research uses focus groups and surveys to elicit driver errors (Blockey et al., 1995). There is a need to develop guidelines or a framework indicating what analysis method is appropriate for what data, and what the limitations are.

The chunking method presented in Paper I facilitates the robust and consistent calculation of parameters and minimizes bias when analyzing NDD. Thus it is highly relevant for most research which involves a continuous metric (e.g., speed, lane position, head-way) and the application of an operator (e.g., standard deviation, minima, maxima or mean) over segments of discretized continuous data.

5.3.1 Benefits and drawbacks

Studying normal (baseline) driving in the context of traffic safety research has many benefits: (a) the identification of the prevalence of appropriate vs. risky behavior, (b) the quantification of comfort-zone boundaries in a variety of scenarios in everyday driving, and (c) the study of baseline, drivers' vigilance and fatigue. These benefits can be used to improve policy-making, driver training, ADAS design, and the development of AD solutions. For example, Paper I explicitly shows the benefit of the chunking method in the calculation of the performance indictor *standard deviation of lane position* (SDLP). In Paper IV, chunking is shown to be an attractive alternative to the high-pass filtering of lane position data, used in previous studies (Östlund et al., 2005) to deal with the bias caused by different segment durations.

One possible drawback of studying only normal driving is that it may not provide much information about driver behavior in the crucial few seconds just prior to crashes, which is often needed during the development of safety measures.

5.4 Analysis foci: Safety-critical events (SCEs)

In section 3.2 the traditional, pragmatic approach to extracting SCEs is described as a two-step process: (a) automated identification of potential conflicts (SCE candidates) based on sensors; and (b) a visual review of videos of the situation according to a set coding schema, classifying the SCE candidates by whether they are relevant for traffic safety or not. In this section I describe the process in more detail, pointing out benefits and drawbacks. However, I will start with describing a less pragmatic and what, I argue, is a more scientifically rigorous definition of SCEs.

An SCE occurs when, and only when, the following three criteria are met for at least one of the involved road users. First, the drivers' expectations of the situation and their corresponding actions do not match the actual situation. Second, the involved road users would have acted differently had they anticipated the actual unfolding of the situation. Finally, the outcome of the event has the potential to produce bodily harm and/or some level of property damage (which needs to be defined), if the driver doesn't react. Thus, hitting a squirrel on a highway, very low-speed impacts (e.g., parking damage), and most curb strikes are examples of events that most people would not consider to be SCEs.

By this definition, SCEs are based on hindsight, and exclude events in which the involved road-users voluntarily enter into the conflict situation. One example of an

SCE is a driver reaching an intersection with the right-of-way, as another road user is encroaching without yielding. In this situation the driver's expectations (and actions) do not correspond to the actual situation; any driver who knew that the road user would be entering the roadway would probably have acted differently. Using these criteria, the encroachment by the other road user qualifies as an SCE.

Drivers' reactions to SCEs are primarily compensatory, but may also include anticipatory components in, for example, the choice of evasive actions. An example of the latter is the aiming for the hind legs of a moose, instead of trying to pass in front of it as it crosses the road. That is, similar to normal driving, SCE involvement is likely to include both anticipatory and compensatory components. Therefore the concepts of anticipatory and compensatory control can't be used to differentiate between normal driving and SCEs. Instead, the difference is that, in normal driving, the unfolding of the situation matches the driver's expectations, while, in SCE involvement, the driver is not expecting what is actually unfolding.

Unfortunately, data about driver expectations cannot be collected in NDD, at least not with today's data acquisition technologies. Expectations may possibly be inferred from driver actions (Räsänen et al., 1998) as an intervening variable, but there are no *expectation data* that can be used to find SCEs in NDD.

Because we lack both expectation data and rigorous, accepted metrics for quantifying the risks for injury or property damage of individual SCEs, we must make some compromises in the identification and extraction of SCEs.

Although practically all studies using SCEs to date manually review the relevance of the SCEs with respect to safety, no structured, peer-reviewed validation of the method was found in a literature review. This is not surprising, since the visual review of video to classify SCE relevance so far has been a subjective process (see, e.g., the projects Dingus et al., 2006; TRB, 2013). It is not likely that the research community will come to a consensus on these definitions, or that an objective definition of SCEs and safety criticality will be found any time soon.

5.4.1 Benefits and drawbacks

This section describes the strengths and weaknesses of different options in the two-step process of SCE identification, the automatic extraction of SCEs and the visual review of video from NDD. It is important to consider the pros and cons in relation to the aim of the study, when deciding to adopt a particular approach.

The first step is the implementation of sensor-based triggers, which I call SCE triggers. The two main types of SCE triggers are kinematic triggers (e.g., acceleration or jerk thresholds) and proximity triggers (e.g., time-to-collision or time-to-lane-crossing thresholds) (Victor et al., 2010). The events identified by applying SCE triggers are called SCE candidates. Kinematic triggers have a critical, specific disadvantage: they miss SCEs if the driver does not perform an evasive maneuver. The disavantage of proximity triggers is that they miss SCEs whenever sensors fail to capture the other road user's behavior. The fact that sensor-based triggers miss some SCEs is the main criticism of the automatic extraction of SCEs from vehicle-based NDD. Unfortunately, this is an inherent limitation of NDD; no one (not even a graduate student) can watch every second of the recordings of every trip driven. Even if every second could be watched, many true SCEs would still be missed, due to, for example, lack of expectation data. However, because we are aware of this limitation, conclusions can be presented with the appropriate caveats.

In the second step of SCE identification, the SCE candidates are subjected to a visual validation review. Each individual SCE is subjectively evaluated for its relevance to traffic safety. Since the review process is sensitive to inter-rater reliability, a multi-rater regime with inter-rater evaluation is often employed (Klauer et al., 2011). The review process often includes categorization of the SCEs into different levels of severity, i.e. crashes, near-crashes, and various levels of incidents.

There are at least three issues with the visual review of SCE identification. First, it is difficult to define the different levels of SCEs in a way that entirely eliminates ambiguity. Second, since naturalistic driving includes all types of interactions between drivers, there are often events that can't easily be categorized. Third, the research community has yet to agree on a common set of definitions to guide visual review of SCEs. This makes comparison across studies difficult. Unfortunately, there are few (or no) alternatives to the two-step approach when studying why crashes happen using research-based (see section 5.6) NDD.

Traditionally, the safety relevance of SCE candidates is decided by annotators judging the criticality of the scene, based on videos taken by cameras mounted in or on the car and pointing outward. This approach forces the annotators to use their experience in interpreting the scene. An alternative approach has been used in a few studies that primarily study the reaction of the driver instead of the traffic and the scene. This approach creates a driver-centered definition of SCE. When a facial expression or change in body posture reveals surprise ("oops") or even dread, the driver is likely to be experiencing an SCE (Dozza et al., 2013). There are two main issues with this approach: the variability of drivers' surprise reactions may bias the SCE selection towards a certain type of driver, and drivers who did not see the critical situation will show no reaction by which the event can be identified. Although the driver-centered *oops reaction* approach cannot claim to produce objectively relevant SCEs, it does provide a means of avoiding having annotators interpret a wide variety of situations. The oops reaction can be seen as an indirect measure of a mismatch between the driver's expectations and the unfolding of the event.

The use of drivers' expectations as a component in the definition of SCEs may be criticized because objective severity is not considered, and SCEs may differ across cultures. For example, in China, France, or Italy, drivers are likely to expect closer calls and more aggressive driving than drivers in Sweden, U.S.A., or Germany. The debate on SCE definitions will continue. If the aim of a specific SCE analysis is to study normative aspects of driving, the more traditional approach to SCE operationalization (Klauer et al., 2011) may be more appropriate. Cultural differences between annotators is a fundamental issue with my proposed SCE definition as well. However, unless video annotators across all studies are trained by the same teacher, the effect of cultural or regional differences in annotators' classifications of SCEs is likely to be present even in the traditional classification (Neale et al., 2005; SHRP2, 2010).

To sum up, traffic safety research benefits in many ways from studies that use naturalistically collected SCE data. First, data about the unfolding situation can be found in the few seconds just before a critical event (precisely the time when active safety systems are assumed to have the highest benefit). Second, driver behavior can be studied throughout the unfolding SCE. Third, it is possible to make comparisons between crashes and near-crashes and/or between SCEs and baseline (normal driving). Analysis of SCEs from NDD has the potential to improve the design of policy-making and legislation, driver training, infrastructure, ADAS, and AD systems.

None of the papers in this thesis explicitly address methodological aspects of SCE selection. In Papers II and III we use convenience sampling to acquire and analyze SCEs. The methods in both papers are applicable to a variety of different SCEs. Paper III discusses researchers' lack of control over the basic sampling procedure and the selection bias inherent in commercially collected data from projects in which the drivers take part in safety coaching (Lytx, 2014).

The drawbacks of collecting SCEs from NDD are that the identification of relevant SCEs is difficult and subject to selection biases, and there are very few crashes (particularly in research data). The validity of the assumed relationship between near-crashes and crashes is therefore often crucial.

5.5 Data origins: Commercial data

Access to commercial data is governed by contractual as well as purely commercial considerations, including agreements regarding the use of the data. Given the nature of capitalism, a commercial data provider (Lytx, 2014; SmartDrive, 2014) is likely to grant external researchers access to their data if and only if it receives a direct financial benefit. Examples of such benefits are: branding of company name as safety-conscious, which can provide a competitive advantage; and refinement of the products or services as a result of the research findings. It is not likely that a company would release data for research if there are potential conflicts with respect to the use of the data at any time in the future. However, from my perspective the benefits for the companies releasing the data (e.g., positive publicity, brand development and product refinement) are likely greater than the potential drawbacks, discussed in the following section.

5.5.1 Benefits and drawbacks

Other researchers have made limited use of commercial data. In our research, both in this thesis and in Paper III, we have discussed the benefits and drawbacks of using commercial data. This section distills what we have learned, to guide future users of commercial data.

There are several benefits of commercial data. For one thing, the data collection does not need to be government-sponsored (McGehee et al., 2007a; McGehee et al., 2007b; Lich et al., 2012; Paper III), so there is a potentially large cost savings to the researchers and society. Furthermore, because the providers generate income with each vehicle installed with the data collection system, they strive for a large number of vehicle installations, so a large number of SCEs are likely to be collected. With a large number of SCEs, not only can crashes can be sub-categorized (stratified) and studied in detail (Paper III), but the similarities and differences between crashes and near-crashes can be established more readily.

There are five main drawbacks to commercial data. First, the vehicle selection cannot be controlled by the researchers. Second, the initial event selection procedures are not set by the researchers (Hickman et al., 2010b, p.; Paper III). Third, the fidelity of the data is usually lower than researchers would prefer, with limited sensing equipment and low sample rates (Paper III). Fourth, the drivers studied are likely to be taking part in a behavior-based safety program and thus their behavior may not be representative of the general population (Paper III). Finally, baseline data from normal driving are usually not collected, since a traditional control group is likely not part of the business model of the service providers.

One implication of the lack of a baseline (control) in commercial data is that in order to perform risk calculations, non-traditional controls must be used. For example, to calculate risk, Hickman et al. (2010b) use events kinematically triggered by the in-vehicle system, but not classified as safety-related, as controls. Continued method development is needed to establish effective baseline-selection methods and validate their use in risk calculations.

5.6 Data origins: Research data

Access to research data is governed by the contractual agreements with the financing body and the partners in the project. In most cases, research data have been accessible only to the partners in the project in which they were collected. However, data from two ongoing projects-- UDrive (UDrive-consortium, 2014) in Europe and SHRP2 (TRB, 2014b; Victor et al., 2014) in the U.S.-- are going to be made more readily available to researchers unaffiliated with the projects, when and as long as ethical and privacy issues are adhered to. Other projects are expected to follow this open approach. For example, the European Commission has adopted a scientific information package on open access to data from projects it has funded (European_Commission, 2014).

The benefits of research data are that: (a) sensing suites, connectivity, data acquisition and other vehicle instrumentation are usually extensive (e.g., CAN bus and radar; Dingus et al., 2006; Selpi et al., 2012; TRB, 2014a), (b) sample frequency and sensor fidelity are typically high, (c) both normal driving (baseline) and SCEs are usually captured (Victor et al., 2010; Benmimoun et al., 2011), and (d) researchers can define vehicle, driver selection, and SCE extraction criteria.

The primary drawback with research data is that data collection is expensive. As a result, the dataset typically contains only a small number of crashes (and other SCEs), and data analysis tends to receive a relatively small share of the budget. The qualitative methods presented in Papers II and III address this drawback, since they are to some extent applicable to all forms of SCEs (not just crashes), and can profitably be used on datasets with relatively few crashes. To my understanding there are currently no other methods that use qualitative analysis of time-series data and video in NDD to identify the factors and mechanisms that contribute to crashes and other SCEs. Thus, these papers make a strong scientific contribution to traffic safety research by providing two alternative and structured expert-assessment approaches to identifying factors and mechanisms that contribute to the occurrence of SCEs.

5.6.1 Implications of the commercial/research dichotomy

In general, commercial data has a much higher probability of providing a greater number of crashes and near-crashes than research data. The main reason for this is that the former has a business model unconnected to pure research, while the latter is connected to the need for government sponsorship. Most providers of commercial data include data collection as a main part of their business model. They want to expand and ultimately earn more money. The business model for such companies may not align with the aims of researchers, who want to analyze the data to understanding the underlying behavioral mechanisms in order crashes to develop different safety measures, such as legislation and safe infrastructure designs. Thus it is important for researchers and governments to show the providers of commercial data that collaborating adds value to their business model. I argue that Paper III demonstrates the relevance of commercial data for developing behavior-based safety services, and may support the development of other safety solutions as well - supporting safer driving on our roads. The analysis in the paper takes us one step closer to convincing commercial-data providers of the benefit of releasing data for traffic safety research.

Analysis of data with a research origin has been performed for several decades, while analysis of commercial-origin data for traffic safety research is relatively new and has been performed by only a few researchers. However, I foresee an increase in the use of data with a commercial origin in the next few years. Analyses of these data are likely to raise our awareness about crash causation in general and the role of the driver in particular. Methods must be further developed and refined (Paper I-IV) for both types of data analysis to deal with some of the drawbacks identified in this thesis.

5.7 Sustainable development

The ultimate aim of automotive safety research (and this thesis) is to reduce the number of fatalities and injuries on roads to zero, in line with the Swedish Vision Zero (Tingvall et al., 1999). Any safety measure that reduces the number of fatalities or severe injuries on our roads has huge sustainability implications. Specifically, any part of my research that saves lives or reduces injuries will provide a higher quality-of-life both for those directly affected and for their friends and relatives. Furthermore, the added productivity and functional-years (Levinson et al., 1998) increase the impact of the research on sustainable development event more. Human suffering and grief due to traffic crashes are well in line with the category Life Support in sustainable development (Kates et al., 2005). For the individual, the research presented in this thesis has no (or few) drawbacks. That said, one potential drawback may be a larger environmental footprint of products promoting traffic safety.

The economic benefit of reducing the need for health care and of avoiding loss-of-functional years (Guria, 1993) for killed or disabled people is also large. The financial benefits to society of saving a large fraction of the 3.9 million lives forecast to be lost in traffic by 2030 (WHO, 2008),would be immense.

ADASs have great potential to contribute to sustainability in the long term, but a possible drawback of this research is that, in the short term, ADAS implementation may add weight to vehicles. This in turn may increase fuel consumption and the use of raw materials. In the long term, it may be possible to replace large amounts of steel and other material in vehicles, which today are needed to protect vehicle occupants, with lighter material. If ADASs and AD systems get to the point where crashes rarely happen, or occur only at low speeds, vehicles can be made very light. Lighter vehicles require less energy for propulsion. There will continue to be a demand for ground transport solutions in the future, and the technologies and knowledge that are provided within the safety research domain are not inevitably tied to the fossil fuel vehicles of today and can easily be ported to other modes of transport. Finally, ADASs are promoted by the automotive industry to improve their vehicle sales. This is a part of local and global economic growth, which is another key aspect of sustainable development (WTO, 2001).

6 Conclusions

This thesis presents an overview of traditional and new methods for the analysis of NDD with the goal of enhancing traffic safety, and examines a variety of sources of NDD used in such analyses. The papers included in the thesis are complemented by a novel framework that organizes methods and data used in traffic safety research. In accordance with the aim, the thesis has provided new methods capable of taking advantage of the vast store of information in NDD to improve traffic safety, particularly in terms of (a) facilitating robust analysis of continuous NDD, and (b) providing tools to understand why crashes and near-crashes occur. Furthermore, the framework is intended as an aid for future researchers, clarifying the advantages and disadvantages of various choices they will be making, in order to guarantee the optimal methods and data sources for the project at hand.

The papers included in this thesis make several contributions to traffic safety research. Paper I presents a novel method, chunking, that addresses the methodological issues inherent in the analysis of continuous NDD. Specifically, chunking mitigates the effect of size bias due to different segment durations, facilitating the robust analysis of continuous NDD.

A second contribution, from Papers II and III, comprises methods for identifying factors contributing to the occurrence of crashes and other safety-critical events, based on expert assessment of NDD with video. The methods were applied to research-based (Paper II) and commercially collected (Paper III) NDD. It was shown that inattention is a main contributing factor to rear-end crashes, while occlusion and insufficient safety margins are key factors for intersection crashes. A further contribution by Paper II is its successful application of a method originally developed for traditional in-depth crash investigations to NDD with video. Paper III further contributes by being the first study, to our knowledge, to analyze commercially collected event-based data of crashes to identify factors contributing to crashes.

Paper IV contributes to traffic safety research by presenting and validating a pragmatic approach to extracting optical parameters and range to the lead vehicle from video captured in the following vehicle, in rear-end, safety-critical events. The method is especially useful for event-based NDD with video when the video frame rate is low and image processing is not a realistic option.

In summary, this thesis provides a foundation for future analyses of NDD. It presents a set of novel analysis methods and demonstrates their successful application to a variety of NDD sources. Pre-crash safety measures will be further advanced not only by these insights, but also by future applications of the methods developed herein.

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