Accident Analysis and Prevention 153 (2021) 106016

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

A systematic mapping review of surrogate safety assessment using traffic conflict techniques

Ashutosh Arun [a], Md Mazharul Haque [a,*], Ashish Bhaskar [a], Simon Washington [b], Tarek Sayed [c]

[a] School of Civil & Environmental Engineering, Science & Engineering Faculty, Queensland University of Technology, Brisbane, QLD, 4000, Australia
[b] School of Civil Engineering, Faculty of Engineering, Architecture and Information Technology, The University of Queensland, Brisbane, QLD, 4072, Australia
[c] Department of Civil Engineering, Faculty of Applied Science, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada

ARTICLE INFO

Keywords:
Traffic conflicts
Surrogate safety framework
Crash-conflict relationship
Crash surrogates
Surrogate based crash severity

ABSTRACT

Safety assessment of road sections and networks have historically relied on police-reported crash data. These data have several noteworthy and significant shortcomings, including under-reporting, subjectivism, post hoc assessment of crash causes and contributing factors, limited behavioural information, and omitted potential important crash-related factors resulting in an omitted variable bias. Moreover, crashes are relatively rare events and require long observation periods to justify expenditures. The rarity of crashes leads to a moral dilemma—we must wait for sufficient crashes to accrue at a site—some involving injuries and even death—to then justify improvements to prevent crashes. The more quickly the profession can end its reliance on crashes to assess road safety, the better.

Surrogate safety assessment methodologies, in contrast, are proactive in design, do not rely on crashes, and require shorter observation timeframes in which to formulate reliable safety assessments. Although surrogate safety assessment methodologies have been developed and assessed over the past 50 years, an overarching and unifying framework does not exist to date. A unifying framework will help to contextualize the role of various methodological developments and begin a productive discussion in the literature about how the various pieces do or should fit together to understand road user risk better.

This paper aims to fill this gap by thoroughly mapping traffic conflicts and surrogate safety methodologies. A total of 549 studies were meticulously reviewed to achieve this aim of developing a unifying framework. The resulting framework provides a consolidated and up-to-date summary of surrogate safety assessment methodologies and conflict measures and metrics.

Further work is needed to advance surrogate safety methodologies. Critical research needs to include identifying a comprehensive and reliable set of surrogate measures for risk assessment, establishing rigorous relationships between conflicts and crashes, developing ways to capture road user behaviours into surrogate-based safety assessment, and integrating crash severity measures into risk estimation.

1. Introduction

Road safety assessment has matured over the last 50 years. There are well-established methods of road safety assessment that traditionally rely on the analysis of police-reported crash data for the development of countermeasures to improve safety. The crash-based assessment, however, is plagued by several well-known shortcomings (Tarko, 2018b). A significant issue with crash-based assessment is that it is a slow, reactive process, which limits its applicability for applications like a quick evaluation of the effectiveness of new engineering treatments and assessing the crash risk associated with disruptive technologies like connected and automated vehicles (CAV).

Surrogate safety assessment, on the other hand, is an alternative method of assessing safety that relies on the analysis of safety-critical events known as traffic conflicts. Over the last 50 years, there have been numerous studies based on traffic conflict-based safety assessments (Amundsen and Hyden, 1977; Kraay, 1982). However, a comprehensive review to help consolidate the research efforts in the field of surrogate safety assessment is currently lacking.

A scoping review of the existing review studies on surrogate safety assessment was conducted to illustrate this point further. The results of this scoping review, as presented in Table 1, highlight the major topics

* Corresponding author.
E-mail address: m1.haque@qut.edu.au (M.M. Haque).

https://doi.org/10.1016/j.aap.2021.106016
Received 16 June 2020; Received in revised form 3 October 2020; Accepted 14 January 2021
Available online 11 February 2021

Table 1
Review studies on the surrogate safety assessment.

S. No.	Authors & Date	Publication type	Major topics discussed
1	Chin and Quek (1997)	Discussion paper	• Issues with prior conflict research • A framework for conflict studies
2	Gettman and Head (2003)	Original research	• Overview of microsimulation application in surrogate safety • Measures of surrogate safety that can be extracted from microsimulation models
3	Tarko et al. (2009)	White paper	• Concept of crash surrogacy • Application of surrogate measures in safety assessment
4	Laureshyn et al. (2010)	Discussion paper	• Aetiological relationship between crashes and conflicts • Review and illustration of a few surrogate measures
5	Tarko (2012)	Original research	• Aetiological relationship between crashes and conflicts • Methods of estimation of the empirical relationship between crashes and conflicts • A framework for modelling crash causation using surrogate safety events
6	Zheng et al. (2014b)	Review paper	• Review of popular proximity measures that are used as surrogates • Definitions of traffic conflicts • Some conceptual issues of traffic conflicts • Methods of observing conflicts • Discussion on the crash-conflict relationship
7	Chang et al. (2017)	White paper	• Concept of crash surrogacy • Methods of observing conflicts • Application of surrogate measures in safety assessment
8	Tarko (2018a)	Book chapter	• An overview of traffic conflicts technique • An aetiological relationship between conflicts and crashes • Measures of proximity and observation of conflicts
9	Johnsson et al. (2018a)	Review paper	• Aetiological relationship between crashes and conflicts • Surrogate measures for vulnerable road users

discussed in the earlier review studies. Importantly, the scoping review identified several gaps in the consolidated knowledge about surrogate safety assessment. Firstly, the concepts related to crash surrogacy remain relatively unclear. Although traffic conflicts are understood to be good safety surrogates, there are many competing definitions of what constitutes a traffic conflict that affects the understanding of how they might be related to crashes. Secondly, there are several surrogate safety measures (also called conflict indicators), and there are no guidelines regarding the contexts in which specific surrogate measures should be applied. Thirdly, the techniques for identifying traffic conflicts from surrogate measurements remain under-reported. Lastly, the understanding of the nature and specification of the crash-conflict relationship and the various safety applications for which surrogate measures can be used is lacking. In summary, the lack of consolidated knowledge about the various aspects of surrogate safety assessment significantly hinders the development of the field as an attractive alternative to crash-based safety assessment.

Therefore, this study aims to address the gaps in the current review literature by conducting a systematic mapping review of surrogate road safety assessment. This study will focus on mapping the concepts and methods related to the state-of-the-art surrogate safety assessment using traffic conflicts. The paper is organized in the following manner. Section 2 presents the research methodology adopted for collecting the relevant literature. The methodology includes discussion about the research questions, search protocols, inclusion and exclusion criteria, and the developed classification scheme. Section 3 presents the results of the study considering nine scientific research questions developed as part of a scoping review, and Section 4 provides a detailed discussion on the identified research gaps and the future research directions. Finally, the paper concludes with a summary of the significant results of the study in Section 5.

2. Methodology

This paper proposes a novel conceptual framework of surrogate safety assessment, as presented in Fig. 1. This conceptual framework acted as a visual reference for the systematic mapping review and was instrumental in developing the specific research questions for this study.

The first component of this framework is the definition of traffic conflicts. Depending on the nature of road user interactions, the conflicts can be defined in four ways based on (a) evasive action, (b) proximity, (c) severity hierarchy, and (d) counterfactual probability. A range of surrogate measures is available for each type of conflict (i.e., rear-end, angle and sideswipe) depending on the intended crash dimensions (frequency or severity) to be captured. The selection of surrogate measure/s suitable for the context of a study forms the next most crucial component of the framework. Subsequently, methods of observation of conflicts need to be decided. There are three major approaches under this heading, viz. (a) road user-level observation, (b) facility-level observation, and (c) microsimulation-based observation. After surrogate measurements, the identified conflicts can be utilized in either of the following two ways; (a) they can be directly used in safety assessment and other relevant applications *assuming* a correlation between conflicts and crashes, or (b) they can be used to estimate the crash-conflict relationship. Further, there are two major approaches to the estimation of crash frequency using conflicts, viz., (a) statistical association approach, and (b) causal relationship approach. Another significant dimension in the prediction of crashes using conflicts is the estimation of crash severity using severity-specific surrogates. All these components of the framework and the related concepts are subsequently discussed in detail.

This study follows a systematic mapping review methodology. A mapping review aims to answer higher-level research questions related to a field of study to discover the research trends, map out the sub-topics related to that field that have been extensively studied in the past, and capture the empirical methods that have been used to investigate those sub-topics (Kitchenham et al., 2011). The biggest strength of a mapping review is in flagging sub-topics that have been overlooked by previous researchers and, thus, identify future research needs. Following the guideline provided by Petersen et al. (2015), this mapping review study follows three main steps: (1) identification of studies (search protocol, inclusion and exclusion criteria), (2) classification schemes and processes, and (3) visualisation of results. The visualisation of the results is provided in Fig. 1, while the search protocols and classification schemes are discussed in the following subsections.

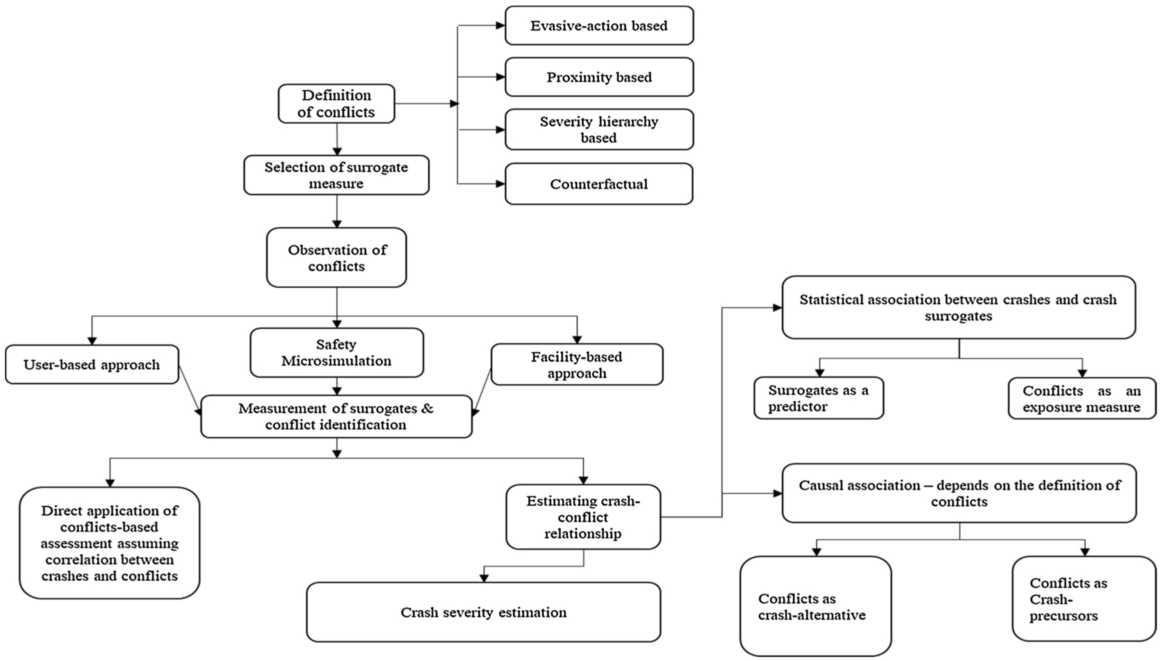

Fig. 1. Conceptual framework of surrogate safety assessment.

2.1. Research questions

A systematic classification scheme (SCS) was applied to formulate the research questions of this study. In particular, the research questions intended to summarize all the components proposed in the conceptual framework (Fig. 1) and address the gaps identified during the scoping review (Table 1). These research questions are as below:

RQ.1What is crash surrogacy and how to identify a good crash surrogate?

RQ.2What is/are the definition/s of traffic conflicts?

RQ.3 What dimensions of traffic crashes are/can be captured using surrogate safety measures?

RQ.4How are the traffic conflicts observed?

RQ.5What are the various surrogate measures being used to measure safety?

RQ 6What are the thresholds distinguishing a conflict from a regular traffic interaction?

RQ.7What are the various safety-relevant applications for which traffic conflicts/surrogate measures are used?

RQ.8What is the nature and specification of the relationship between traffic conflicts and crashes?

RQ.9How is the validation of conflict-based safety assessment performed?

2.2. Search protocol

Following the scoping review, a snowballing method (Wohlin, 2014) was applied to collect an initial set of papers to refine the search protocol and strategy. There are several synonyms of "traffic conflicts" used in literature, such as near crash, near miss, safety critical events, and risky events. In some studies, "traffic conflicts" are themselves referred to as "surrogate measures", while in others the term "surrogate measures" stands to mean "conflict indicators", or physically measured quantities such as vehicular proximity in time and space or vehicular acceleration measures that indicate nearness to a collision. Thus, for comprehensiveness, the following keywords and their combinations were used as search terms in scientific databases:

"conflict", "conflict technique*", "conflict indicator*", "surrogate*", "surrogate measure*", "safety critical event", "safety relevant event", "indirect safety", "near-crash (with and without hyphen)", "near-accident (with and without hyphen)" and "near-miss (with and without hyphen)"

The terms *"road", "traffic"* and *"safety"* were used as the qualification terms to restrict the ambit of search to relevant studies only. An example of such a combination is the search query *(surrogate OR conflict) AND crash AND (road or traffic)* performed in the Title, Abstract, and Keywords fields on the Scopus database that fetched 650 results on 1st May 2019.

2.3. Search strategy

The following scientific databases were searched for relevant literature: Scopus, Web of Science, Science Direct, Transport Research International Documentation (TRID), Taylor & Francis, Google Scholar, Mendeley, and QUT Library.

For valuable technical reports or manuals such as the FHWA Surrogate Safety Assessment Model, a direct search on Google was made. The website of the International Cooperation on Theories and Concepts in Traffic Safety (ICTCT) hosts certain seminal past studies, which were also downloaded for review. Following a preliminary screening, the snowballing method was used again to find other missing relevant papers (Wohlin, 2014). It needs to be mentioned that this methodological approach was not designed to be an exhaustive search of surrogate safety literature. Rather it was specifically evolved to search for relevant studies needed to answer all the 9 research questions posited in Section 2.1. In total, the search strategy resulted in 588 relevant studies for further processing.

2.4. Inclusion and exclusion criteria

Only the studies conforming to the following inclusion criteria were selected:

- Only English language studies
- Studies published in peer-reviewed journals and conferences
- Studies defining and explaining the key concepts such as traffic conflicts and surrogate measures of safety

- Studies specifying methods of conflict observation and surrogate measurement
- Studies establishing or investigating the relationship between crashes and conflicts

Both original research and case studies demonstrating the application of traffic conflicts in safety assessment

Theses, dissertations, and technical reports were generally excluded from the study except for significant reports such as the "Surrogate safety assessment model and validation" (Gettman et al., 2008). The studies published within the past ten years were given preference to maintain the relevance of the study results. Only highly cited and pioneering research from previous years that still inform the current research and practice, such as Amundsen and Hyden (1977) and Hydén (1987), were included through the snowballing method. After applying the above criteria, a total of 549 studies were finally selected for the mapping review.

2.5. Data extraction

EndNote X9, a reference management tool, was used to manage the large number of references collected for this study, and perform sorting and classification exercises. The 'create groups' function of the software was used for the latter purpose. NVivo 12, a qualitative research tool, was used for more refined coding for, say, recording the various surrogate measures used in the literature.

The data extraction process further involved a two-stage screening process. Firstly, the downloaded papers were classified according to their Titles, Abstracts, and Keywords, and then, secondly, according to the specific topics dealt with in the paper. As the objective of the paper is to present a systematic map, these classifications were not "hard classifications", allowing for overlaps and cross-classifications. Table 2 presents the result of the data extraction process, along with the final Systematic Classification Scheme (SCS) and the research questions of this study.

3. Results

The results of the systematic mapping review are given subsequently, with each subsection corresponding to a specific research question of the study.

3.1. Concept of crash surrogacy [RQ.1]

The first research question investigated in this study is "what is crash surrogacy and how to identify a good crash surrogate?" Tarko et al. (2009) mentioned that conflicts are but one of the many "surrogate measures of safety". The other surrogate measures, as per them, include critical events such as aggressive lane changing, speeding and red-light running, acceleration noise, post-encroachment time, time-integrated time-to-collision, deceleration-to-safety-time, and even traffic characteristics like volume, speed, and delay. The inclusion of traffic characteristics among the list of surrogates opens the interpretation of a "surrogate measure" to be anything that can be related to crash risk. Thus, there is a critical need to lay down some criteria to determine whether a measure can qualify as a crash surrogate.

Fortunately, some studies have strived to provide specific criteria to facilitate the correct use of crash surrogates (Tarko et al., 2009; Tarko, 2018a). Particularly, Wu and Jovanis (2012) have critically deliberated on desirable criteria for crash surrogates, stating that a crash surrogate (a) should have a short observation period, (b) should be correlated with clinically meaningful outcomes, i.e., crashes, (c) should be statistically and causally related to crashes, (d) should be affected by a safety treatment similarly to how a safety treatment would affect crashes, and (e) should be "markers" of crashes with a time-scale underpinning, meaning that they should be part of the same sequence of events that produce crashes.

Based on the above criteria, traffic conflicts, also known as near-crashes, near-misses and safety-critical events, are found to be the most suitable crash surrogates. Traffic conflicts are typically observed in the field for a few hours or a few days; thus, they have a shorter observation period compared to crashes. Peesapati et al. (2013) evaluated the correlation of traffic conflicts, defined using Post-Encroachment Time (PET) measure, with crashes and found the two to be correlated, with very high correlations at lower PET thresholds of 1 s. The statistical and causal relationship of conflicts with crashes has been investigated in several studies (Davis et al., 2011; Tarko, 2012; Jonasson and Rootzen, 2014; Tarko, 2018b; Zheng et al., 2018) as reviewed in Section 3.8. Sacchi et al. (2013) found that safety treatments led to comparable reductions in both the number of conflicts as well as crashes. Finally, the last criterion emphasizes that crash surrogates and the crashes should ideally be different end products of the same underlying process, which is a key aspect of the safety continuum theory that models crash as an extension of a traffic conflict (Hydén, 1987; Laureshyn et al., 2010; Zheng et al., 2014b). Hence, traffic conflicts have been discussed as the most suitable tool for carrying out surrogate safety assessment in the rest of the paper.

3.2. Definition of traffic conflicts [RQ.2]

Defining a traffic conflict has remained a significant source of contention over the years. The first-ever mention of the term "traffic conflicts" was by Klebelsberg (1964) (as cited in Tarko (2018a)), who defined them as dangerous traffic interactions. Thereafter, Perkins and Harris (1968) used traffic conflicts to define situations necessitating evasive actions such as braking. However, this definition had quite a few drawbacks. For example, braking habits are subjective, and it is hard to distinguish between events involving precautionary braking and evasive braking.

Thus, an alternative definition of conflicts was mooted as "…an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged" (Amundsen and Hyden, 1977). The proximity of road users to each other could be physically measured in temporal and/or spatial dimensions, and thresholds could be used to identify conflicts. The above definition of traffic conflicts was widely adopted in many countries such as Sweden and The Netherlands (Hydén, 1987; Kraay et al., 2013) and even in the recent Surrogate Safety Assessment Model (SSAM) (Gettman et al., 2008).

The above two definitions of traffic conflicts, however, indicate that only the most extreme of traffic interactions have been thought of as potentially associated with crashes. In contrast, Hydén (1987) proposed that there is a whole hierarchy of traffic events varying in severity (Fig. 2), where even the seemingly non-serious traffic interactions may carry pertinent safety information. The width and height of each layer of the safety pyramid correspond to the frequency and severity (riskiness or

Table 2
Data classification scheme for the systematic mapping review.

Class	No. of papers	Research question addressed
Concept of crash surrogacy (RQ1)	46	RQ. 1
Definition of traffic conflicts (RQ2)	19	RQ. 2
Crash dimensions measured through surrogate assessment (RQ3)	37	RQ. 3
Observation of traffic conflicts (RQ4)	428	RQ. 4
Selection of surrogate measures (RQ5)	244	RQ. 5
Thresholds to identify traffic conflicts (RQ6)	48	RQ. 6
Applications of traffic conflicts/surrogate measures (RQ7)	263	RQ. 7
Nature of crash-conflict relationship (RQ8)	101	RQ. 8
Validity of conflict-based safety assessment (RQ9)	45	RQ. 9

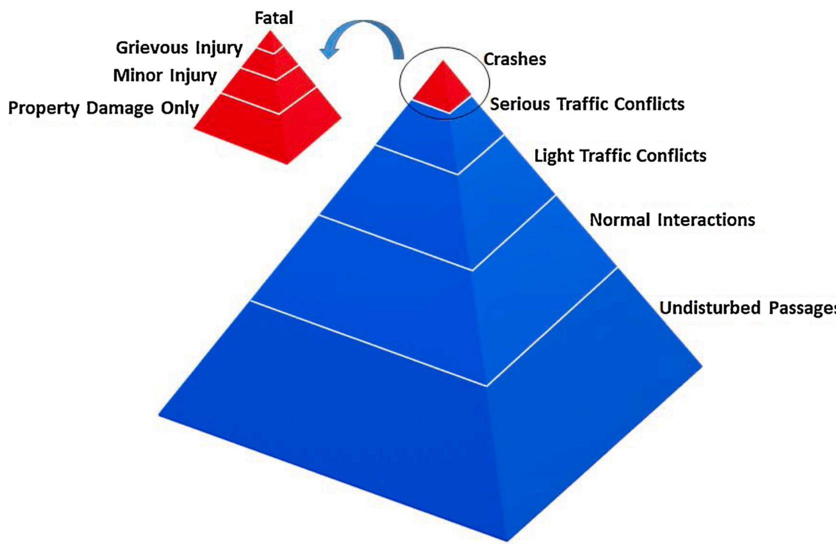

Fig. 2. Safety pyramid of traffic events (adapted from Hydén, 1987). The extension to the pyramid integrating crash severity in the safety hierarchy is based on Laureshyn et al. (2010).

Table 3
Review of the definitions of traffic conflicts.

	Conflicts defined based on evasive-actions	Conflicts defined based on spatial and/or temporal proximity	Conflicts defined in a common severity framework	Conflicts defined based on counterfactual probability
Definition	- A traffic event that requires a rapid evasive maneuver by the subject vehicle, or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. A rapid, evasive maneuver can be steering, braking, accelerating, or any combination of control inputs that approaches the limit of the vehicle capabilities. (Tarko et al., 2009)	- An observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged. (Amundsen and Hyden, 1977)	A traffic event that lies just below crashes in the severity hierarchy of traffic events, and that shares many of the characteristics of crashes that are indicated by the common severity indicator. (Laureshyn et al., 2010)	- The probability of a conflict is the probability of unsuccessful evasion in a traffic interaction, estimated by specifying a counterfactual frequency distribution of evasive actions taken. (Davis et al., 2011)
Advantages	- Suitable for the Naturalistic driving studies where road user and vehicle-level information is readily available - Assessment of behavioural changes to changes in the driving environment is possible	- Suitable for the Facility-based traffic safety evaluation - Vehicle-to-vehicle and vehicle-to-infrastructure level safety communication can utilize this definition of conflicts for collision avoidance applications	- Suitable for studying the crash mechanism, i.e., how an interaction evolves into a crash - The severity of events, even the non-threatening ones, can be studied and utilized in safety assessment, thereby ensuring holistic safety improvement	- Shares the advantages of the common severity framework definition - Can incorporate driver, vehicle, and interaction-level heterogeneity information due to the probabilistic nature of conflict estimation
Disadvantages	- Important to distinguish between precautionary and evasive maneuvers while applying this definition. - Cannot be used in cases where no evasive actions were attempted by either party or the road user under observation (Dingus et al., 1999, Tarko 2018) - Manual intervention/ judgment is still required to identify conflicts, and hence automation is not easy	- Precludes road user-level safety assessment - The threshold between risky events and conflicts need to be clearly defined - Relative riskiness or nearness-to-collision of events cannot be calculated	- The choice of the common severity indicator is open-ended, and threshold definition for the various hierarchical levels may again involve subjectivity - Practically, employing the information of all traffic events in safety assessment is cumbersome. Even the studies using this definition focus only on serious conflicts or pre-crash events, indicating potential loss of information	- Estimating counterfactual distributions for all possible evasive actions in all possible conflict situations are complicated. The studies that employ this definition usually focus on a small subset of possible interactions and participants - Accuracy depends entirely on the correct specification of the underlying counterfactual distribution

nearness to collision) of such events, respectively.

Another definition of traffic conflicts is based on counterfactual theory. Davis et al. (2011) argued that the conflicts might be defined as the counterfactual probability of obtaining a crash, i.e., the probability of obtaining a crash if the evasive actions taken by the road users involved were unsuccessful. Thus, if there is a significant counterfactual crash probability associated with a traffic event, then that event can be called a conflict.

The various definitions of traffic conflicts, with their respective advantages and disadvantages, are summarised in Table 3.

3.3. Crash dimensions measured through surrogate assessment [RQ.3]

Traditionally, surrogate safety assessment has mainly been used for estimation of the probability of crash occurrence. The other safety dimension, i.e., crash severity, has received less attention from researchers, possibly because the resultant crash severity is conditional on the actual occurrence of a crash. Before proceeding further, it is important to clarify the distinction between the frequently confused terms of “conflict severity” and “crash severity”. Conflict Severity, introduced by Hydén (1987), represents the riskiness of the traffic interaction in terms of “nearness to a collision”. Thus, a more severe conflict will be more likely to evolve into a crash than a less severe conflict. Typical measures of conflict severity include Conflicting Vehicle Speed (Hydén, 1987) and Severity Index (Autey et al., 2012; Essa and Sayed, 2019). Crash Severity, on the other hand, is the result of a crash event and represents the seriousness of the injuries to the victim/s of the crash. Crash severity is typically measured on standard scales of injury measurement, such as the Abbreviated Injury Scale (AIS) (Medicine, 2018) that range from minimal (property damage only) to maximal (fatality).

Laureshyn et al. (2010) argued that Hyden's safety continuum model could be extended to accommodate crash severities as well (Fig. 2). Subsequently, some studies have incorporated severity prediction through conflict analysis (Zhou et al., 2011; Laureshyn et al., 2017a). The current approaches of crash severity estimation using surrogate methods broadly fall into the following categories:

- *Using dedicated severity indicator/s*: Specialised surrogate measure for crash severity are computed in this approach. A popular severity surrogate measure is delta-V (or ΔV), which is the predicted change in the velocity of the subject vehicle after a crash (Sobhani et al., 2011). However, the current delta-V estimation method involves trajectory extrapolation at a constant velocity, which is unrealistic because some users invariably take evasive maneuvers in the event of a conflict. Consequently, Laureshyn et al. (2017a) sought to improve delta-V estimation by including two distinct levels of deceleration, including -4 m/s^2 (normal braking) and -8 m/s^2 (emergency braking) in the estimation process.
- *Integrated indicator for both crash frequency and severity*: Ozbay et al. (2008) devised a Crash Index integrating Modified TTC, relative speed and relative acceleration of the interacting vehicles to indicate both crash frequency and severity. Alhajyaseen (2014) developed a Conflict Index that predicted the Kinetic Energy released in a collision, which is weighted by Post-Encroachment Time (PET). Bagdadi (2013) developed a conflict severity index based on delta-V, the masses of the involved road users, and Time-to-Accident. Alternatively, Wang and Stamatiadis (2014a) adopted a multi-step sequential integration of indicators for developing an Aggregated Severe Crash Metric (ASCM). Here, firstly, the crash probability is estimated based on TTC and the maximum braking rate, and then severity is estimated based on power models of delta-V.

3.4. Observation of traffic conflicts [RQ.4]

The earliest conflict studies observed and recorded conflicts in the field with the help of trained manual enumerators (Amundsen and Hyden, 1977; Hydén, 1987; Kraay et al., 2013). However, concerns regarding the subjectivity and reliability of manually observed traffic conflicts led researchers to explore other avenues. Currently, traffic conflicts can be observed through the following methods:

3.4.1. Road user-level observations

The road user-level methods observe conflicts from the point-of-view of the road users. The mode of data collection in such studies is mostly naturalistic driving. Under naturalistic methods, data is collected by unobtrusive instruments from road users who are travelling naturally under real-world conditions without being given any special instructions. The naturalistic methods generally collect travel data over a long period, providing a rich dataset that may contain both conflicts and crashes, and thus, offer a huge advantage when it comes to modelling the crash-conflict relationship.

Most of the naturalistic driving studies use instrumented vehicles, usually equipped with sensors like GPS and accelerometers to record kinematic information, sensors for headway and side obstacle detection, incident logging device for manual input by drivers, cameras for recording the vehicle environment and near-misses, and an on-board data acquisition system to acquire data from all these sensors. Some significant naturalistic driving studies are 100-car naturalistic study (Dingus et al., 2006), Second Strategic Highway Research Program (SHRP2) naturalistic study (Antin et al., 2019), and the Shanghai Naturalistic Driving Study (Glaser et al., 2017). Naturalistic methods have also been used for non-motorized users, such as bicyclists (Dozza and Werneke, 2014; Mehta et al., 2019).

A newer method of naturalistic data collection leverages the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies for conflict identification (Wu et al., 2018b). The Safety Pilot Model Deployment (SPMD) program has collected data using the Connected Vehicle (CV) technologies in real-world conditions (Liu and Khattak, 2016).

The biggest drawback of studies involving instrumented vehicles, however, is the prohibitive cost involved in fitting sensors to a large number of vehicles and/or driving them for extended periods. Low-cost innovations in this field include cheaper sensor technologies such as Video Drive Recorders that are portable devices that get triggered only by near-crash conditions (Lu et al., 2011; Matsui et al., 2013); speed measurement through Intelligent Speed Adaptation systems (Bagdadi and Varhelyi, 2011); vehicle kinematics measurement through GPS (Wang et al., 2015b) or other proprietary in-vehicle sensing systems such as i2D (Kim et al., 2016); and even extracting vehicle kinematics data from smartphone sensors (Strauss et al., 2017; Stipancic et al., 2018a, b).

Driving simulator experiments are another popular method of road user-level conflict observations (Tarko, 2012; Orsini et al., 2018). Driving simulators provide the added capability of controlling the road environment so that specific problems can be studied with more confidence (Haque and Washington, 2014, 2015). Moreover, it is a safer way to examine conflicts, particularly those involving vulnerable road users such as bicyclists and pedestrians (Lubbe, 2017; Warner et al., 2017). However, establishing the fidelity and validity of the driving simulation is still an issue on which research is ongoing (Allen et al., 2011). Driving simulator experiments are also typically plagued by small sample size issues. Moreover, crucially, many road users are not comfortable with driving simulator experiments due to the lack of realism of the real-world driving experience, simulator sickness, or for avoiding scrutiny of driving habits. Hence, the conflict results obtained through this method may be biased.

3.4.2. Facility-level observations

Although road user-level observations provide richer information about crash mechanisms, it takes quite long to collect an adequate amount of data using naturalistic methods. Engineers are generally more interested in the assessment of a few problematic locations in a transport network such as high crash intersections for which naturalistic methods are not cost-effective. Therefore, facility-level conflict observation, where an observer (or sensor/s) is placed at the traffic facility being scrutinized, is a preferred approach for facility-specific surrogate analysis.

Many existing traffic sensors such as inductive loop detectors (Oh et al., 2006; Li et al., 2014a; Dimitriou et al., 2018), microwave radars (Wu et al., 2018c; Gecchele et al., 2019), plate magnetometers (Stipancic et al., 2015), Weigh-in-Motion (WIM) detectors (Jo et al., 2019) and roadside LiDAR detectors (Wu et al., 2018a) have been utilized for the measurement of surrogates. Infrastructure-based Intelligent Transport Systems (ITS) such as SMART-signals have also been used for violation detections, crossing conflict identification, and crash reconstruction at signalised intersections (Chatterjee and Davis, 2011; Shen et al., 2017). A disadvantage of these sensors is that they often do not provide microscopic details regarding traffic interactions. For instance, most of the studies employing loop detectors use 5-minute aggregated data for analysis purposes (Oh et al., 2006; Fallah Zavareh et al., 2017; Dimitriou et al., 2018). Also, when compared with other facility-based observation methods such as video recordings, detectors like microwave radars and plate magnetometers were found to be less accurate Stipancic et al. (2015).

Video-based conflict observation involves recording vehicle trajectories and interactions at a roadway facility through video cameras. Some studies apply manual extraction of conflicts from video data (van der Horst et al., 2014; van Haperen et al., 2018; Oh and Kim, 2010; Pawar et al., 2016), which is often criticized for subjective bias. However, the rapid advancements in computer vision technology have led researchers to develop a semi or fully automated conflict extraction process (Saunier and Sayed, 2007; Laureshyn et al., 2009). Semi-automated methods of conflict extraction include using virtual detectors in videos (Guido et al., 2011), and manual tracking of road users across frames using software like TrafficAnalyzer (Iryo-Asano and Alhajyaseen, 2017) and T-Analyst (Johnsson et al., 2018b). T-Analyst can additionally provide some safety indicators such as Time-to-Collision, Time Advantage, and Time Gap (Laureshyn et al., 2017a). Another application called RUBA reduces the video length to only the portions containing safety-relevant events and can be used in conjunction with the above semi-automated software (Madsen and Lahrmann, 2017). However, the semi-automated methods are labour-intensive and require extensive manual intervention.

With the advent of computer vision techniques, many studies now rely on automated detection, identification, and tracking of the moving objects in the videos to track road users (Sayed et al., 2012). These studies mainly use well-established tracking algorithms such as detection-based and feature-based tracking. Some detection-based tracking methods include 3-D model-based tracking (Fazekas et al., 2017), background/foreground segmentation (Zhang et al., 2019), and appearance-based tracking for pedestrians (Shirazi and Morris, 2015). The feature-based tracking methods rely on tracking distinct vehicle features such as corners and edges (Saunier and Sayed, 2007). Studies using feature-based tracking have reported a high degree of accuracy, even in the case of partial occlusions (Ismail et al., 2009b, a; Ismail et al., 2010a, b; Jackson et al., 2013; Saunier et al., 2010; St-Aubin et al., 2015). An improvement on this platform for cyclist tracking is implemented in Kassim et al. (2014). Further improvements to this method have been reported by combining feature-tracking with foreground/background segmentation (Li et al., 2015). The application "Urban Tracker" uses this combined method specifically for dealing with multiple object tracking in urban environments with mixed traffic (Jodoin et al., 2016). Xie et al. (2019) combined feature-tracking with robust Principal Component Analysis (rPCA)-based background subtraction and Dirichlet Process Gaussian Mixture Model (DPGMM)-based tracklet clustering.

Deep-learning methods like Convolutional Neural Networks for road user trajectory extraction alleviate manual intervention altogether and improve the accuracy of detections (Chen et al., 2017; Wang et al., 2018). However, these methods are computationally intensive.

Apart from regular cameras, videos can also be collected using Unmanned Aerial Vehicles (UAV) (Park et al., 2018; Wang et al., 2019) and thermal video cameras (Fu et al., 2016; Olszewski et al., 2019). The former provides a comprehensive bird's eye view of the entire facility, although their limited flying time and regulations concerning their operations are some significant disadvantages. Thermal cameras allow better detection of vulnerable road users such as pedestrians, especially at night, as they eliminate the false-positive errors arising due to shadows. However, their accuracy can be affected by hot weather.

3.4.3. Microscopic simulation

A significant number of studies have used microsimulation to study and estimate traffic conflicts. Young et al. (2014) and Mahmud et al. (2018) provide excellent reviews of the various simulation methods used in the safety analysis.

VISSIM by PTV group is by far the most used traffic microsimulation package for surrogate safety applications, mostly in conjunction with the Surrogate Safety Assessment Model (SSAM). The majority of microsimulation studies (77 out of 144, 53 %) reviewed in this paper have used VISSIM as the go-to application. However, comparisons among simulation platforms have found that after two-stage calibration (based on both delays as well as the number of conflicts), all software provide comparable surrogate measure output (Essa and Sayed, 2016; Astarita and Giofré, 2019).

Importantly, researchers at the University of Calabria have developed a new microsimulation package called TRITONE (Astarita et al., 2012) that provides surrogate measures like Deceleration Rate to Avoid Crash (DRAC) and Crash Potential Index (CPI) without the need for additional processing through SSAM. Furthermore, customized simulation tools like Cellular automata (CA) models have become popular because of their simplicity and computational efficiency (Li et al., 2012; Kuang et al., 2014; Gao et al., 2018; Wu et al., 2018d). Chai and Wong (2015) found the output of their cellular automata simulation model to be more correlated with field-observed conflicts than that from VISSIM-SSAM.

A summary of all the methods of conflict observations, with their respective advantages and disadvantages, is presented in Table 4.

3.5. Surrogate measures to assess safety [RQ.5]

Surrogate safety measures (SSM) or conflict indicators are the metrics that are used to measure the riskiness or nearness to a collision of traffic events. The most popular surrogate measure is Time-to-Collision (TTC) that is defined as the time remaining to a potential collision if the speed and direction of the interacting road users remain unchanged (Hayward, 1972). Almost a third (28.6 %) of the studies reviewed in this current review study employed the TTC measure uniquely or in combination with other surrogate measures. Another popular measure is the Post-Encroachment Time (PET) that is defined as the time between the departure of one road user from a point (or an area of potential collision) and the arrival of another road user to the same point (Allen et al., 1978). Both TTC and PET are measures of temporal proximity. Zheng et al. (2014b) review several other measures of temporal and spatial proximity.

Other review studies on surrogate measures (Mahmud et al., 2017; Yang et al., 2010; Johnsson et al., 2018a; Kuang and Qu, 2014) mention other families of indicators such as acceleration-based indicators like the Deceleration Rate to Avoid Crash (DRAC) as well. Unfortunately, these reviews have failed to include several context-specific surrogate measures like Lane Change Risk Index (Park et al., 2018) and Loom Rate (Ward et al., 2015) that do not fall into the aforementioned families of surrogate measures.

Another issue concerning surrogate measures is the use of multiple indicators for conflict identification. Ismail et al. (2011) argue that individual surrogate measures represent partial images of the actual severity of traffic events. Thus, it is preferable to use multiple indicators to capture the severity of the traffic conflict holistically. There are two ways to incorporate more than two surrogate measures in conflict identification: a) defining conflicts as an incident that occurs when any combination of some predetermined "triggers" is activated, and b) mapping several measures to a common severity indicator. An example of the former method is the near-crash definition used in naturalistic driving studies that use several kinematic triggers such as lateral and longitudinal acceleration (Dingus et al., 2006). A "trigger" event occurs when those indicators either individually or simultaneously exceed their respective threshold values. The trigger events are then evaluated by safety experts to identify truly critical events. This subjectivity is, however, the biggest drawback of this approach. There is also no uniformity in the kinematic indicators used and their threshold values, as evidenced by different trigger criteria used in other studies (Wu and

Table 4
A summary of the methods of conflict observation.

	Road User Level Observation Methods	Facility Level Observation Methods	Microscopic Simulation Methods
Description	A sample of the road user-type to be studied is equipped with various sensors to record their naturalistic driving/movement behaviour under real-world traffic conditions	Observers/sensors are positioned at/next to the facility that is being monitored, and the road user trajectories are obtained unobtrusively	Microscopic simulation software is used to simulate traffic flow conditions existing on the traffic network. Surrogate measures are obtained either directly from the software or through post-processing using SSAM.
Advantages	Microscopic-level information about road user behaviour in real-world traffic conditions is available Road user, vehicle, and sometimes even traffic environment (e.g., in driving simulators) are controlled for studying the safety Assessment of behavioural adaptations to changes in the driving environment is possible Assessment of in-vehicle safety technologies such as Forward Collision Warning systems, as well as some facility-based ones such as Intersection Movement Assist (Wu et al., 2018b) is possible Data can also be readily obtained by employing everyday devices such as smartphones and GPS Based on the objective of the study, various sensors such as proximity sensors, eye trackers, and front and rear cameras can be used to provide precise information about the behavioural and/or environmental characteristics of interest Data can be collected in all types of weather conditions. Some extreme conditions such as fog and rain can be simulated in driving simulators A more suitable approach to carry out studies throughout a wider area such as network screening studies	Analysis of facility-level safety and assessment of engineering countermeasures are possible using these methods. A broader view of the traffic and other conditions in which the conflicts occur is available. Thus, conflicts can be related to causal conditions, and prediction models can be developed Some microscopic-level behavioural information such as violations, sudden changes in speed and acceleration can be extracted Shorter duration of data collection and extraction are possible. Datasets of durations even less than an hour have been utilized for specific applications Due to the rapidity of data collection and analysis, countermeasures can be quickly identified and implemented A large number of road users can be observed remotely, allowing for more significant variation in the sample All kinds of road users, including vulnerable road users, can be studied based on the facility-type and the objective of the study such as only pedestrians on a crossing More control over the survey instrument allowing quick redressal of faults with the devices and changes in study requirements More suitable for carrying out studies on a few specific locations such as safety assessment of crash/conflict hotspots	Combines the advantages of both the other methods as facility-based observations can be conducted while exercising strict control over road, users, and conditions Data collection and post-processing duration is the shortest among all the methods for comparable applications Conflicts involving all kinds of road users, including vulnerable road users can be simulated Particularly useful in the assessment of new facility designs and upcoming technologies like connected and automated vehicles (CAV). Also vital for the evaluation of safety treatments implemented following the surrogate safety assessment, facilitating flexibility to evaluate multiple candidate scenarios and in cases where field data from treatments are not available.
Disadvantages	Data collection and extraction are usually tedious and costly Raw data size may be significant that may necessitate specialist data management and mining Sample size issues may surface if the data are not collected for a large number of participants and long durations Given that only certain types of road users may participate in data collection, the results may be biased Significant manual intervention is involved in determining whether a flagged incident is a conflict Only a limited perspective of the evolving crash risk is usually available. Thus, it is difficult to relate the conflicts with the broader conditions that may be generating them such as average stream speed at the time of occurrence of conflict	Privacy concerns especially with video-based methods The raw data size can become prohibitively large with video-based methods Sample size issues with video-based methods, primarily when deriving crash-conflict relationships Automated methods of data extraction and conflict identification are still under development, so manual intervention is still required which can be quite expensive Data resolution may be an issue with certain kinds of sensors such as loop detectors where the obtained data are usually in aggregated form Data collection is affected by weather conditions especially for non-embedded type sensors	The accuracy of the simulated conflicts is heavily dependent on the accuracy of the underlying behavioural models and associated assumptions Behavioural models for all types of road users, particularly motorcyclists, cyclists and pedestrians, are not available Since the underlying behavioural models have an inbuilt factor of safety, questions have been raised over the validity of microsimulation for simulating conflicts Microsimulation models thus cannot capture crash-generating process and do not provide high correlations with the actual conflicts at low thresholds Spatial distribution of the observed and simulated conflicts are significantly different

Jovanis, 2012, 2013).

Alternatively, the mapping approach uses the following two methods combining multiple surrogate measures:

- *Functional mapping:* It is a more popular mapping approach where closed-form functions are used to map the values of various surrogate measures to a common severity index (Ismail et al., 2011; Ghanipoor Machiani and Abbas, 2016). Many studies have used functional mapping to simultaneously map both crash frequency and severity surrogates (Zhou et al., 2011; Wang and Stamatiadis, 2014a; Zheng and Ismail, 2017).
- *Distribution mapping:* For distribution mapping, frequency distributions such as gamma distributions (Ismail et al., 2011) are assigned to the surrogate measures, and then their extremes based on measures of deviation are jointly evaluated to identify conflicts. Examples of such measures include Aggregated Crash Propensity Metric (ACPM) (Wang and Stamatiadis, 2014b) that combines TTC and Required Braking Rate (RBR) in a single probabilistic structure. Another method is bivariate extreme value modelling that employs Generalised Extreme Value (GEV) or Generalised Pareto (GP) distributions to approximate the marginal distribution of the extremes of any two measures (Zheng and Sayed, 2019c).

3.6. *Conflict identification using surrogate measures [RQ.6]*

Identification of traffic conflicts using surrogate measures is a significant challenge. Usually, a surrogate threshold value is used to distinguish conflicts from other traffic events. This threshold must be sufficiently small (or large, depending upon the indicator) for conflicts to have some bearing on the eventual crashes (Tarko et al., 2009; Sayed and Zein, 1999). Hayward (1972) suggested that the threshold for TTC should be between 0.5 s, which is close to the driver brake reaction time, and the empirical mean value of 1.46 s. However, often thresholds are chosen arbitrarily based on previous studies without justification for their suitability for the context of their studies.

Another issue is that safety literature suggests multiple thresholds for a surrogate measure even under the same context. For example, the TTC thresholds for rear-end conflicts at signalised intersections vary widely between 0.5 s (Shahdah et al., 2014) to 6.0 s (Ghanipoor Machiani and Abbas, 2016). Zheng et al. (2016) noted that the same issue existed for PET thresholds as well.

In the naturalistic driving studies as well, the kinematic triggers are not universal and need to be adapted for different contexts to reduce false alarms (Wang and Xu, 2019). Moreover, the trigger events are still required to be manually reviewed to identify actual near-crash events, which is difficult and time-consuming. Alternatively, Dozza and Gonzalez (2012) proposed using automated analysis of driver videos from the cameras installed in the driving chamber to identify actual safety-critical events that elicited a severe human behavioural response.

The wide variations in the prescribed surrogate thresholds have led some researchers to estimate the thresholds empirically. There are six major approaches for empirical estimation of conflict thresholds:

1 *Correlational approach*: Several thresholds are used for estimating conflicts, and the most suitable threshold is selected based on the following:
   a The highest correlation between the cumulative density functions (CDF) of the number of conflicts and the number of observed annual crashes (Peesapati et al., 2013)
   b The highest correlation between the return level estimates from Extreme Value models and the observed crashes (Zheng and Ismail, 2017)
   c Lowest false alarm rate of conflict detection (Park et al., 2011)
   d ROC (Receiver Operating Characteristic) curves that simultaneously maximize highest true positive and false negative rates (correct identification of crash and near-crash events) and penalize false positive and true negative rates (incorrect identifications) (Perez et al., 2017)
2 *Distribution-based approach:* The distribution-based approach analyses the distributions of surrogate measures. It has the following three methods:
   a *Bimodal histogram method:* The histogram for estimated crash risk should have two peaks, one corresponding to the crashes and the other corresponding to the non-crashes. The lowest point on the trough between the two peaks can be taken as the threshold (Yang et al., 2018).
   b *Percentile method:* The cumulative proportion of estimated crashes and non-crashes should be the same as the proportion of observed crashes and non-crashes (Yang et al., 2018).
   c *Deviation method:* The measures of deviation, such as standard deviation of kinematic measures, are used to identify the most extreme traffic events (Wang et al., 2015b).
3 *Optimization methods:* Yang et al. (2018) explained three methods similar to the optimization techniques in the field of image segmentation. These techniques either seek to maximize the between-class variance or minimize the cross-entropy of the two classes (crashes and non-crashes) based on various thresholds.
4 *Classification methods:* The identification of traffic conflicts is a classification problem solved using the following methods:
   a *Linear discriminant analysis:* In this method, the threshold of the discriminant function provides the threshold of the surrogate measure (Cao et al., 2014)
   b *Discrete choice modelling*: The normality and equal covariance assumptions of Fisher's discriminant analysis are constrictive; therefore, discrete choice logit models can be adopted for conflict classification (Cao et al., 2016)
   c *Machine learning:* This method involves conflict classification using applications like Support Vector Machines (SVM), K-nearest neighbour (KNN), Random Forest (RF), and Neural Networks (NN) (Ghanipoor Machiani and Abbas, 2016; Katrakazas et al., 2019). Threshold determination based on classification methods is not straightforward because of the need for a training dataset containing input traffic conflicts that themselves need to be firstly accurately identified using other methods.
5 *Time Series Analysis:* Traffic conflicts are a result of some unusual traffic behaviour by the participating road users. Thus, time-series analysis of the conflict indicators around the occurrence of safety-critical events may provide useful information. The following analysis methods have been applied:
   a Permutation entropy of pedestrian ambulatory characteristics (Tageldin et al., 2017) and vehicle kinematic indicators (Wei et al., 2019) are used to identify conflicts
   b Kluger et al. (2016) used Discrete Fourier Transform along with K-means clustering on vehicular accelerations to identify crashes and near-crashes
   c Xiong et al. (2019) used spectral clustering on deceleration to find critical driving profiles, and then mapped the surrogate measures (TTC, TH, and PICUD) onto the identified driving profiles to extract classification rules
6 *Extreme value estimation:* Extreme Value (EV) methods are based on the probabilistic analysis of extreme events (Tarko, 2012). Studies using the Peak-Over Threshold EV method (Zheng et al., 2016) can identify suitable thresholds based on the following plots:
   a *Mean residual life plot*: The mean residuals obtained using all the thresholds are plotted, and the threshold above which it becomes approximately linear is selected, and
   b *Threshold stability plot:* The threshold above which the plots of the shape and the modified scale parameter become constant is selected.

In a recent EV theory-based paper, Zheng and Sayed (2019b) carried out a quantile regression of surrogate measures where the quantiles were parameterized as functions of some traffic characteristics. Subsequently, the thresholds corresponding to the estimated quantiles were analyzed through the above plots for finding the most optimum threshold.

3.7. Applications of surrogate safety assessment [RQ.7]

Gettman et al. (2008) found that the ratio of traffic conflicts to observed crashes was approximately 20,000–1, which means that traffic conflicts occur much more frequently than crashes. Thus, traffic conflicts, and by extension surrogate measures, are considered as an attractive alternative to crashes for various safety-related applications. The current state-of-the-practice involving surrogate safety methods can be divided into two branches:

Methods focussed on general safety assessments and safety-relevant applications that require basic correlation between surrogates and crashes, and

Methods that specifically focus on the investigation of crash mechanism, i.e., how a traffic interaction progresses into a severe event such as a conflict or a crash

The latter methods are discussed at length in the next section. Table 5 provides a glimpse of the wide range of surrogate assessment applications of the former category. The popularity of surrogate assessment for such applications is due to the following advantages over crash-based analysis:

1 The paucity/absence of crash data for new designs of road facilities such as diverging diamond interchange (Mehrara Molan et al., 2019) and novel technologies such as connected vehicles (Songchitruksa and Zha, 2014) means crash-based safety assessments cannot be carried out in such cases

Table 5
Review of the various applications of surrogate methods.

Category	Application	Studies
Safety assessment of transport facilities	General safety assessment	Autey et al. (2012); Haque et al. (2017)
	Before-and-after type assessment	Autey et al. (2012); St-Aubin et al. (2012)
	Case-control type assessment	Zangenehpour et al. (2016)
	Comparisons of alternative facility designs	Saccomanno et al. (2008); Madsen and Lahrmann (2017); Kiec et al. (2018)
	Safety assessment of new facility designs	Mehrara Molan et al. (2019); Hallmark et al. (2018); Giuffrè et al. (2018)
	Identification of safety hotspots and priority ranking of traffic facilities for safety treatments	Shahdah et al. (2012); Stipancic et al. (2018b); So et al. (2015)
	Development of safety performance functions and crash modification factors	El-Basyouny and Sayed (2013); Shahdah et al. (2014); Essa and Sayed (2019)
	Development and evaluation of safety engineering treatments	Lee et al. (2018); Zheng and Sayed (2019a)
	Real-time crash risk prediction	Essa and Sayed (2019); Essa et al. (2019)
	Traffic signal optimisations	Ma et al. (2015); Stevanovic et al. (2013), 2015
Road-users based safety assessment	Safety assessment focussed on low volume road users	Goh et al. (2014); van der Horst et al. (2014); Bai et al. (2015); Pawar et al. (2016)
	Behavioural analysis of drivers under various traffic, weather and road conditions	Habtemichael and de Picado Santos (2014); Gao et al. (2019); Zhang et al. (2018); Zhao et al. (2018)
Assessment of new technologies	Safety assessment of Connected Vehicles (CV)	Jeong et al. (2014); Songchitruksa and Zha (2014)
	Impact assessment of CV technologies on safety at various types of road facilities	Liu and Khattak (2016); Genders and Razavi (2016); Tian et al. (2017)
	Safety assessment of Active Vehicle Safety Systems (AVSS) such as Forward Collision Warning/Avoidance System and Automated Emergency Braking System	Park et al. (2011); Wang et al. (2016); Sander (2017)
	Impact assessment of AVSS on drivers of equipped vehicles	Yan et al. (2015); Xiang et al. (2016)
	Impact assessment of AVSS on drivers of unequipped vehicles	Preuk et al. (2016)
	Safety assessment of Advanced Driver Assistance Systems (ADAS) such as Intelligent Speed Adaptation, Overtaking Assistant, Lane Keeping Systems, and Adaptive Cruise Control	Lundgren and Tapani (2006); Kessler et al. (2012); Biondi et al. (2017); Li et al. (2017); Katrakazas et al. (2019); Deluka Tibljaš et al. (2018)
	Development of new safety and mobility enhancing solutions based on Vehicle-to-Vehicle (V2V) communication technologies	Mirheli et al. (2018); Rahman and Abdel-Aty (2018); Park and Oh (2019); Zhao et al. (2019)
	Safety assessment of infrastructural Intelligent Transport Systems (ITS) such as Variable Speed Limits (VSL), Intersection Movement Assistance (IMA), Ramp Metering (RM), Adaptive Traffic Signal Control, and Automatic Toll Collection	Li et al. (2014b); Fallah Zavareh et al. (2017); Wu et al. (2018b); Young and Archer (2009); Oskarbski et al. (2018)
	Safety assessment of combined Vehicle-to-Infrastructure (V2I) and V2V technologies	Li et al. (2016); Jeong et al. (2017)
Policy and planning-level decision making	Network-level route safety assessment	Dijkstra et al. (2018)
	Investment optimization for network-level safety management	Cafiso and Di Graziano (2011)
	Implementation of safety measures for the public transport fleet	Battiato et al. (2018)
	Decision system for the structure of traffic fines	Baratian-Ghorghi et al. (2016)

2 The surrogate analysis is a rapid method; hence, safety assessments such as identification of safety hotspots and priority ranking of intersections can be done quickly, allowing for faster deployment of safety treatments. Also, the deployed safety engineering treatments can be readily evaluated using surrogate assessment without having to wait for post-implementation accrual of crashes
3 The size of crash data for low volume road users such as cyclists, pedestrians, and commercial vehicles is even lesser than that of, say, cars. Therefore, surrogate methods can provide a better alternative for their safety assessment
4 Given the paucity and unreliability of crash records in low- and middle-income countries, surrogate methods provide an easy and cost-effective way of safety assessments (Guo et al., 2018; Tageldin and Sayed, 2018). Moreover, since mixed traffic and unorganized flow of traffic are the norms in such driving cultures, arguably surrogate methods can offer more insights into the crash mechanism than simple crash counts (Tageldin et al., 2015; Wei et al., 2019)

3.8. *Nature of crash-conflict relationship [RQ.8]*

The immense applications of crash surrogates are based on the theoretical validity of the crash-conflict relationship. Hence, considerable attention has been given to specify this crash-conflict relationship. Tarko (2012) has encapsulated two strategies used for this purpose:

1 *Statistical association*: The primary objective of this approach is to establish a statistical association between conflict counts and crash frequencies. It is a practical method to develop a decision support tool to undertake safety evaluations (Songchitruksa and Tarko, 2006a). Within this stream, there are further two approaches:
   a *Conflicts as an explanatory variable:* The conflicts are used as an explanatory factor in a crash prediction model with/without other exogenous variables (Sayed and Zein, 1999; Guo et al., 2010; Caliendo and Guida, 2012; Shahdah et al., 2015). Poisson-based regression models are usually employed in such studies (Shahdah et al., 2014; Peesapati et al., 2018). If the dependent variable is the probability of crash occurrence instead of crash counts, then discrete choice models are used (Jovanis et al., 2011; Wu and Jovanis, 2012).
   b *Conflicts as an exposure variable*: The conflicts are used as the exposure variable instead of traffic volume. Given that conflicts themselves are dangerous traffic events, such a formulation reduces the solution space for the crash frequency variable (El-Basyouny and Sayed, 2013; Sacchi and Sayed, 2016). Naturalistic driving studies, on the other hand, firstly shortlist safety-critical incidents based on triggers and then crashes and near-crashes are analyzed in that restricted sample space (Jovanis et al., 2011; Wu and Jovanis, 2012). The latter approach allows for simultaneous estimation models of conflicts and crashes using common as well as individual factors for both dependent variables (Gordon et al., 2011).
2 *Causal relationship*: Davis et al. (2011) argued that traffic conflicts are counterfactually related to crashes. Thus, there is a common causal

link between crashes and conflicts. There are two schools of thought regarding the nature of this relationship:

a *Conflicts as an alternative of crashes*: Jovanis et al. (2011) argued a near-crash is an alternative event that is observed when a crash just gets avoided. Thus, crashes and near-crashes can be modelled as alternative outcomes in a binary choice model (Wu and Jovanis, 2012, 2013).

b *Conflicts as precursor events to a crash*: Various traffic events are causally linked to each other, forming a chain of conditions necessary for a crash occurrence (Tarko, 2012). Thus, the probability of a crash can be calculated as the product of the probability of initiating conditions (conflicts), the conditional probability of evasive actions given the initiating conditions, and the conditional probability of crashes given the evasive actions. Extreme value models (Songchitruksa and Tarko, 2006b; Tarko, 2012; Zheng et al., 2014a; Zheng and Sayed, 2019a) use this approach where the Extreme Value Theory (EVT) is used to estimate the conditional probability of crashes given the occurrence of extreme traffic events such as conflicts (Tarko, 2018b). A significant advantage of this approach is that crash data are not required in the model development phase. Therefore, the probability estimates are immune to the inadequacies of crash data.

The various approaches to modelling the crash-conflict relationship are summarised with their respective advantages and disadvantages in Table 6.

3.9. Validation of the Crash-Conflict Relationship [RQ.9]

Validation of the crash-conflict relationship is a nascent field of research. To date, the following validation strategies have been applied in this regard:

Table 6
Review of the various approaches to modelling crash-conflict relationships.

	Statistical Association		Causal Link	
Description	Conflicts as Explanatory Variable: The number of observed conflicts is used as an explanatory variable with/without other covariates in a crash prediction model	Conflicts as Exposure Variable: The number of conflicts is used as the exposure variable instead of traffic volume in a crash prediction model	Conflicts as Alternatives to Crashes: Conflicts (near-crashes) and crashes are two possible outcomes, with driver, event and context parameters used as explanatory variables in a binary choice model	Conflicts as Precursors to Crashes: Crashes are an extension of conflicts; thus, crashes can be estimated by modelling the tail of the conflict distribution using Extreme Value Theory
Rationale	Conflicts are dangerous and undesirable interactions; hence they must be correlated with the crash occurrence	Crashes can only occur between vehicles that are interacting with each other. Since all vehicles in a traffic stream do not interact with each other, therefore traffic volume is a weak exposure measure. Contrarily, traffic conflicts capture the result of vehicle interactions; hence, they are a better exposure measure.	Conflicts and crashes are both products of the same underlying process. A conflict (near-crash) is a result of a critical event where a crash did not occur. Thus, binary choice models can be used to predict both crashes and conflicts	Crashes are extreme forms of conflicts that result in physical damage. In other words, the occurrence of a conflict is a necessary condition for the occurrence of a crash of the same interaction type (e.g., rear-end, sideswipe, head-on) as the conflict. Thus, conflicts are precursor events to a crash and causally linked with them.
Advantages	Crash prediction modelling is a mature field of practice, with all the methods and tools already specified. Conflicts only constitute another variable in the model that may enhance the accuracy of predictions Several conflict indicators can be considered simultaneously	In addition to sharing the advantages of the 'conflicts as explanatory variable' approach, this approach has a more logical appeal than the former	The approach has a more intuitive and logical appeal than the statistical association approaches Binary choice modelling is straightforward, with an easier inference of the direction and magnitude of the effects of the independent variables on critical events Several "trigger" events can be accommodated in determining a near-crash, thus providing more holistic information on the safety system failure	By leveraging the information from a chain of traffic events, i.e., from low severity ones to higher severity conflicts, it can explain the crash mechanism, i.e., how the conflicts develop and evolve into a crash, in a better manner, thus providing richer insights into the crash process Crash data are not required in the model development stage. Additionally, in the model validation stage, the uncertainty in crash observations is taken into account
Disadvantages	Given the temporal discrepancy between the observation of crashes and conflicts, where conflicts are obtained for a few hours while crashes are observed for several years, the precipitating conditions for both types of events may be completely different. Therefore, conflicts may not have adequate explanatory power, which is evident in the mixed results observed in the literature The accuracy of the approach is dependent on the accuracy and comprehensiveness of the crash data	The temporal discordance problem is even more pronounced in this approach as the conflicts act as exposure to crashes. Thus, conflicts need to be observed for adequate lengths of time or else estimated for the same periods as crashes using some models Studies that have estimated conflicts for use in this approach have used the same variables for predicting conflicts as those used in traditional crash prediction models. Therefore, no new information is gleaned by using conflicts in the model Again, the conditions of conflict and crash occurrences may be different, leading to low accuracy and incorrect inferences The accuracy of results is dependent on the accuracy and comprehensiveness of the crash data	Model development is dependent on crash data. Thus, lengthy and extensive simultaneous observations for both conflicts and crashes are required, which is expensive and cumbersome Due to the randomness of crashes, even after long periods of observation, an adequate number of crashes may not be observed. Thus, the data would be plagued by the usual small sample size problem	The modelling is complicated, especially when considering more than one conflict indicators Considering the effect of other exogenous factors is not straightforward. Their effect needs to be considered in the estimation of the location (or scale) parameter. Thus, inferring their effect on conflicts and crashes is somewhat difficult Extreme value models are data-hungry; hence sample size can be an issue

1 *Correlation between observed and estimated crashes:* Correlation methods, such as Pearson's correlation coefficient between the estimated and the observed number of crashes (Peesapati et al., 2018; Stipancic et al., 2018a; Zheng et al., 2018) have been used for validation of the conflict methods. Due to the low number of observed crashes, some studies test the correlation between the outputs of crash-conflict models and established safety performance functions (Asljung et al., 2017; So et al., 2015). In the EVT-based studies, Zheng et al. (2015) have proposed to examine the correlation between the observed crashes and the return levels, which is a standard risk measure generated by extreme value methods, to overcome the imprecision of estimated crashes caused by small sample sizes.
2 *Analyzing the variance of the observed/estimated crashes:* Songchitruksa and Tarko (2006b) have introduced a method for EVT models where they determine if the estimated crashes lie within the Poisson confidence interval of observed crashes.
3 *Comparison between crash modification factors (CMF):* Instead of direct comparison between crash estimated, some studies have compared the crash modification factors estimated from the established crash prediction models such as Empirical Bayes-based Safety Performance Functions (EB-SPF) and those estimated using the developed crash-conflict models (Shahdah et al., 2014, 2015; Persaud et al., 2018; Qin et al., 2018).

Transferability of validated conflict-based crash prediction model parameters among various application contexts is another challenge (Persaud et al., 2018). However, only a few studies have investigated this aspect (Shew et al., 2013; Essa et al., 2019). Importantly, Shew et al. (2013) found that the transferability of model parameters was not uniform among US freeway sections, with sections needing additional calibration using local data. Essentially, there are two approaches for investigating the transferability of model parameters (Essa et al., 2019):

1 *Application-based approach:* Uncalibrated models are used to estimate the crash risk at the destination road facilities, and the prediction performance is evaluated using specialised statistical measures like Transfer Index (TI) (Koppelman and Wilmot, 1982) or Goodness-Of-Fit statistics like Chi-squared statistic (χ^2).
2 *Estimation-based approach:* The models are either partially (only intercept and distributional parameters such as shape parameter) or fully-calibrated (reestimation). Transferability can be evaluated as in the previous approach.

4. Discussion and Future Research Needs

This study provides an extensive systematic mapping review, driven by specific research questions to summarize the concepts and methods of surrogate safety assessment and develop a comprehensive surrogate safety assessment framework (Fig. 1). The conceptual framework helped to summarize the state-of-the-art and led to the identification of critical research needs, discussed subsequently.

4.1. Concept of crash surrogacy

Despite more than 50 years of development, the concept of crash surrogacy is relatively unclear within the broader research community. This confusion has led to the use of macroscopic traffic characteristics such as average speeds as crash surrogates (Bai et al., 2013) even though such characteristics possess low explanatory power regarding crash mechanism. Such confusion can also lead to counterintuitive results. For example, treating a site based on pedestrian exposure alone to reduce vehicle-pedestrian crashes may reduce the number of low-intensity crashes but increase the probability of higher severity crashes. The critical issue here is that the distinction between crash surrogates and factors of general safety degradation needs to be understood and highlighted. For instance, high variations of average speed at a location may be an indicator of safety degradation but cannot provide quantified crash risk on its own. Traffic characteristics have a correlation with crashes, but so do other factors such as weather and lighting conditions. Hence, mistaking them for crash surrogates may not be appropriate.

Given that a crash is a microscopic event, i.e., a physical collision between two objects (i.e. two road users or a road user and an object), a crash surrogate must either be microscopic or must aggregate information from several microscopic indicators. It should be able to capture the interactions of individual road users and convey the severity of each interaction. That is why microscopic proximity measures such as minimum Time to Collision (TTC) and Post Encroachment Time (PET) are popular surrogate safety measures. Indeed, some microscopic traffic flow variables like accepted/rejected gaps by road users that are typically used in capacity estimation applications are also recognised as potent surrogate measures of safety (Petzoldt, 2014; Yuan et al., 2019a). Macroscopic variables such as traffic volume, on the other hand, merely represent opportunities for crashes to happen but fail to capture the actual crash mechanism, and can only constitute exposure to crashes at a broader level.

Therefore, adopting a standard, validated criteria for crash surrogates is essential to enable accurate and reliable safety assessments. Following the broad consensus on the topic, this study proposes that the five criteria of crash surrogates proposed by Wu and Jovanis (2012) should serve as the standard for classifying a crash surrogate measure. For instance, spatial and temporal violations by pedestrians alone do not constitute significant safety risks in the absence of conflicting traffic and hence are not reliable or effective crash surrogates. Hence, developing suitable crash surrogates in alignment with the above criteria constitutes a significant future research need.

Another point of clarification in this regard, however, is the distinction between surrogate events and surrogate measures. Based on the crash surrogate criteria mentioned earlier, traffic conflicts are found to the most suitable crash surrogates. However, traffic conflicts are generally viewed and understood as distinct traffic "events". From literature (Allen et al., 1978; Tarko et al., 2009; Laureshyn et al., 2010), on the other hand, it is clear that all the "surrogate measures" are continuous measures of the severity of a traffic interaction and reflect its nearness-to-collision. For instance, a TTC < 1.5 s represents a more severe traffic conflict than TTC < 3 s. Therefore, if someone defines a traffic conflict as all the interactions having minimum TTC ≤ 1.5 s, then those conflicts are the surrogate events (or crash surrogates), and the TTC is the surrogate measure that gives the severity of such events.

4.2. Definition of traffic conflicts

Traffic conflicts are the most popular crash surrogates in literature. However, from Table 3, there are several definitions of traffic conflicts, each with their relative strengths and weaknesses.

The spatial/temporal proximity-based definition of traffic conflicts is the most widely used definition of traffic conflicts, which is evidenced by the immense use of proximity measures such as TTC and PET as surrogate safety measures. However, this definition is restrictive in the sense that it relies on the assumption of a constant velocity of road users and ignores their possible evasive actions. It also categorically excludes single-vehicle crashes from the ambit of surrogate analysis. Furthermore, by selecting a single threshold for identifying conflict events, an equivalence is imposed between events of varying intensity, e.g., an interaction between two light vehicles with a time-to-collision value of 1.5 s carried the same seriousness as an interaction between heavy trucks with equal time-to-collision value.

Traffic conflicts defined based on evasive actions are another practical definition of conflicts used in several studies. However, this definition fails to take into account precautionary actions on the part of road users into account. It also categorically excludes cases where a near-miss happened, but no evasive action was taken by the road users, possibly because they failed to detect the presence of conflicting road users. For instance, Guo et al. (2010) observed that 34 % of drivers involved in crashes in their study failed to take any evasive action.

Due to the above limitations, surrogates based on evasive actions and vehicle proximity are practical but may have a weak correlation with the actual crashes (Zheng et al., 2014b). For instance, Ito et al. (2018) found that TTC values at the time of evasive actions in car-cyclist interactions were different for crashes (<1.2 s) and near-crashes (>2.0 s). Thus, conflicts defined based on near-crashes alone in such a scenario would not be meaningfully related to crashes.

On the other hand, the common severity framework and counterfactual definitions can better explain the crash-conflict relationship. Particularly, the severity hierarchy definition simplifies the estimation of crash frequency from conflicts as crashes are now assumed to be an extension of traffic conflicts. Another advantage of Hyden's specification was that single-vehicle events such as road departures could also be assimilated in the surrogate assessment framework (Tarko, 2012). However, the specification of the common severity dimension used in the definition is critical, and unfortunately, there is no consensus regarding which measure to be used. Hydén (1987) used the ratio of the time remaining to an accident for the road user that has initiated the evasive action (Time-to-Accident; TA) and the speed of that road user at the moment of initiation (Conflict Speed; CS) as the common severity measure. Zhang et al. (2017) used lane-based PET criteria to differentiate between serious, slight, and no conflict situations involving pedestrians at an uncontrolled mid-block crossing. Similarly, the practical application of the counterfactual definition is also cumbersome. As Yamada and Kuroki (2019) noted, it is challenging to derive all the information regarding evasive actions over a range of conflict severities and their relative probabilities.

Hence, there is a critical need to develop a comprehensive definition of traffic conflicts by extracting relevant elements from the current definitions that possess desirable criteria for crash surrogates. Also, the current definitions of conflicts are constrained by their reliance on the method of observation and the choice of surrogate measures. For instance, a study employing facility-based observation methods typically adopts the proximity-based definition, thus sacrificing accuracy for the sake of ease of detection. Thus, a comprehensive definition of conflicts should strive to make them independent of the method of observation and establish them as distinct traffic events like crashes.

4.3. Crash dimensions measured through surrogate assessment

The consideration of crash severity within the surrogate safety assessment framework has received relatively less attention in the literature. The resultant crash severity is a function of the kinetic energy exchanged by the crash participants that cannot be measured by any of the usual proximity or acceleration-based conflict indicators. Hence, Tarko (2012) suggested that under surrogate safety assessment, conflicts should be used for estimating crash frequencies only, and crash severity should be modelled using discrete choice models with traditional severity factors. However, several authors argue that excluding crash severity from the surrogate assessment framework does not fully leverage the process validity inherent in the safety continuum model and makes the surrogate analysis less efficient (Dingus et al., 1999; Laureshyn et al., 2010). For instance, a TTC value of 0 indicates a crash, but the crash outcome in terms of severity can vary widely.

Consequently, several researchers have focussed on integrating crash severity estimation in the surrogate analysis framework; however, these efforts are marred by the following shortcomings:

The relationship between crash severity surrogates and actual crash severity remains to be thoroughly investigated. Although delta-V is the primary severity indicator, only a few validation studies (Evans, 1994; Bahouth et al., 2012) have been conducted, with a focus only on the homogenous case of vehicle-vehicle conflicts. Thus, validation of the current surrogate measures of crash severity, especially in mixed traffic environments, constitutes a critical research need.

Current surrogate methods do not yield severity estimates consistent with the crash severity scales, such as the Abbreviated Injury Scale (AIS) (Medicine, 2018). For the delta-V measure, the correlation with standard severity scales is available only for cars conflicting with other cars or fixed roadside objects (Evans, 1994). This shortcoming limits their utility in practical safety applications such as crash hotspot rectification. Thus, fundamental research in this regard is critically needed.

Traffic conflict observation methods

The accuracy of conflict-based safety assessment greatly relies on the accuracy of the surrogate measurement. Considerable progress has been made in this field since the days of manual observation of traffic conflicts. Three main methods of observation include road-user level (naturalistic) observations, facility-level observations, and microscopic traffic simulation. Importantly, all three approaches possess significant weaknesses (Table 4) that present significant future research opportunities.

Road user-level observations provide the most granular information regarding driver behaviour and vehicular performance during a conflict, the greatest advantage owing in part to video observations of the driver in addition to surrounding traffic. A significant advantage also is the observation of events that are not conditional on crashes (in comparison to a crash outcome database, for example). Despite the advantages, the major issues confronting this approach are:

- Innovations are required to reduce the high cost of data collection through naturalistic methods to allow for the collection of larger data samples.
- Even among relatively large samples of traffic observations, the actual number of conflicts observed using naturalistic methods remains small because conflicts are also infrequent events. Thus, robust analytical methods for small sample data need to be investigated, especially in the case of developing countries where large secondary data sources such as SHRP2 are typically not available.
- Due to the low frequency of conflicts in naturalistic data, data mining tools such as Classification and Regression Trees (CART) (Wang et al., 2015a) are required to identify them. Investigating other data mining methods, especially machine learning tools for big data such as Support Vector Machines (SVM) and Convolutional Neural Network (CNN) for this purpose, presents another research opportunity.
- There is no "standard list" of kinematic triggers in literature for shortlisting safety-critical events using naturalistic driving. Therefore, research towards identifying the suitable kinematic triggers relevant to various study contexts is critically needed.
- Road user-level observation methods often suffer from selection bias in the selection of study participants because some types of drivers are not comfortable with extensive external scrutiny. Such a bias presents a critical challenge in extending the inferences made from the sample to the whole population.
- Extension of road user-level observation methods to vulnerable road users (VRU) presents another research opportunity. For instance, only a few studies have investigated the car-to-pedestrian conflict case using road user-level observations (Matsui et al., 2013; Rahman et al., 2019). Although naturalistic observation of cyclist-involving conflicts has gained impetus in the recent years (Strauss et al., 2017; Dozza and Werneke, 2014; Dozza et al., 2016; Hamann and Peek-Asa, 2017; Feng et al., 2018), most of the studies are focussed on evaluating traffic safety on longitudinal facilities and few have analyzed the cyclist safety at intersections. As Ito et al. (2018) note, the road environment affects the vehicle-to-cyclist crash mechanism. Since road user-level observation methods can provide the most granular road user information to assist in the understanding of crash mechanism at various facilities, research using such methods for VRU applications is critically needed.

The most significant advantage of facility-level observation techniques such as video or lidar capture is the ability to assess road user risk of individual sites, and relatively low cost of data collection. However, critical research using this approach is needed for the following:

The computational costs and time of processing data from facility-level methods (e.g., video capture) have meant that analysis periods had been typically limited to several days. The representativeness of several days of observation, as indicative of road user risk throughout the year, is questionable—particularly in locations with wide fluctuations in traffic, road user profiles, or weather (e.g., ice, snow). Moreover, the estimation of the crash-conflict relationship is challenging and can result in inconsistent estimates and reduced precision (Songchitruksa and Tarko, 2006b; Zheng et al., 2014a, 2018). Thus, further research into an optimum sampling of observation periods through facility-level methods is acutely needed.

Massive data is generated daily by various traffic sensors such as CCTV cameras and embedded loops installed by transport authorities. However, only a few studies have utilized data from such sources for surrogate assessment (Wu et al., 2018e). Thus, more research is needed for optimal strategies to use data from such sources. A significant challenge in this regard would be combining data from disparate sources, but doing so can provide more significant insights into road user behaviours (Hossain et al., 2019).

Misclassification of challenging road users like motorcyclists, cyclists and pedestrians presents a critical challenge for the facility level observation methods. Although a few studies have been conducted in this regard (Ismail et al., 2010a; Zaki et al., 2012; Tageldin et al., 2017; Guo et al., 2018; Tageldin and Sayed, 2018; Fu et al., 2017), much work still needs to be carried out in this space to improve the accuracy of such methods for classifying and tracking existing as well as upcoming modes of transportation such as e-scooters and hoverboards, especially in shared space environments.

The precision of video and lidar data for classifying and determining exact positions and conflicts of road users can be improved. As conflict metrics are defined to capture precise conflicts among road users, their accurate calculation requires accurate classification and position information. Using object centroids, for example, to calculate a TTC may inject inaccuracies into this surrogate measure. Moreover, objective measures of surrogate measure performance are lacking—making comparisons across different providers or platforms very difficult.

A potential opportunity that has remained largely overlooked in the current literature, and has the potential to advance the practice significantly—is research into methods and technologies that combine data extracted from both facility-level and road user-level observation methods. The latest opportunity is regarding mining big data such as Basic Safety Messages (BSM) exchanged between vehicles and infrastructure in a connected vehicle environment (Kamrani et al., 2017) that contain rich information regarding vehicles' motion and position. These data sources can be used for both facility-level and driver-level safety analysis (Wali et al., 2019; Arvin et al., 2019). However, it is still a nascent field of research, and further efforts are needed. A key research opportunity here is the consideration of vulnerable road users like pedestrians, where vehicle and site tracking can be combined to reduce this crash risk.

Although surrogate safety assessment with microsimulation is a rapidly evolving approach, several issues need to be resolved before its widespread adoption. Specifically, although a reasonable correlation between simulated and real traffic conflicts can be obtained after proper two-stage calibration of simulation models, recent studies demonstrate that the increased correlation is simply due to exposure correspondence (Essa and Sayed, 2015a). Essa and Sayed (2015b) and Guo et al. (2019) demonstrated that the spatial distribution of simulated and field-measured conflicts was significantly different, indicating that the simulation did not capture the conflict mechanism. Zheng et al. (2019b) also cautioned against testing and validating surrogate measures using simulation methods. Therefore, even though microsimulation methods are now being extensively used for surrogate safety assessment, researchers must be aware of the limitations of the approach for surrogate safety assessment and be judiciously cautious in its application. However, the advantages of microsimulation over both road user-level and facility-level observation methods in specialised applications such as the planning-level safety assessment of new facility designs and new technologies like CAV presents tremendous research opportunities. Thus, there needs to be a concerted effort to evolve safety-specific microsimulation tools. In particular, significant research is needed in developing validated safety-relevant behavioural models for vehicles and other road users like motorcyclists, cyclists and pedestrians for improved conflict estimation using simulation. Moreover, fundamental research is needed for capturing conflicts caused by unexpected driving maneuvers, such as illegal lane changes in simulation models (Huang et al., 2013). Given the behavioural modelling challenges that must be overcome with simulation, the viability of this approach remains the most elusive at the current time.

4.4. Selection of surrogate measures

There is a crucial need to assimilate and synthesize knowledge regarding the various surrogate safety measures. The abundance of surrogate measures in the literature raises critical questions regarding their relative advantages/disadvantages and the specific contexts within which they are most suitable. The latter is specifically an important lacuna in the current surrogate safety literature. Existing review studies (Zheng et al., 2014b; Mahmud et al., 2017; Johnsson et al., 2018a) have failed to examine the contextuality of surrogate measures. It has been argued that context and event-specific classification of surrogate measures may be more useful in safety estimation (Wu and Jovanis, 2012). The context here can include various characteristics of surrogate application such as the geographical region of the location, the type of facility (e.g., intersection, freeway segment), and the purpose of the study (e.g., site-specific safety assessment, network assessment, understanding crash mechanism). For example, the current classification methods (based on proximity and vehicle kinematics) do not give adequate guidance regarding the applicability of surrogate measures like the Aggregated Crash Index (ACI) (Kuang et al., 2015) and the more recent Disturbance Accommodate Index (DAI) (Kuang et al., 2020) that have been developed specifically for freeway safety assessment. Similarly, targeted road users can be another point of classification as in the case of pedestrian-specific surrogate measures that include indicators like Lane-based PET (Zhang et al., 2017) and Time Difference to the Point of Intersection (TDPI) (Wu et al., 2018a). Thus, a systematic review of the various surrogate measures and their suitability in different contexts is crucially required.

Using multiple surrogate measures can significantly improve crash predictions using conflicts (Ismail et al., 2011), but which specific measures to be used is again a question that has remained relatively unexplored. Moreover, the use of multiple triggers in disaggregated form for shortlisting safety-relevant events is marred by the subjectivity in choosing the relevant surrogate measures and their safety thresholds. Thus, research is needed for automatically detecting safety-relevant events based on the most efficient triggers for different types of interactions.

Mapping several surrogate measures into a common severity indicator is a promising approach that has received relatively little attention. Critical research needs in this area concern issues such as the form of the mapping function adopted for functional mapping, and the type of distribution/s selected for distributional mapping. Another potential approach is to construct linear functions of severity indicators that serve as reliable crash predictors.

4.5. Conflict identification using surrogate measures

Typically, threshold values are determined to identify traffic conflicts using surrogate measures—for example, two road users on a collision course below a threshold of 3 s. Currently, thresholds for various surrogate measures are either arbitrarily chosen or adopted based on previous studies, but without proper justification for the context. Tarko (2018b) warned that selecting an incorrect threshold would capture intentional maneuvers along with genuine road user errors and, thus, would not lend useful insights into the underlying crash mechanisms. Thus, further research is needed to establish reliable and robust thresholds for various surrogate measures.

One research direction in this regard concerns the empirical estimation of thresholds. Previously, this paper enumerated six empirical methods of threshold determination; each of those methods has scope for further research and improvement. Mostly these empirical methods, though, rely on simple correlations with historical crash data, which is a challenge because crash data are known to be deficient owing to the randomness of crash events and underrepresentation of low severity crashes. Hence, unbiased empirical estimation methods for surrogate thresholds that preferably avoid the dependence on crash data need to be developed.

Another research direction was flagged by Tarko (2018b), where he argued that, theoretically, if an adopted threshold is sufficiently small, identified conflicts will consistently yield an unbiased estimate of the expected number of crashes, even under heterogeneous conditions. This important finding ensures that the conflict identification process is insulated against heterogeneity bias due to factors such as drivers, vehicles, traffic environment, and context. However, more empirical research is needed to validate this finding.

4.6. Nature of crash-conflict relationship

Traffic conflicts are argued to serve as an attractive alternative to crashes, as they both are markers of the same underlying crash risk generating process. However, the exact nature and specification of the relationship between crashes and conflicts are fundamental issues that are not yet sufficiently understood.

Tarko et al. (2009) deliberated upon the aetiological relationship between crashes and conflicts and conceptualized that surrogate measures/events and crashes must have a common chain of causation events (precipitating conditions), differing from each other only in the severity of the outcome due to the presence of certain uncontrollable factors such as driver responses to stimuli. The stronger their relationship, the lesser would be the number of such exogenous factors that affect crashes and conflicts separately, leading to more accurate safety estimates.

Many studies simply assume the validity of this aetiological crash-conflict relationship while using traffic conflicts for a myriad of applications (Table 5). However, in the absence of a robust and validated crash-conflict relationship, such safety applications run the risk of being unreliable and inefficient at best. In a worst-case scenario, such safety measures could have counterproductive results and increase the risk of crashes.

Two different approaches to viewing the crash-conflict relationship can be gleaned from the literature: statistical association and counterfactual causality (Table 6). The statistical approach, though practical, is merely associative, and mostly ignores any causal link between crashes and conflicts. It is also affected by several critical challenges, such as the temporal discrepancy between conflicts and crashes. Therefore, the counterfactual causal link approach that seeks to explain the crash mechanism fundamentally represents a more appealing prospect from this perspective and remains a promising area of future research. The future research needs concerning this approach are provided below:

- *"Conflicts as crash alternatives" approach*: This approach is mostly adopted in studies using naturalistic observation methods. Thus, this approach will benefit greatly from innovations in big data collection and analytics mentioned in Section 4.3. Moreover, since model development in this approach depends on crash data, auxiliary sources of data that can augment the deficient police-reported crash data need to be investigated. In parallel, future research might focus on more efficient use of the police-reported crash data. For example, data on fatal and severe injury (FSI) crashes are more accurate than data on low severity crashes. Thus, conflict-based models with only FSI crashes as dependent variables can be more accurate and should be investigated.
- *"Conflicts as crash precursors" approach:* It is a promising approach, especially because EVT models do not require crash data for model estimation. However, several research needs are identified in this regard:
  - o Small sample sizes of conflict data have been identified as a major cause of the low precision of the crash estimates from EVT models. Songchitruksa and Tarko (2006b) conducted a simulation experiment and found that conflicts need to be observed for 3–6 weeks to obtain precise safety estimates comparable to those obtained from 4-year observed crash counts. Thus, research into EVT models with larger data sets such as those being continuously generated by roadside surveillance cameras is urgently needed.
  - o Beirlant et al. (2004) argue that the assumption that all the exceedances in Peak Over Threshold approach would follow a strict Pareto-type distribution is sometimes too optimistic. However, current studies employing the Peak Over Threshold approach have not investigated other types of distributions, which constitutes a significant research gap.
  - o Crucially, research into multivariate EVT models that can employ more than two surrogate measures for crash estimation is required. Importantly, such models can potentially be used to simultaneously estimate crash occurrence as well as severity by incorporating severity indicators such as delta-V.
  - o The threshold estimation of surrogates in EVT models presents another critical research direction. The current methods still rely on subjective judgment regarding the suitability of the thresholds. Beirlant et al. (2004) stated that the distribution of threshold exceedances *approaches* a GP distribution only if the thresholds are high enough. Thus, incorrect thresholds can seriously affect the accuracy and validity of the models. Moreover, modelling the thresholds themselves as a function of some covariates can incorporate the effects of important variables such as traffic and geometric characteristics in model estimation. Recently, Zheng and Sayed (2019b) employed a quantile regression to estimate thresholds that showed encouraging results. However, they had only used rear-end conflicts observed at four intersections selected from nearby areas. Therefore, further research is needed.

Importantly, the scale of the surrogate assessment application plays a significant role in the adoption of the crash-conflict relationship model. Count data regression models such as Poisson and Poisson-Lognormal regression that investigate the statistical association between crashes and surrogate measures have been successfully established even for large datasets that contain network-wide information collected using newer technologies such as CV (Wali et al., 2018; Arvin et al., 2019). Similarly, binary choice models that estimate the probability of near-crashes as an alternative to the probability of crashes have been successfully utilized in establishing the crash-conflict relationship using large naturalistic driving data (Jovanis et al., 2011; Wu and Jovanis, 2012). In contrast, the conflicts as crash precursors approach that primarily employs EVT has till now only been investigated for comparatively smaller datasets that contain surrogate data collected on similar types of infrastructure facilities such as freeway segments (Zheng et al., 2014a) or signalised intersection approaches (Zheng et al., 2019a). The inclusion of varying types of traffic facilities or even different conflict types on similar types of traffic facilities in a single modelling structure has remained a challenge for the researchers and constitutes a critical future research need. Big data analytics and machine learning tools have a great potential in this regard.

One critical area of research is in the utilization of behavioural aspects such as spatial and temporal violations by road users that increase crash opportunities. Currently, conflicts and violations are treated separately when it comes to crash prediction. For instance, actions such as red-light running that heighten the risk of a crash are typically not used along with conflicts in crash prediction. It can be argued that such violations also carry significant safety information that can improve the overall accuracy of safety estimates. Nevertheless, caution needs to be exercised when combining conflict and violation information as some violative behaviours such as tailgating are already captured by the usual surrogate measures like TTC and Time Headway.

Another upcoming area of research is the real-time crash risk prediction. Only a handful of studies have ventured towards real-time risk analysis (Yuan et al., 2019b), and they typically rely only on operational variables such as volume, speed, and occupancy to compute crash risk. With CAV on the horizon and the increase in the use of telematics in transport operations, it is now possible to use proactive surrogate analysis for real-time crash risk prediction. Surrogate measures like TTC, PET, and DRAC can continuously flag developing conflict situations and potentially provide a graded objective criterion for monitoring crash risk on a network in real-time. Another major challenge is to overcome the vast number of false positives predicted when using non-conflict based measures such as speeds, flow, and density. Thus, research is needed to develop methods for real-time risk estimation using suitable indicators at various types of transport facilities.

4.7. Validation of the crash-conflict relationship

The developed crash-conflict relationships need to be validated through appropriate methods, which is challenging because both crashes and conflicts are random variables subject to statistical variations, and both variables are unreliably measured (Chin and Quek, 1997). Traffic conflicts that depend upon evasive actions alone may lead to underestimation of crashes, especially if there are multiple observed crash cases where no evasive actions are taken. Choosing suitable surrogate measures and their thresholds are critical because incorrect thresholds can also adversely affect the validity of a crash-conflict relationship (Tarko, 2018b).

Among current methods of validation, Laureshyn et al. (2017b) have criticized the linear correlation approach as they argue that since both conflicts and crashes are random events a direct correlation between the two or its absence may be misleading, especially if the number of observed crashes is low. On the other hand, given that the engineering countermeasures are targeted upon enhancing safety, a comparison of CMF estimated from crash-SPF with those from the developed crash-conflict models would be a prudent strategy. However, this approach requires data on both treated and untreated sites, which may not be available in all cases. Thus, a relatively more recent approach of comparing the variances of the observed and estimated crashes, usually employed with EVT models, seems promising. However, there are at least two aspects of the variance analysis approach that need to be properly investigated. Firstly, the imprecision of the current EVT models is a huge impediment in deriving a valid crash-conflict relationship. Thus, research areas are flagged in Section 4.6 that can improve the estimation accuracy and precision of the EVT models. Secondly, applying a variance analysis approach for validating other types of conflict-based crash prediction models (Poisson GLM and logit regression models) can be a worthwhile direction for future research.

The transferability of the validated crash-conflict models is another issue that presents a critical research gap. Apart from the obvious benefits, transferability analysis is also important because if the model parameters are found transferable to similar facilities in a new traffic environment, it will provide impetus to surrogate safety assessment as a viable alternative to crash-based assessment. It will also underline the strength of the underlying crash-conflict relationship. However, as pointed out before, only a few studies have investigated this aspect and only for the case of real-time risk assessment on freeways and signalised intersections. Even those studies found that models estimated for one application context are not readily transferable to another context and may require some calibration. Investigating the transferability of crash-conflict models across transport facilities represents a worthwhile research direction.

5. Conclusions

Surrogate safety assessment is gaining traction over the traditional crash-based safety assessment as the latter has numerous shortcomings. This mapping review study aimed to develop an understanding of the concepts and methods related to surrogate safety assessment and produced a comprehensive conceptual framework of safety assessment using traffic conflicts.

In a nutshell, this study delves into specific topics associated with surrogate safety assessment, including the concept of crash surrogacy, the definition of traffic conflicts, surrogate measures of safety, methods of observation and identification of traffic conflicts, the nature and specification of the crash-conflict relationship, and validation methods of such relationships. The study provides an overview of these topics and identifies issues within each topic that challenge the current practice. More importantly, the study has helped identify the comparatively less-researched topics such as crash severity estimation using surrogates and the absence of reliable surrogate measures for prediction of crash severity. The study highlights the critical gaps in the current knowledge about surrogate methods and discusses future research needs.

Finally, the most significant and unique contribution of this study is a comprehensive surrogate safety assessment framework that details various aspects of traffic conflicts ranging from their observation to their relationship with road crashes. Essentially, it emphasizes the profession to adopt a more holistic view of the road safety problem and to embrace surrogate analysis as a significant part of the bigger picture of traffic safety assessment. Road safety is a complex problem, one that requires a multi-pronged approach for reaching an optimum solution. A surrogates-based analysis is an attractive alternative to traditional safety assessment methods and provides a theoretically robust foundation for understanding crash causation. However, it can only complement current efforts towards solving the problem if it is used strategically to address the gaps in the current knowledge about the safety process. For instance, the isolated view of surrogate safety assessment as an objective unto itself has given rise to a lop-sided amount of research into the development of novel surrogate measures that at the most provide incremental benefits over traditional ones and less research into critical issues like the development and validation of crash-conflict relationships. The latter, along with the need for surrogate-based crash severity estimation, constitute the most significant lacunae in surrogate assessment and are critical for maturing this approach. Given insights gained into the surrogate framework, it is hoped that future efforts shall focus on focussed research into the specific gaps identified in this study.

CRediT authorship contribution statement

Ashutosh Arun: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing - original draft, Visualization. **Md Mazharul Haque:** Conceptualization, Methodology, Investigation, Validation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Ashish Bhaskar:** Writing - review & editing, Supervision. **Simon Washington:** Conceptualization, Methodology, Writing - review & editing. **Tarek Sayed:** Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alhajyaseen, W.K.M., 2014. The development of conflict index for the safety assessment of intersections considering crash probability and severity. Procedia Comput. Sci. 32, 364–371.

Allen, B.L., Shin, B.T., Cooper, P.J., 1978. Analysis of Traffic Conflicts and Collisions.

Allen, R., Rosenthal, T., Cook, M.L., 2011. A short history of driving simulation. In: FISHER, D., RIZZO, M., CAIRD, J., LEE, J. (Eds.), Handbook of Driving Simulation for Engineering, Medicine, and Psychology. CRC Press.

Amundsen, F.H., Hyden, C., 1977. Proceedings: firstworkshop on trafficconflicts. In: AMUNDSEN, F.H., HYDEN, C. (Eds.), First Workshop on Traffic Conflicts. Oslo, Norway.

AntIN, J.F., Lee, S., Perez, M.A., Dingus, T.A., Hankey, J.M., Brach, A., 2019. Second strategic highway research program naturalistic driving study methods. Saf. Sci.

Arvin, R., Kamrani, M., Khattak, A.J., 2019. How instantaneous driving behavior contributes to crashes at intersections: extracting useful information from connected vehicle message data. Accid. Anal. Prev. 127, 118–133.

Asljung, D., Nilsson, J., Fredriksson, J., 2017. Using extreme value theory for vehicle level safety validation and implications for autonomous vehicles. IEEE Trans. Intell. Veh. 2, 288–297.

Astarita, V., Giofré, V.P., 2019. From traffic conflict simulation to traffic crash simulation: introducing traffic safety indicators based on the explicit simulation of potential driver errors. Simul. Model. Pract. Theory 94, 215–236.

Astarita, V., Guido, G., Vitale, A., Giofré, V., 2012. A New Microsimulation Model for the Evaluation of Traffic Safety Performances. European Transport\Trasporti Europei.

Autey, J., Sayed, T., Zaki, M.H., 2012. Safety evaluation of right-turn smart channels using automated traffic conflict analysis. Accid. Anal. Prev. 45, 120–130.

Bagdadi, O., 2013. Estimation of the severity of safety critical events. Accid. Anal. Prev. 50, 167–174.

Bagdadi, O., VarhelYI, A., 2011. Jerky driving–An indicator of accident proneness? Accid. Anal. Prev. 43, 1359–1363.

Bahouth, G., Digges, K., Schulman, C., 2012. Influence of injury risk thresholds on the performance of an algorithm to predict crashes with serious injuries. In: Annals of Advances in AutomotiveMedicine. Association for the Advancement of AutomotiveMedicine. Annual Scientific Conference, 56, pp. 223–230.

Bai, L., Liu, P., Chen, Y., Zhang, X., Wang, W., 2013. Comparative analysis of the safety effects of electric bikes at signalized intersections. Transp. Res. D Transp. Environ. 20, 48–54.

Bai, L., Liu, P., Guo, Y., Xu, C., 2015. Understanding factors affecting frequency of traffic conflicts between electric bicycles and motorized vehicles at signalized intersections. Transp. Res. Rec. 2514, 68–78.

Baratian-Ghorghi, F., Zhou, H.G., Zech, W.C., 2016. Red-light running traffic violations: a novel time-based method for determining a fine structure. Transp. Res. Part A 93, 55–65.

Battiato, S., Farinella, G.M., Gallo, G., Giudice, O., 2018. On-board monitoring system for road traffic safety analysis. Comput. Ind. 98, 208–217.

Beirlant, J., Goegebeur, Y., Segers, J., Teugels, J., 2004. Statistics of Extremes: Theory and Applications. John Wiley & Sons, Ltd., Wiltshire, UK.

Biondi, F., Strayer, D.L., Rossi, R., Gastaldi, M., Mulatti, C., 2017. Advanced driver assistance systems: using multimodal redundant warnings to enhance road safety. Appl. Ergon. 58, 238–244.

Cafiso, S., Di graziano, A., 2011. Surrogate safety measures for optimizing investments in local rural road networks. Transp. Res. Rec. 2237, 20–30.

Caliendo, C., Guida, M., 2012. Microsimulation approach for predicting crashes at unsignalized intersections using traffic conflicts. J. Transp. Eng. 138, 1453–1467.

Cao, X., Young, W., Sarvi, M., Aghabayk, K., 2014. Automatic discrimination of traffic conflicts during lane changing manoeuvres. In: 26th ARRB Conference. Sydney, New South Wales, Australia: ARRB Group Ltd..

Cao, X., Young, W., Sarvi, M., Kim, I., 2016. Study of mandatory lane change execution behavior model for heavy vehicles and passenger cars. Transp. Res. Rec. 2561, 73–80.

Chai, C., Wong, Y.D., 2015. Comparison of two simulation approaches to safety assessment: cellular automata and SSAM. J. Transp. Eng. 141, 05015002.

Chang, A., Saunier, N., Laureshyn, A., 2017. Proactive Methods for Road Safety Analysis. SAE International.

Chatterjee, I., DAVIS, G.A., 2011. High-resolution detector and signal data to support crash identification and reconstruction. Transp. Res. Rec. 2237, 126–133.

Chen, L., AI, H., Shang, C., Zhuang, Z., Bai, B., 2017. Online multi-object tracking with convolutional neural networks. 2017 IEEE International Conference on Image Processing (ICIP) 645–649, 17-20 Sept. 2017.

Chin, H.-C., Quek, S.-T., 1997. Measurement of traffic conflicts. Saf. Sci. 26, 169–185.

Davis, G.A., Hourdos, J., Xiong, H., Chatterjee, I., 2011. Outline for a causal model of traffic conflicts and crashes. Accid. Anal. Prev. 43, 1907–1919.

Deluka Tibljaš, A., Giuffrè, T., Surdonja, S., Trubia, S., 2018. Introduction of autonomous vehicles: roundabouts design and safety performance evaluation. Sustainability 10.

Dijkstra, A., Drolenga, H., Van Maarseveen, M., 2018. Method for assessing safety of routes in a road network. Transp. Res. Rec. 2019, 82–90.

Dimitriou, L., Stylianou, K., Abdel-aty, M.A., 2018. Assessing Rear-end Crash Potential in Urban Locations Based on Vehicle-by-vehicle Interactions, Geometric Characteristics and Operational Conditions. Accid Anal Prev.

Dingus, T.A., Hetrick, S., Mollenhauer, M., 1999. Empirical methods in support of crash avoidance model building and benefits estimation. ITS J 5, 93–125.

Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., Sudweeks, J., Perez, M.A., Hankey, J., Ramsey, D., Gupta, S., 2006. The 100-car Naturalistic Driving Study, Phase II-results of the 100-car Field Experiment. Virginia Polytechnic Institute and State University, Blacksburg, Washington, D.C.

Dozza, M., Gonzalez, N.P.E., 2012. Recognizing safetycritical events from naturalistic driving data. Procedia 48, 505–515.

Dozza, M., Werneke, J., 2014. Introducing naturalistic cycling data: What factors influence bicyclists' safety in the real world? Transp. Res. Part F 24, 83–91.

Dozza, M., Bianchi piccinini, G.F., Werneke, J., 2016. Using naturalistic data to assess e-cyclist behavior. Transp. Res. Part F 41, 217–226.

El-basyouny, K., Sayed, T., 2013. Safety performance functions using traffic conflicts. Saf. Sci. 51, 160–164.

Essa, M., Sayed, T., 2015a. Simulated traffic conflicts - do they accurately represent field-measured conflicts? Transp. Res. Rec. 2514, 48–57.

Essa, M., Sayed, T., 2015b. Transferability of calibrated microsimulation model parameters for safety assessment using simulated conflicts. Accid. Anal. Prev. 84, 41–53.

Essa, M., Sayed, T., 2016. A comparison between PARAMICS and VISSIM in estimating automated field-measured traffic conflicts at signalized intersections. J. Adv. Transp. 50, 897–917.

Essa, M., Sayed, T., 2019. Full Bayesian conflict-based models for real time safety evaluation of signalized intersections. Accid. Anal. Prev. 129, 367–381.

Essa, M., Sayed, T., Reyad, P., 2019. Transferability of real-time safety performance functions for signalized intersections. Accid. Anal. Prev. 129, 263–276.

Evans, L., 1994. Driver injury and fatality risk in two-car crashes versus mass ratio inferred using Newtonian mechanics. Accid. Anal. Prev. 26, 609–616.

Fallah zavareh, M., Mamdoohi, A.R., Nordfjærn, T., 2017. The effects of indicating rear-end collision risk via variable message signs on traffic behaviour. Transp. Res. Part F 46, 524–536.

Fazekas, A., Hennecke, F., Kallo, E., OESER, M., 2017. A novel surrogate safety Indicator Based on constant initial acceleration and reaction time assumption. J. Adv. Transp. 2017, 9.

Feng, F., Bao, S., Hampshire, R.C., Delp, M., 2018. Drivers overtaking bicyclists-An examination using naturalistic driving data. Accid. Anal. Prev. 115, 98–109.

Fu, T., Miranda-moreno, L., Saunier, N., 2016. Pedestrian crosswalk safety at nonsignalized crossings during nighttime. Transp. Res. Rec. 2586, 90–99.

Fu, T., Stipancic, J., Zangenehpour, S., Miranda-moreno, L., Saunier, N., 2017. Automatic traffic data collection under varying lighting and temperature conditions in multimodal environments: thermal versus visible Spectrum video-Based systems. J. Adv. Transp. 2017, 1–15.

Gao, Y., Zhou, Q., Chai, C., Wong, Y.D., 2018. Safety impact of right-turn waiting area at signalised junctions conditioned on driver's decision-making based on fuzzy cellular automata. Accid. Anal. Prev. 123, 341–349.

Gao, Y., Liu, Y., Hu, H., Ge, Y.E., 2019. Signal optimization for an isolated intersection with illegal permissive left-turning movement. Transp. B Transp. Dyn. 7, 928–949.

Gecchele, G., Orsini, F., Gastaldi, M., Rossi, R., 2019. Freeway rear-end collision risk estimation with extreme value theory approach. A case study. Transp. Res. Procedia 37, 195–202.

Genders, W., Razavi, S.N., 2016. Impact of connected vehicle on work zone network safety through dynamic route guidance. J. Comput. Civ. Eng. 30, 04015020.

Gettman, D., Head, L., 2003. Surrogate safety measures from traffic simulation models. Transp. Res. Rec. 1840, 104–115.

Gettman, D., Pu, L., Sayed, T., Shelby, S.G., 2008. Surrogate Safety Assessment Model and Validation.

Ghanipoor machiani, S., Abbas, M., 2016. Safety surrogate histograms (SSH): a novel real-time safety assessment of dilemma zone related conflicts at signalized intersections. Accid. Anal. Prev. 96, 361–370.

Giuffrè, O., Granà, A., Tumminello, M.L., Giuffrè, T., Trubia, S., Sferlazza, A., Rencelj, M., 2018. Evaluation of roundabout safety performance through surrogate safety measures from microsimulation. J. Adv. Transp. 2018, 14.

Glaser, Y.G., Guo, F., Fang, Y., Deng, B., Hankey, J., 2017. Investigate moped-car conflicts in China using a naturalistic driving study approach. J. Safety Res. 63, 171–175.

Goh, K.C.K., Currie, G., Sarvi, M., Logan, D., 2014. Experimental microsimulation modeling of road safety impacts of bus priority. Transp. Res. Rec. 2402, 9–18.

Gordon, T., Kostyniuk, L., Green, P., Barnes, M., Blower, D., Blankespoor, A., Bogard, S., 2011. Analysis of crash rates and surrogate events - unified approach. Transp. Res. Rec. 2237, 1–9.

Guido, G., Astarita, V., Giofré, V., Vitale, A., 2011. Safety performance measures: a comparison between microsimulation and observational data. Procedia - Soc. Behav. Sci. 20, 217–225.

Guo, F., Klauer, S., Hankey, J., Dingus, T., 2010. Near crashes as crash surrogate for naturalistic driving studies. Transp. Res. Rec. 2147, 66–74.

Guo, Y., Sayed, T., Zaki, M.H., 2018. Exploring evasive action–Based indicators for PTW conflicts in shared traffic facility environments. J. Transp. Eng. Part A Syst. 144, 04018065.

Guo, Y., Essa, M., Sayed, T., Haque, M.M., Washington, S., 2019. A comparison between simulated and field-measured conflicts for safety assessment of signalized intersections in Australia. Transp. Res. Part C 101, 96–110.

Habtemichael, F.G., De picado santos, L., 2014. Crash risk evaluation of aggressive driving on motorways: microscopic traffic simulation approach. Transp. Res. Part F 23, 101–112.

Hallmark, S., Hawkins, N., THAPA, R., KNICKERBOCKER, S., 2018. Evaluation of truck and agricultural vehicle behavior at reduced conflict intersections. Adv. Transp. Stud. 1, 15–24.

Hamann, C.J., Peek-asa, C., 2017. Examination of adult and child bicyclist safety-relevant events using naturalistic bicycling methodology. Accid. Anal. Prev. 102, 1–11.

Haque, M.M., Washington, S., 2014. A parametric duration model of the reaction times of drivers distracted by mobile phone conversations. Accid. Anal. Prev. 62, 42–53.

Haque, M.M., Washington, S., 2015. The impact of mobile phone distraction on the braking behaviour of young drivers: a hazard-based duration model. Transp. Res. Part C 50, 13–27.

Haque, M.M.S., Washington, S., Bunker, J., Sayed, T., Debnath, A.K., Saifuzzaman, M., 2017. Video Analysis of Three Complex Brisbane Intersections: A Safety Evaluation Using Advanced Video Recognition Technology. Queensland University of Technology., Brisbane, Australia.

Hayward, J.C., 1972. Near-miss determination through use of a scale of danger. Highway Res. Rec. 384, 24–34.

Hossain, M., Abdel-aty, M., Quddus, M.A., Muromachi, Y., Sadeek, S.N., 2019. Real-time crash prediction models: state-of-the-art, design pathways and ubiquitous requirements. Accid. Anal. Prev. 124, 66–84.

Huang, F., Liu, P., Yu, H., Wang, W., 2013. Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. Accid. Anal. Prev. 50, 1014–1024.

Hydén, C., 1987. The Development of a Method of Traffic Safety Evaluations: the Swedish Traffic Conflicts Technique. PhD. Lund University.

Iryo-asano, M., Alhajyaseen, W.K.M., 2017. Modeling pedestrian crossing speed profiles considering speed change behavior for the safety assessment of signalized intersections. Accid. Anal. Prev. 108, 332–342.

Ismail, K., Sayed, T., Saunier, N., 2009a. Automated Collection Of Pedestrian Data Using Computer Vision Techniques. Annual Meeting of the Transportation Research Board. Transportation Research Board., Washington, D.C.

Ismail, K., Sayed, T., Saunier, N., 2009b. Automated pedestrian safety analysis using video data in the context of scramble phase intersections. In: Annual Conference of the Transportation Association of Canada. Vancouver, B.C..

Ismail, K., Sayed, T., Saunier, N., 2010a. Automated analysis of pedestrian-vehicle conflicts: context for before-and-After studies. Transp. Res. Rec. 2198, 52–64.

Ismail, K., Sayed, T., Saunier, N., 2010b. Automated safety analysis using video sensors: technology and case studies. In: Canadian Multidisciplinary Road Safety Conference. Niagara Falls, Ontario.

Ismail, K., Sayed, T., Saunier, N., 2011. Methodologies for aggregating indicators of traffic conflict. Transp. Res. Rec. 2237, 10–19.

Ito, D., Hayakawa, K., Kondo, Y., Mizuno, K., Thomson, R., Piccinini, G.B., Hosokawa, N., 2018. Difference between car-to-cyclist crash and near crash in a perpendicular crash configuration based on driving recorder analysis. Accid. Anal. Prev. 117, 1–9.

Jackson, S., Miranda-moreno, L.F., St-aubin, P., Saunier, N., 2013. Flexible, mobile video camera system and open source video analysis software for road safety and behavioral analysis. Transp. Res. Rec. 2365, 90–98.

Jeong, E., Oh, C., Lee, G., Cho, H., 2014. Safety impacts of intervehicle warning information systems for moving hazards in connected vehicle environments. Transp. Res. Rec. 2424, 11–19.

Jeong, E., Oh, C., Lee, S., 2017. Is vehicle automation enough to prevent crashes? Role of traffic operations in automated driving environments for traffic safety. Accid. Anal. Prev. 104, 115–124.

Jo, Y., Oh, C., Kim, S., 2019. Estimation of heavy vehicle-involved rear-end crash potential using WIM data. Accid. Anal. Prev. 128, 103–113.

Jodoin, J.-P., Bilodeau, G.-A., Saunier, N., 2016. Tracking all road users at multimodal urban traffic intersections. IEEE Trans. Intell. Transp. Syst. 17, 3241–3251.

Johnsson, C., Laureshyn, A., De ceunynck, T., 2018a. In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators. Transp. Rev. 1–21.

Johnsson, C., Norén, H., Laureshyn, A., Ivina, D., 2018b. T-Analyst - Semi-automated Tool for Traffic Conflict Analysis. Lund, Sweden: Lund University, Sweden.

Jonasson, J.K., Rootzen, H., 2014. Internal validation of near-crashes in naturalistic driving studies: a continuous and multivariate approach. Accid. Anal. Prev. 62, 102–109.

Jovanis, P., AGuero-valverde, J., Wu, K.-F., Shankar, V., 2011. Analysis of naturalistic driving event data- omitted-variable Bias and multilevel modeling approaches. Transp. Res. Rec. 2236, 49–57.

Kamrani, M., Wali, B., Khattak, A.J., 2017. Can data generated by connected vehicles enhance safety? Transp. Res. Rec. 2659, 80–90.

Kassim, A., Ismail, K., Hassan, Y., 2014. Automated measuring of cyclist – motor vehicle post encroachment time at signalized intersections. Can. J. Civ. Eng. 41, 605–614.

Katrakazas, C., Quddus, M., Chen, W.H., 2019. A new integrated collision risk assessment methodology for autonomous vehicles. Accid. Anal. Prev. 127, 61–79.

Kessler, C., Etemad, A., Alessandretti, G., Heinig, K., Selpi, Brouwer, R., Cserpinszky, A., Hagleitner, W., Benmimoun, M., 2012. EuroFOT-European Large-Scale Field Operational Test on In-Vehicle Systems. Ford Forschungszentrum Aachen GmbH, Aachen, Germany.

Kiec, M., Ambros, J., Bak, R., Gogolin, O., 2018. Evaluation of safety effect of turbo-roundabout lane dividers using floating car data and video observation. Accid. Anal. Prev.

Kim, S., Song, T.-J., Rouphail, N.M., Aghdashi, S., Amaro, A., Gonçalves, G., 2016. Exploring the association of rear-end crash propensity and micro-scale driver behavior. Saf. Sci. 89, 45–54.

Kitchenham, B.A., Budgen, D., PEarl brereton, O., 2011. Using mapping studies as the basis for further research – a participant-observer case study. Inf. Softw. Technol. 53, 638–651.

Klebelsberg, D., 1964. Derzeitiger Sand der Verhaltensanalyse des Kraftfahrens. Zrbeit und Leitsung. Ablt. Arbeitswissenscaft soziale betriebspraxis 18, 33–37.

Kluger, R., Smith, B.L., ParK, H., Dailey, D.J., 2016. Identification of safety-critical events using kinematic vehicle data and the discrete fourier transform. Accid. Anal. Prev. 96, 162–168.

Koppelman, F.S., Wilmot, C.G.J.T.R.R., 1982. Transferability analysis of disaggregate choice models. Transp. Res. Rec. 895, 18–24.

Kraay, J.H., 1982. Proceedings of the Third International workshop on trafficconflictstechniques. In: KRAAY, J.H. (Ed.), Third International Workshop On Traffic Conflicts Techniques. Institute for Road Safety Research, SWOV, Leidschendam, The Netherlands.

Kraay, J.H., HorST, A.R.A.V.D., Oppe, S., 2013. Manual Conflict Observation Technique DOCTOR: Dutch Objective Conflict Technique for Operation and Research. Foundation Road safety for all., Voorburg, The Netherlands.

Kuang, Y., Qu, X., 2014. A review of crashsurrogateevents. In: Second International Conference on Vulnerability and Risk Analysis and Management (ICVRAM) and the Sixth International Symposium on Uncertainty, Modeling, and Analysis (ISUMA). Liverpool, UK: American Society of Civil Engineers.

Kuang, Y., Qu, X., Wang, S., 2014. Propagation and dissipation of crash risk on saturated freeways. Transp. B 2, 203–214.

Kuang, Y., Qu, X., Wang, S., 2015. A tree-structured crash surrogate measure for freeways. Accid. Anal. Prev. 77, 137–148.

Kuang, Y., Yu, Y., Qu, X., 2020. Novel crash surrogate measure for freeways. J. Transp. Eng. Part A Syst. 146.

Laureshyn, A., Ardö, H., Svensson, A., Jonsson, T., 2009. Application of automated video analysis for behavioural studies: concept and experience. IET Intell. Transp. Syst. 3, 345.

Laureshyn, A., Svensson, A., Hyden, C., 2010. Evaluation of traffic safety, based on micro-level behavioural data: theoretical framework and first implementation. Accid. Anal. Prev. 42, 1637–1646.

Laureshyn, A., De ceunynck, T., Karlsson, C., Svensson, A., Daniels, S., 2017a. In search of the severity dimension of traffic events: extended Delta-V as a traffic conflict indicator. Accid. Anal. Prev. 98, 46–56.

Laureshyn, A., Johnsson, C., Madsen, T., Varhelyi, A., De Goede, M., Svensson, Å., Saunier, N., Van haperen, W., 2017b. Exploration of a method to validate surrogate safety measures with a focus on vulnerable road users. In: Road Safety & Simulation International Conference. The Hague, Netherlands, 17-19 October 2017.

Lee, C., So, J.J., Ma, J., 2018. Evaluation of countermeasures for red light running by traffic simulator-based surrogate safety measures. Traffic Inj. Prev. 19, 1–8.

Li, X., Yan, X., Li, X., Wang, J., 2012. Using cellular automata to investigate pedestrian conflicts with vehicles in Crosswalk at signalized intersection. Discrete Dyn. Nat. Soc. 2012, 1–16.

Li, Z., Ahn, S., Chung, K., Ragland, D.R., Wang, W., Yu, J.W., 2014a. Surrogate safety measure for evaluating rear-end collision risk related to kinematic waves near freeway recurrent bottlenecks. Accid. Anal. Prev. 64, 52–61.

Li, Z., Li, Y., Liu, P., Wang, W., Xu, C., 2014b. Development of a variable speed limit strategy to reduce secondary collision risks during inclement weathers. Accid. Anal. Prev. 72, 134–145.

Li, J., Liu, Y., Tageldin, A., Zaki, M.H., Mori, G., Sayed, T., 2015. Automated region-based vehicle conflict detection using computer vision techniques. Transp. Res. Rec. 2528, 49–59.

Li, Y., Wang, H., Wang, W., Liu, S., Xiang, Y., 2016. Reducing the risk of rear-end collisions with infrastructure-to-vehicle (I2V) integration of variable speed limit control and adaptive cruise control system. Traffic Inj. Prev. 17, 597–603.

Li, Y., Li, Z., Wang, H., Wang, W., Xing, L., 2017. Evaluating the safety impact of adaptive cruise control in traffic oscillations on freeways. Accid. Anal. Prev. 104, 137–145.

Liu, J., Khattak, A.J., 2016. Delivering improved alerts, warnings, and control assistance using basic safety messages transmitted between connected vehicles. Transp. Res. Part C 68, 83–100.

Lu, G., Cheng, B., Kuzumaki, S., Mei, B., 2011. Relationship between road traffic accidents and conflicts recorded by drive recorders. Traffic Inj. Prev. 12, 320–326.

Lubbe, N., 2017. Brake reactions of distracted drivers to pedestrian forward Collision Warning systems. J. Safety Res. 61, 23–32.

Lundgren, J., Tapani, A., 2006. Evaluation of safety effects of driver assistance systems through traffic simulation. Transp. Res. Rec. 1953, 81–88.

Ma, W., Liao, D., Liu, Y., Lo, H.K., 2015. Optimization of pedestrian phase patterns and signal timings for isolated intersection. Transp. Res. Part C 58, 502–514.

Madsen, T.K.O., Lahrmann, H., 2017. Comparison of five bicycle facility designs in signalized intersections using traffic conflict studies. Transp. Res. Part F 46, 438–450.

Mahmud, S.M.S., Ferreira, L., Hoque, M.S., Tavassoli, A., 2017. Application of proximal surrogate indicators for safety evaluation: a review of recent developments and research needs. IATSS Res. 41, 153–163.

Mahmud, S.M.S., Ferreira, L., Hoque, M.S., Tavassoli, A., 2018. Micro-simulation modelling for traffic safety: a review and potential application to heterogeneous traffic environment. IATSS Res.

Matsui, Y., Hitosugi, M., Takahashi, K., Doi, T., 2013. Situations of car-to-pedestrian contact. Traffic Inj. Prev. 14, 73–77.

Medicine, A.F.T.A.O.A., 2018. Abbreviated Injury Scale: 2015 Revision, 6 ed. Association for the Advancement of Automotive Medicine, Chicago, IL.

Mehrara molan, A., Hummer, J.E., Ksaibati, K., 2019. Modeling safety performance of the new super DDI design in terms of vehicular traffic and pedestrian. Accid. Anal. Prev. 127, 198–209.

Mehta, K., Mehran, B., Hellinga, B., 2019. A methodology to estimate the number of unsafe vehicle-cyclist passing events on urban arterials. Accid. Anal. Prev. 124, 92–103.

Mirheli, A., Hajibabai, L., Hajbabaie, A., 2018. Development of a signal-head-free intersection control logic in a fully connected and autonomous vehicle environment. Transp. Res. Part C 92, 412–425.

Oh, C., Kim, T., 2010. Estimation of rear-end crash potential using vehicle trajectory data. Accid. Anal. Prev. 42, 1888–1893.

Oh, C., Park, S., Ritchie, S.G., 2006. A method for identifying rear-end collision risks using inductive loop detectors. Accid. Anal. Prev. 38, 295–301.

Olszewski, P., Czajewski, W., Osińska, B., Szagała, P., Włodarek, P., 2019. Investigation of traffic conflicts at signalised intersections in Warsaw. MATEC Web of Conferences 262.
Orsini, F., Gecchele, G., Gastaldi, M., Rossi, R., 2018. Collision prediction in roundabouts: a comparative study of extreme value theory approaches. Transp. A 1–17.
Oskarbski, J., Gumińska, L., ŻARSKI, K., 2018. Influence of Toll Collection Method on Motorways on Traffic Safety and Efficiency, 897, pp. 142–156.
Ozbay, K., Yang, H., Bartin, B., Mudigonda, S., 2008. Derivation and validation of new simulation-based surrogate safety measure. Transp. Res. Rec. 2083, 105–113.
Park, H., Oh, C., 2019. A vehicle speed harmonization strategy for minimizing inter-vehicle crash risks. Accid. Anal. Prev. 128, 230–239.
Park, B., Chen, Y., Hourdos, J., 2011. Opportunities for preventing rear-end crashes: findings from the analysis of actual freeway crash data. J. Transp. Saf. Secur. 3, 95–107.
Park, H., Oh, C., Moon, J., Kim, S., 2018. Development of a lane change risk index using vehicle trajectory data. Accid. Anal. Prev. 110, 1–8.
Pawar, D.S., Kumar, V., Singh, N., Patil, G.R., 2016. Analysis of dilemma zone for pedestrians at high-speed uncontrolled midblock crossing. Transp. Res. Part C 70, 42–52.
Peesapati, L., Hunter, M., Rodgers, M., 2013. Evaluation of postencroachment time as surrogate for opposing left-turn crashes. Transp. Res. Rec. 2386, 42–51.
Peesapati, L.N., Hunter, M.P., Rodgers, M.O., 2018. Can post encroachment time substitute intersection characteristics in crash prediction models? J. Safety Res.
Perez, M.A., Sudweeks, J.D., Sears, E., Antin, J., Lee, S., Hankey, J.M., Dingus, T.A., 2017. Performance of basic kinematic thresholds in the identification of crash and near-crash events within naturalistic driving data. Accid. Anal. Prev. 103, 10–19.
Perkins, S.R., Harris, J.L.J.H.R.R., 1968. Traffic Conflict Characteristics-accident Potential at Intersections.
Persaud, B., Saleem, T., Granados, M.E., Rajeswaran, T., 2018. Can crash modification factors be estimated from surrogate measures of safety? Adv. Transp. Stud.: Int. J. 1, 149–162.
Petersen, K., Vakkalanka, S., Kuzniarz, L., 2015. Guidelines for conducting systematic mapping studies in software engineering: an update. Inf. Softw. Technol. 64, 1–18.
Petzoldt, T., 2014. On the relationship between pedestrian gap acceptance and time to arrival estimates. Accid. Anal. Prev. 72, 127–133.
Preuk, K., Stemmler, E., Schiessl, C., Jipp, M., 2016. Does assisted driving behavior lead to safety-critical encounters with unequipped vehicles' drivers? Accid. Anal. Prev. 95, 149–156.
Qin, L., Persaud, B., Saleem, T., 2018. Safety evaluation of freeway acceleration lanes based on crashes and simulated conflicts. Can. J. Civ. Eng. 45, 51–60.
Rahman, M.S., Abdel-aty, M., 2018. Longitudinal safety evaluation of connected vehicles' platooning on expressways. Accid. Anal. Prev. 117, 381–391.
Rahman, Z., Mattingly, S.P., Kawadgave, R., Nostikasari, D., Roeglin, N., Casey, C., Johnson, T., 2019. Using crowd sourcing to locate and characterize conflicts for vulnerable modes. Accid. Anal. Prev. 128, 32–39.
Sacchi, E., Sayed, T., 2016. Conflict-based safety performance functions for predicting traffic collisions by type. Transp. Res. Rec. 2583, 50–55.
Sacchi, E., Sayed, T., Deleur, P., 2013. A comparison of collision-based and conflict-based safety evaluations: the case of right-turn smart channels. Accid. Anal. Prev. 59, 260–266.
Saccomanno, F.F., Cunto, F., Guido, G., Vitale, A., 2008. Comparing safety at signalized intersections and roundabouts using simulated rear-end conflicts. Transp. Res. Rec. 2078, 90–95.
Sander, U., 2017. Opportunities and limitations for intersection collision intervention: a study of real world left turn across path accidents. Accid. Anal. Prev. 99, 342–355.
Saunier, N., Sayed, T., 2007. Automated analysis of road safety with video data. Transp. Res. Rec. 2019, 57–64.
Saunier, N., Sayed, T., Ismail, K., 2010. Large-scale automated analysis of vehicle interactions and collisions. Transp. Res. Rec. 2147, 42–50.
Sayed, T., Ismail, K., Zaki, M.H., Autey, J., 2012. Feasibility of computer vision-based safety evaluations - case study of a signalized right-turn safety treatment. Transp. Res. Rec. 2280, 18–27.
Sayed, T., Zein, S., 1999. Traffic conflict standards for intersections. Transp. Plan. Technol. 22, 309–323.
Shahdah, U.E., Saccomanno, F.F., Persaud, B., 2012. Integrating observational and traffic simulation models for priority ranking of unsafe intersections. Transp. Res. Rec. 2280, 118–126.
Shahdah, U., Saccomanno, F., Persaud, B., 2014. Integrated traffic conflict model for estimating crash modification factors. Accid. Anal. Prev. 71, 228–235.
Shahdah, U., Saccomanno, F., Persaud, B., 2015. Application of traffic microsimulation for evaluating safety performance of urban signalized intersections. Transp. Res. Part C 60, 96–104.
Shen, S., Di, X., Liu, H.X., Misgen, S., 2017. Estimation of crossingconflict at signalizedintersectionusing High-Resolution trafficdata. In: Transportation Research Board 96th Annual Meeting. Washington DC, United States: Transportation Research Board..
Shew, C., Pande, A., Nuworsoo, C., 2013. Transferability and robustness of real-time freeway crash risk assessment. J. Safety Res. 46, 83–90.
Shirazi, M.S., Morris, B., 2015. Safety Quantification of Intersections Using Computer Vision Techniques. Cham. Springer International Publishing, pp. 752–761.
So, J., Lim, I.-K., Kweon, Y.-J., 2015. Exploring traffic conflict-based surrogate approach for safety assessment of highway facilities. Transp. Res. Rec. 2513, 56–62.
Sobhani, A., Young, W., Logan, D., Bahrololoom, S., 2011. A kinetic energy model of two-vehicle crash injury severity. Accid. Anal. Prev. 43, 741–754.
Songchitruksa, P., Tarko, A., 2006a. Practical method for estimating frequency of right-angle collisions at traffic signals. Transp. Res. Rec. 1953, 89–97.
Songchitruksa, P., Tarko, A.P., 2006b. The extreme value theory approach to safety estimation. Accid. Anal. Prev. 38, 811–822.
Songchitruksa, P., Zha, L., 2014. Advancing safety performance monitoring at signalized intersections through use of connected vehicle technology. Transp. Res. Rec. 2432, 99–109.
St-aubin, P., Miranda-moreno, L., Saunier, N., 2012. A surrogatesafetyanalysis at protectedfreewayrampsusing Cross-sectional and Before-aftervideodata. In: Transportation Research Board 91st Annual Meeting. Washington DC, United States: Transportation Research Board.
St-aubin, P., Saunier, N., Miranda-moreno, L., 2015. Large-scale automated proactive road safety analysis using video data. Transp. Res. Part C 58, 363–379.
Stevanovic, A., Stevanovic, J., Kergaye, C., 2013. Optimization of traffic signal timings based on surrogate measures of safety. Transp. Res. Part C 32, 159–178.
Stevanovic, A., Stevanovic, J., SO, J., Ostojic, M., 2015. Multi-criteria optimization of traffic signals: mobility, safety, and environment. Transp. Res. Part C 55, 46–68.
Stipancic, J., Miranda-moreno, L.F., Saunier, N., 2015. Traffic parameter methods for surrogate safety- comparative study of three non-intrusive sensor technologies. In: Canadian Association of Road Safety Professionals (CARSP) Conference. Ottawa, Ontario.
Stipancic, J., Miranda-moreno, L., Saunier, N., 2018a. Vehicle manoeuvers as surrogate safety measures: extracting data from the gps-enabled smartphones of regular drivers. Accid. Anal. Prev. 115, 160–169.
Stipancic, J., Miranda-moreno, L., Saunier, N., Labbe, A., 2018b. Surrogate safety and network screening: modelling crash frequency using GPS travel data and latent Gaussian Spatial Models. Accid. Anal. Prev. 120, 174–187.
Strauss, J., Zangenehpour, S., Miranda-moreno, L.F., Saunier, N., 2017. Cyclist deceleration rate as surrogate safety measure in Montreal using smartphone GPS data. Accid. Anal. Prev. 99, 287–296.
Tageldin, A., Sayed, T., 2018. Models to evaluate the severity of pedestrian-vehicle conflicts in five cities. Transp. A 1–22.
Tageldin, A., Sayed, T., Wang, X., 2015. Can time proximity measures Be used as safety indicators in all driving cultures? Case study of motorcycle safety in China. Transp. Res. Rec. 2520, 165–174.
Tageldin, A., Zaki, M.H., Sayed, T., 2017. Examining pedestrian evasive actions as a potential indicator for traffic conflicts. Iet Intell. Transp. Syst. 11, 282–289.
Tarko, A.P., 2012. Use of crash surrogates and exceedance statistics to estimate road safety. Accid. Anal. Prev. 45, 230–240.
Tarko, A.P., 2018a. Chapter 17. Surrogate Measures of Safety. Safe Mobility: Challenges, Methodology and Solutions.
Tarko, A.P., 2018b. Estimating the expected number of crashes with traffic conflicts and the Lomax Distribution - A theoretical and numerical exploration. Accid. Anal. Prev. 113, 63–73.
Tarko, A., Davis, G., Saunier, N., Sayed, T., Washington, S., 2009. Surrogate Measures of Safety (White Paper). ANB20 Committee on Safety Data Evaluation and Analysis.
Tian, D., Yuan, Y., Wang, J., Xia, H., Wang, J., 2017. Collision avoidance on winding roads using dedicated short-range communication. Transport 33, 461–469.
Van der horst, A.R., De goede, M., DE HAIR-BUIJSSEN, S., METHORST, R., 2014. Traffic conflicts on bicycle paths: a systematic observation of behaviour from video. Accid. Anal. Prev. 62, 358–368.
Van haperen, W., Daniels, S., De ceunynck, T., Saunier, N., BRIJS, T., WETS, G., 2018. Yielding behavior and traffic conflicts at cyclist crossing facilities on channelized right-turn lanes. Transp. Res. Part F 55, 272–281.
Wali, B., Khattak, A.J., Bozdogan, H., Kamrani, M., 2018. How is driving volatility related to intersection safety? A Bayesian heterogeneity-based analysis of instrumented vehicles data. Transp. Res. Part C 92, 504–524.
Wali, B., Khattak, A.J., Karnowski, T., 2019. Exploring microscopic driving volatility in naturalistic driving environment prior to involvement in safety critical events-Concept of event-based driving volatility. Accid. Anal. Prev. 132, 105277.
Wang, C., Stamatiadis, N., 2014a. Derivation of a new surrogate measure of crash severity. Transp. Res. Rec. 2432, 37–45.
Wang, C., Stamatiadis, N., 2014b. Evaluation of a simulation-based surrogate safety metric. Accid. Anal. Prev. 71, 82–92.
Wang, X., Xu, X., 2019. Assessing the relationship between self-reported driving behaviors and driver risk using a naturalistic driving study. Accid. Anal. Prev. 128, 8–16.
Wang, J., Zheng, Y., Li, X., Yu, C., KODAKA, K., LI, K., 2015a. Driving risk assessment using near-crash database through data mining of tree-based model. Accid. Anal. Prev. 84, 54–64.
Wang, X., Khattak, A.J., Liu, J., MASGHATI-AMOLI, G., SON, S., 2015b. What is the level of volatility in instantaneous driving decisions? Transp. Res. Part C 58, 413–427.
Wang, J., Wu, J., Zheng, X., Ni, D., Li, K., 2016. Driving safety field theory modeling and its application in pre-collision warning system. Transp. Res. Part C 72, 306–324.
Wang, J., Zeng, X., An, W., 2018. Convolutional neuralnetwork-based simpleonlinemultipleobjecttracking. 2018 IEEE 4th International Conference on Computer and Communications (ICCC), 7-10 Dec. 2018 2091–2094.
Wang, C., Xu, C., Dai, Y., 2019. A crash prediction method based on bivariate extreme value theory and video-based vehicle trajectory data. Accid. Anal. Prev. 123, 365–373.
Ward, J.R., Agamennoni, G., Worrall, S., Bender, A., Nebot, E., 2015. Extending Time to Collision for probabilistic reasoning in general traffic scenarios. Transp. Res. Part C 51, 66–82.
Warner, J., Hurwitz, D.S., Monsere, C.M., Fleskes, K., 2017. A simulator-based analysis of engineering treatments for right-hook bicycle crashes at signalized intersections. Accid. Anal. Prev. 104, 46–57.

Wei, Y., Li, K., Tang, K., 2019. Trajectory-based identification of critical instantaneous decision events at mixed-flow signalized intersections. Accid. Anal. Prev. 123, 324–335.

Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering. Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14.

Wu, K.F., Jovanis, P.P., 2012. Crashes and crash-surrogate events: exploratory modeling with naturalistic driving data. Accid. Anal. Prev. 45, 507–516.

Wu, K.F., Jovanis, P.P., 2013. Defining and screening crash surrogate events using naturalistic driving data. Accid. Anal. Prev. 61, 10–22.

Wu, J., Xu, H., Zheng, Y., Tian, Z., 2018a. A novel method of vehicle-pedestrian near-crash identification with roadside LiDAR data. Accid. Anal. Prev. 121, 238–249.

Wu, K.F., Ardiansyah, M.N., YE, W.J., 2018b. An evaluation scheme for assessing the effectiveness of intersection movement assist (IMA) on improving traffic safety. Traffic Inj. Prev. 19, 179–183.

Wu, Y., Abdel-aty, M., Cai, Q., Lee, J., Park, J., 2018c. Developing an algorithm to assess the rear-end collision risk under fog conditions using real-time data. Transp. Res. Part C 87, 11–25.

Wu, Y., Abdel-aty, M., Ding, Y., Jia, B., Shi, Q., Yan, X., 2018d. Comparison of proposed countermeasures for dilemma zone at signalized intersections based on cellular automata simulations. Accid. Anal. Prev. 116, 69–78.

Wu, Y., Abdel-aty, M., Lee, J., 2018e. Crash risk analysis during fog conditions using real-time traffic data. Accid. Anal. Prev. 114, 4–11.

Xiang, W., Yan, X., Weng, J., Li, X., 2016. Effect of auditory in-vehicle warning information on drivers' brake response time to red-light running vehicles during collision avoidance. Transp. Res. Part F 40, 56–67.

Xie, K., Ozbay, K., Yang, H., Li, C., 2019. Mining automatically extracted vehicle trajectory data for proactive safety analytics. Transp. Res. Part C 106, 61–72.

Xiong, X., Wang, M., Cai, Y., Chen, L., Farah, H., Hagenzieker, M., 2019. A forward collision avoidance algorithm based on driver braking behavior. Accid. Anal. Prev. 129, 30–43.

Yamada, K., Kuroki, M., 2019. New traffic conflict measure based on a potential outcome model. J. Causal Inference 7.

Yan, X., Zhang, Y., Ma, L., 2015. The influence of in-vehicle speech warning timing on drivers' collision avoidance performance at signalized intersections. Transp. Res. Part C 51, 231–242.

Yang, H., Ozbay, K., Bartin, B., 2010. Application of Simulation-based Traffic Conflict Analysis for Highway Safety Evaluation.

Yang, K., Yu, R., Wang, X., Quddus, M., Xue, L., 2018. How to determine an optimal threshold to classify real-time crash-prone traffic conditions? Accid. Anal. Prev. 117, 250–261.

Young, W., Archer, J., 2009. Traffic microsimulation modeling to study a traffic signal incident reduction function. Transp. Res. Rec. 2103, 80–87.

Young, W., Sobhani, A., Lenné, M.G., Sarvi, M., 2014. Simulation of safety: a review of the state of the art in road safety simulation modelling. Accid. Anal. Prev. 66, 89–103.

Yuan, J., Abdel-aty, M., Cai, Q., Lee, J., 2019a. Investigating drivers' mandatory lane change behavior on the weaving section of freeway with managed lanes: a driving simulator study. Transp. Res. Part F 62, 11–32.

Yuan, J., Abdel-aty, M., Gong, Y., Cai, Q., 2019b. Real-time crash risk prediction using long short-term memory recurrent neural network. Transp. Res. Rec. 2673, 314–326.

Zaki, M.H., Sayed, T., Ismail, K., Alrukaibi, F., 2012. Use of computer vision to identify pedestrians' nonconforming behavior at urban intersections. Transp. Res. Rec. 2279, 54–64.

Zangenehpour, S., Strauss, J., Miranda-moreno, L.F., Saunier, N., 2016. Are signalized intersections with cycle tracks safer? A case-control study based on automated surrogate safety analysis using video data. Accid. Anal. Prev. 86, 161–172.

Zhang, C., Zhou, B., Chen, G., Chen, F., 2017. Quantitative analysis of pedestrian safety at uncontrolled multi-lane mid-block crosswalks in China. Accid. Anal. Prev. 108, 19–26.

Zhang, Y., YaN, X., Li, X., Wu, J., 2018. Changes of drivers' visual performances when approaching a signalized intersection under different collision avoidance warning conditions. Transp. Res. Part F.

Zhang, Q., Yang, Z., Sun, D., 2019. Automated data collection and safety analysis at intersections based on a novel video processing system. Transp. Res. Rec.

Zhao, X., Li, Q., Xie, D., Bi, J., Lu, R., Li, C., 2018. Risk perception and the warning strategy based on microscopic driving state. Accid. Anal. Prev. 118, 154–165.

Zhao, X., Xu, W., Ma, J., Li, H., Chen, Y., Rong, J., 2019. Effects of connected vehicle-based variable speed limit under different foggy conditions based on simulated driving. Accid. Anal. Prev. 128, 206–216.

Zheng, L., Ismail, K., 2017. A generalized exponential link function to map a conflict indicator into severity index within safety continuum framework. Accid. Anal. Prev. 102, 23–30.

Zheng, L., Sayed, T., 2019a. Application of extreme value theory for before-after road safety analysis. Transp. Res. Rec.

Zheng, L., Sayed, T., 2019b. Bayesian hierarchical modeling of traffic conflict extremes for crash estimation: a non-stationary peak over threshold approach. Anal. Methods Accid. Res.

Zheng, L., Sayed, T., 2019c. From univariate to bivariate extreme value models: approaches to integrate traffic conflict indicators for crash estimation. Transp. Res. Part C 103, 211–225.

Zheng, L., Ismail, K., Meng, X., 2014a. Freeway safety estimation using extreme value theory approaches: a comparative study. Accid. Anal. Prev. 62, 32–41.

Zheng, L., Ismail, K., Meng, X., 2014b. Traffic conflict techniques for road safety analysis: open questions and some insights. Can. J. Civ. Eng. 41, 633–641.

Zheng, L., Ismail, K., Meng, X., 2015. Evaluation of peak over threshold approach for road safety estimation. J. Transp. Saf. Secur. 7, 76–90.

Zheng, L., Ismail, K., Meng, X., 2016. Investigating the heterogeneity of postencroachment time thresholds determined by peak over threshold approach. Transp. Res. Rec. 2601, 17–23.

Zheng, L., Ismail, K., Sayed, T., Fatema, T., 2018. Bivariate extreme value modeling for road safety estimation. Accid. Anal. Prev. 120, 83–91.

Zheng, L., Sayed, T., Essa, M., 2019a. Bayesian hierarchical modeling of the non-stationary traffic conflict extremes for crash estimation. Anal. Methods Accid. Res.

Zheng, L., Sayed, T., Essa, M., Guo, Y., 2019b. Do simulatedtrafficconflictspredictcrashes? An investigationusing the extremevalue Approach*. 2019 IEEE Intelligent Transportation Systems Conference (ITSC), 27-30 Oct. 2019 631–636.

Zhou, S., Sun, J., An, X., Li, K., 2011. The development of a conflict hazardous assessment model for evaluating urban intersection safety. Transport 26, 216–223.