Traffic conflict techniques for road safety analysis: open questions and some insights

Lai Zheng, Karim Ismail, and Xianghai Meng

Abstract: Developing non-crash or surrogate measures of road safety has drawn considerable research interest over the past five decades. Traffic conflict techniques, which analyze the safety situations from the aspect of more observable traffic events than crashes, are the most prominent techniques to date. This study provides a comprehensive review of previous research on traffic conflict techniques, striving to find answers to the following open questions: What is a traffic conflict? How to collect the traffic conflict data? And what is the ground to claim that traffic conflicts can be valid surrogates for crashes? The strengths and weaknesses of available answers to these questions are assessed based on methodological and empirical grounds. Directions for the future research are identified and outlined. It is believed that following recommended future directions may offer convincing answers to identified open questions.

Key words: road safety, traffic conflict technique, conflict data collection, validity, literature review.

1. Introduction

Due to the enormous social losses caused by road crashes, safety researchers are on a continual mission to gain a better understanding of factors that affect the crash occurrence and severities (Lord and Manering 2010; Savolainen et al. 2011). These research efforts rely highly on historical crash records, which have well-recognized availability and quality problems. Moreover, observing “crashes” to prevent “crashes” is a reactive approach that is often criticized by its poor timeliness from an ethical standpoint. All of these problems associated with the crash data motivate the development of surrogate measures of safety, the most prominent of which proposed over the past years is the traffic conflict.

With almost 50 years in development, there is a reasonable agreement on the usefulness of traffic conflicts as a surrogate or complementary measure of road safety. Based on forthcoming review, it could be argued that traffic conflict techniques are now passing a transitional period from experiment to application stages. A review of previous studies can help researchers and practicing engineers to gain better understanding of traffic conflict techniques and make informed use of them as well as expand the overall knowledge. This paper is aimed at providing a comprehensive review of studies on the subject of traffic conflict techniques. The review highlights the advantages and disadvantages of different aspects of current traffic conflict techniques, and recommending directions for future research. To do this, the paper mainly answers three questions: What is a traffic conflict? How to collect the traffic conflict data? And what is the ground to claim that traffic conflicts can be valid surrogates for crashes?

2. Definitions of traffic conflicts and conceptual issues

Despite decades of conceptual development and widespread application, there are still some disputes on what traffic conflict is. This finding may raise a question as to whether a traffic conflict should in fact be defined and separated from other non-conflict events. In subsequent parts of this review, studies point out that a continuum of all traffic events are presented in traffic both conflicts and collisions being some extreme manifestation of the process generating all traffic events. Thus the focus shifts from objectively defining the boundary between a conflict and a non-conflict event to searching for a severity dimension along which all traffic events can be arranged. This severity dimension should not merely exist in an abstract sense, but be quantified using objective severity measures.

This attempt however to abandon the definition of a traffic conflict in favor of a unified severity dimension leads away from...
and regular (less severe) events. On the other end, this definition of a conflict is prone to creating a vague boundary between conflict and non-conflict events. (Chin and Quek 1997). The use of evasive actions as a definition of conflict is essentially precautionary ones that do not indicate dangerous situations; a conceptual challenge to the reliance on evasive action in traffic safety. Given these competing views, this review provides a balanced account of both approaches: counting traffic conflicts or quantify a severity dimension which accommodates conflict and non-conflict events.

Different definitions are usually based on underlying understanding on what a traffic conflict is. It is possible to group almost all of the operational definitions of the traffic conflict into two types: those based on evasive actions and those based on temporal (and (or) spatial) proximity. However, none of these types of traffic conflicts have been universally adopted to date. A summary of two types of traffic conflict definitions and conceptual issues is presented as below.

2.1. Traffic conflicts marked by evasive actions

According to this definition, whether an observed situation is a traffic conflict is identified by the appearance of evasive actions. (Perkins and Harris 1968) firstly proposed this idea and adopted the traffic conflict as an operational tool in road safety research. The evasive action based traffic conflicts are now used in many countries such as the USA, France, Norway, and Finland (Muhlrad 1982; Kulmala 1982; Parker and Zegeer 1989; Dingus et al. 2006a; Phillips et al. 2011). A representative definition of evasive action based traffic conflict is "... an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision" (Parker and Zegeer 1989). This definition implies that conflicts and crashes are of similar nature except for the presence and the success of an evasive action.

Without the aid of complicated equipment or advanced techniques, observers may be able to register the appearance of traffic conflicts if a list of the possible evasive actions associated with traffic conflicts could be specified. This approach however is challenged on many accounts. First, creating such an exhaustive list of all possible evasive actions is challenging. It is arguable that braking action alone has different variations depending on time of action initiation and intensity of braking action. Second, whether an evasive action can be fully characterized by simple field observations is questionable. Third, whether the presence and intensity of evasive action is the only dimension to measure severity (e.g., regardless of how close the road users are) is questionable. Besides, a conceptual challenge to the reliance on evasive action in defining traffic conflicts arise when relating them to crashes, because many crashes happen without any evasive action being taken and some evasive actions as braking or lane changing are essentially precautionary ones that do not indicate dangerous situations (Allen et al. 1978; Glauz and Migletz 1980; Gardner 1989; Chin and Quek 1997). The use of evasive actions as a definition of a conflict is prone to creating a vague boundary between conflict and regular (less severe) events. On the other end, this definition creates a solid boundary with crash events, which either involve a failed evasive action or no evasive action at all. On conceptual grounds, it can be argued that this solid boundary also precludes the classic statistical framework based on count models. This is a significant disadvantage because count models, e.g., the classic negative binomial regression, are well-established in the literature of traffic safety. Given this competing views, this review provides a balanced account of both approaches: counting traffic conflicts or quantify a severity dimension which accommodates conflict and non-conflict events.

2.2. Temporal (and (or) spatial) proximity based traffic conflicts

According to this definition, whether an observed situation is a traffic conflict or not is determined by how close in time and (or) space of the involved road users. A representative definition of proximity based traffic conflict is "... 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 Hydén 1977). This is more of a conceptual (theoretical) definition and to make it operational, researchers developed many proximity measures as shown in Table 1. The most popular measures are on the basis of temporal proximity because they integrate both the spatial proximity and the speed, and there are also some measures based solely on spatial proximity. Given the values of some measure of traffic events, traffic conflicts will be registered once the values of the measure is less than a predetermined threshold (Shariat-Mohaymany et al. 2011; Huang et al. 2013; Sayed et al. 2013).

Measures of proximity play an important role in traffic conflict techniques, but there are still issues related to these measures. The first is that although there are many traffic conflict measures, no consensus has been reached on what measures should be used (Guido et al. 2011). The reason might be various measures are different in nature and have their preferable application conditions. Since different measures provide different cues for the underlying level of safety, some researchers suggested the integration use of various measures of traffic conflicts (Kaparias et al. 2010; Laureshyn et al. 2010; Ismail et al. 2011; Salamati et al. 2011; Lu et al. 2012).

The second issue is that almost all of the traffic conflict measures are limited to estimate crash risk with no further account of the possible consequences of a potential crash (Laureshyn et al. 2010; Bagdadi 2013a). This limitation places the severity of traffic conflicts (i.e., the proximity to a crash) and the severity of crashes (i.e., the outcomes of a crash, such as damage only, slight injury, serious injury, and fatal) into two dimensions and brings difficulties when taking all traffic events in a safety continuum. The use of TA (i.e., the time to collision recorded at the time when the evasive action is first taken) and conflicting speed in Swedish traffic conflict technique (Hydén 1987; Svensson 1998; Svensson and Hydén 2006) is an exception, since the conflicting speed can be taken as a measure related to the severity of crashes. However, many studies on severity of crashes showed that the consequence of a crash is dependent not only on the speed but also the mass of involved road users and the angle of a collision (Hydén et al. 1982; Hutchinson 1977; Evans 2001), so the considering of speed only is not sufficient. Bagdadi (2013a) developed a measure incorporating the time to accident, mass, speed, and deceleration to estimate the severity of traffic events in a homogenous way.

The third issue is related to the measures which assume the "unchanged speed and direction", and some researchers assumed

<table>
<thead>
<tr>
<th>Type</th>
<th>Traffic conflict measures</th>
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<tbody>
<tr>
<td>Temporal proximity</td>
<td>Time to collision (TTC) (Hayward 1971), post encroachment time (PET) (Cooper 1984), time to accident (TA) (Hydén 1987), time to stop line (van der Horst 1990), deceleration to safety time (Topp 1998), time exposed time-to-collision (Muhlrad and Bovy 2001), time integrated time-to-collision (Muhlrad and Bovy 2001), time to line crossing (Vogel 2003a), gap time (Gettman and Head 2003), initially attempted post encroachment time (Gettman and Head 2003), encroachment time (Gettman and Head 2003), headway (Vogel 2003b), time advantage (Laureshyn et al. 2010), time to departure (Tarko 2012), braking time (Lu et al. 2012)</td>
</tr>
<tr>
<td>Spatial proximity</td>
<td>Remaining distance to potential point of collision (Allen et al. 1978), proportion of stopping distance (Gettman and Head 2003), range or range rate (Najm and Smith 2004), lateral distance to departure (Tarko 2012)</td>
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</tbody>
</table>
ununchanged directions and constant acceleration or decelerations (van der Horst 1990). However, because of the complex behavior of road users, these simple assumptions and extrapolation have a lot of limitations. Thus, some researchers suggested to consider all the possible options for the road users during the encounter and established probabilistic measures (Saunier and Sayed 2008; Saunier et al. 2010; Berthelot et al. 2012).

2.3. Conceptual issues

Both the evasive action based and proximity based traffic conflicts possess two important conceptual issues, i.e., process model validity and severity consistency.

2.3.1. Process model validity

The process model describes the traffic process based on the understanding of how a crash occurs, and the validity issue arises from the confusion about the place of the traffic conflict in the traffic process. Some researchers argue that the traffic conflict and the collision are two mutually exclusive outcomes depending on the presence as well as the degree of success of an evasive action. In such, the occurrence of a traffic conflict as an event complements the collision (Güttinger 1982; Brown and Cooper 1990; Rajesh 1995). The opposite argument is that the traffic conflict precedes the evasive action and can be either successful (leading to traffic continuation) or not successful (leading to collision). Although there is no agreement on the process model validity, the latter argument gained popularity.

2.3.2. Severity inconsistency

The severity of traffic conflicts is identified by either the intensity of evasive actions (Campbell and King 1970; Malaterre and Muhlrad 1977) or the proximity in time and (or) space (referring to the conflict measures).

The identification based on intensity of evasive actions divides traffic events into different groups in a qualitative way. However, consistent judgments across different groups of observers have been proved difficult by early international comparative studies. An example is the international calibration study undertaken at Malmö in Sweden in 1983, and the results showed that although certain agreement in the rank ordering of conflicts according to severity had been reached, variations in conflict detection rates were apparent (Grayson et al. 1984). Due to issues with consistency, in recent time traffic conflicts are mainly determined using objective measures, and the subjective assessment might be used as a supplement to the objective measures (Sayed and Zein 1999).

The proximity in time and (or) space provides a quantitative way to distinguish conflicts and non-conflict events, but the threshold values vary across studies from 1.0 s to 5.0 s. The most possible reason of the threshold variety is the heterogeneity imposed by type of road, type of vehicle, involved road users, and weather on traffic conflicts (Svensson 1998). The use of exceedance thresholds according to the exogenous variables (Tarko 2012; Zheng et al. 2014a). Peesapati et al. (2013) also suggested to test different thresholds and selected the one that produced the best fitting preceedesthe evadeaction and can beeithersuccessful (leadingto collision). Although there is no agreement on the process model validity, the latter argument gained popularity.

3. Methods for traffic conflict data collection

An important reason to use traffic conflicts as surrogate or complementary of crashes is that conflicts occur more frequently than crashes. However, the collection of traffic conflict data is still not an easy task. Traffic conflicts can be either observed from real traffic situation or estimated from simulated traffic situation. Although there is growing interest in estimating conflicts from micro-simulation approaches, there are fundamental differences between observed conflicts and simulated conflicts, and this study will focus on the former one. A brief summary of methods used for collecting observed traffic conflict data are given in Table 2. The table also lists their advantages and disadvantages. The details of these three methods are discussed in the following subsections.

3.1. Field observation

Field observation includes on-site observations and observing conflicts from videos collected at the survey sites. The observers are firstly trained on the operational rules of recognizing the appearance of conflicts, the type of conflicts, and the severity of conflicts. After preparing the materials and equipment needed for the survey, the trained observers are sent to the pre-selected study sites or be allowed to review the videos of the study sites.

Because of the simplicity of its application and the ability to observe more sensory and contextual information than is in video recordings, first-hand field observation was the firstly proposed and the most widely used method for collecting conflict data. Moreover, some comparative studies have shown that the field observed conflicts are more valid than conflicts determined by objective measures when relating them to crashes (Grayson et al. 1984; Shinar 1984; Kruysse 1991). One possible explanation might be that field observers possibly consider more information about a conflict situation than any single objective measure does. To better use the conflict techniques, many countries have published manuals or handbooks to guide the field observation, and some countries have formed their own standards, e.g., Swedish Traffic Conflict Technique (STCT), U.S. Traffic Conflict Technique (USTCT), Dutch Traffic Conflict Technique (DOCTOR), and German Traffic Conflict Technique. All of these standard techniques have been successfully applied in many studies (Svensson and Hydén 2006; Gstalter and Fastenmeier 2007; van der Horst et al. 2014). However, the focus, the observational method, and the way to define a conflict are different for these standard techniques, and it is difficult to cross-validate these findings. Moreover, for either identifying conflicts by evasive actions or manually analyzing video records, the observers register conflicts in a subjective way, and the reliability problem caused by inter- and intra-observer variability is a big challenge (Glauz et al. 1985; Chin and Quek 1997). The field observation is also an expensive and labor-intensive method.
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ing purposes. Ideally, the traffic conflicts in the recorded video
source of video data, are relatively inexpensive and are widely
and many recent studies showed that the extracted conflict infor-
kinematic triggers and sometimes with the aid of video analysis,
eras and various sensors, which continuously and inconspicu-
ticdrivingstudiesyielduniquerecordsoflongitudinaltrafficcon-
flict data. In naturalistic driving studies, participating vehicles are
objects). A computer vision based traffic conflict detection system
is usually composed by two components: a video-processing mod-
for detecting and tracking objects and an interpretation mod-
for extracting information and detecting traffic conflicts (Saunier and Sayed 2007; Ismail et al. 2009).

3. Computer vision technique

The use of computer vision technique for collecting traffic con-
flict data relies on computer algorithms to track moving objects
detected from videos. The videos should be re-
corded from a relatively high position and with high quality (e.g.,
no vibration, clear images, and little shadow from surrounding
objects). A computer vision based traffic conflict detection system
is usually composed by two components: a video-processing mod-
ule for detecting and tracking objects and an interpretation mod-
ule for extracting information and detecting traffic conflicts (Saunier and Sayed 2007; Ismail et al. 2009).

Computer vision technique provides an objective and efficient
way to detect real-world traffic conflicts. Video cameras, the main
source of video data, are relatively inexpensive and are widely
ployed or relatively inexpensive to deploy for traffic monitor-
ing purposes. Ideally, the traffic conflicts in the recorded video
can be detected automatically to enable relatively large-scale anal-
ysis (e.g., Songchitrucks and Tarko 2006; Saunier et al. 2010). But
so far, using computer vision technique for conflict data collec-
tion is under ongoing development. First of all, algorithms need
to be improved to more accurately track and classify different
types of objects. Developing more sophisticated conflict frame-
works that can make better use of the information extracted and
provide more clues about the underlying level of safety can also
encourage the wide application of this method (Sayed et al. 2013).

The development and application of computer vision techniques
is on the rise (Ismail et al. 2009, 2010; Autey et al. 2012; Sayed et al. 2013), with initial attempts to link these techniques to crash ob-
servations (Saunier et al. 2011; Sacchi et al. 2013). These techniques
offer a strong future potential to address classic shortcomings in
observer-based traffic conflict techniques.

3.3. Naturalistic driving

Different from the previous two site-based methods, naturalis-
tic driving studies yield unique records of longitudinal traffic con-
flict data. In naturalistic driving studies, participating vehicles are
equipped with advanced data acquisition system including cam-
eras and various sensors, which continuously and inconspicu-
ously register vehicle maneuvers, driver behavior and external
conditions for several months and several years. From these data,
traffic conflicts or near crashes can be identified by means of
kinematic triggers and sometimes with the aid of video analysis,
and many recent studies showed that the extracted conflict informa-
tion are valuable for safety analysis (Guo et al. 2010; Uchida
et al. 2010; Wu and Jovanis 2012; Bagdadi 2013b; Jonasson and Rootzén 2014).

Naturalistic driving allows researchers to get insight into the
interactions of road users in normal situations, conflict situations,
and even in actual crash situations, and this offers the potential to
improve the understanding of safety continuum and the knowl-
edge about the most relevant conflict measures for crashes. Com-
pared to the on-site observation methods, the longitudinal data of
naturalistic driving can also significantly improve the under-
standing of traffic safety from the perspectives of driver behavior
and crash causation. Although U.S. (SHRP2), Europe (UDRIVE;
Schagen and Sagberg 2012), Canada (CNDS), Japan (Uchida et al.
2010), and other countries have conducted (or are conducting)
naturalistic driving studies, the sample size of vehicles involved is
still relatively limited. This is an expected shortcoming given the
cost per vehicle as compared to the traditional cross-sectional
approach of monitoring traffic intersections. Another problem
related to the naturalistic driving data are that they are protected
and not fully available for research community; event
screening is time-consuming.

4. Predictive validity of traffic conflict techniques

The predictive validity of traffic conflict techniques is judged by
the statistical significance of the correlation between conflicts
and crashes. In other words, the better the ability of traffic conflict
counts to predict the number of crashes, the more attainable to
support the validity of traffic conflict techniques through statisti-
cal analysis. This stems from crash frequency is the most direct
measure of road safety. The predictive validity of traffic conflict
techniques has been a great concern as early as its first emergence
and many models have been developed to relate the traffic con-
licts to crashes since then.

4.1. Arguments on the predictive validity of traffic conflict techniques

Arguments on the predictive validity of traffic conflict tech-
niques examine whether there is a relationship between traffic

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<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Related research</th>
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<tbody>
<tr>
<td>Field observation</td>
<td>Easy to apply; More valid than many objective measures</td>
<td>Intra- and inter-observer variability; high cost; labor intensive</td>
<td>Hauer (1978); Glauz and Migletz (1980); Nel (1989); Parker and Zegeer (1989); Almqvist and Ekman (2001).</td>
</tr>
<tr>
<td>Computer vision technique</td>
<td>Automatically detect traffic conflicts; cost-effective; reliable and efficient</td>
<td>High requirement about the quality of video; still under development</td>
<td>Wakabayashi and Renge (2002); Saunier and Sayed (2007); Saunier and Sayed (2008); Ismail et al. (2009); Oh et al. (2009); Ismail et al. (2010); Oh et al. (2010); Saunier et al. (2010); Ismail et al. (2011); Autey et al. (2012); Sayed et al. (2012); Sayed et al. (2013)</td>
</tr>
<tr>
<td>Naturalistic driving</td>
<td>Allow to study rare safety situations as conflict and crash situations</td>
<td>Limited data size; data is protected and not fully available for research community; event screening is time-consuming</td>
<td>Dingus et al. (2006a); Dingus et al. (2006b); McLaughlin et al. (2008); Guo et al. (2010); Uchida et al. (2010); Dozza and González (2012); Wu and Jovanis (2012); Bagdadi (2013a); Bagdadi (2013b); Habibovic et al. (2013); Dozza and González (2013) in press; Jonasson and Rootzén (2014) in press; Valero-Mora et al. (2013)</td>
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conflicts and crashes. Although a strong correlation between conflicts and crashes is not sufficient for claiming the validity of traffic conflict techniques, it is a necessary empirical evidence. Validation studies also consider the potential to use traffic conflict counts as covariate to predict the expected number of crashes.

Researchers who tested the correlation between traffic conflicts and crashes through exposure got varied results. Some researchers showed a strong correlation between traffic conflicts and crashes through exposure or took conflict-related exposure into consideration could significantly improve the likelihood of crash prediction models (Amundsen and Larsen 1977; Migletz et al. 1985; Peesapati et al. 2013), while others found a poor relationship between them and considered conflict-related exposure could not gain significant increase in likelihood (Cooper 1977; Williams 1981; Tiwari et al. 1998). Some of researchers analyzed the reasons for poor performances and concluded that part of the predictive validity issues were due to inaccurate (discussions in Peesapati et al. 2013), unreliable and under-reporting of crashes themselves, and another part lay in the nature of conflicts, the definitions as well as data collection methods of which were ill-founded (Oppe et al. 2013), unreliable and under-reporting of crashes themselves, between observation periods for conflicts and crashes might also be a reason. The observation periods for conflicts were usually dramatically shorter than that for crashes, which implies that the observed conflicts may not cover the variability of traffic as crashes do. Thus, researchers suggested that the correlation between traffic conflicts and crashes would increase if: (i) the traffic conflicts are “quantitatively defined, objectively measured, and suitably applied” (Chin and Quek 1997); (ii) and both the traffic conflicts and crashes are disaggregated into specific characteristics as type of road, type of maneuver, and level of severity (Engel 1985); and (iii) the observation periods for traffic conflicts should be reasonable or as long as possible. Hauer and Garder (1986) also suggested the predictive validity should be judged by whether or not the estimation based on conflicts produces unbiased estimates with limited variance. These suggestions have been partially proved by some studies that showed strong correlations between traffic conflicts and crashes (Brown 1994; Lord 1996; Sayed and Zein 1999; Archer 2005; Songchitruksa and Tarko 2006; Ozbay et al. 2008; El-Basyouny and Sayed 2013).

The doubts on the correlation between traffic conflicts and crashes have not stopped the growth and widespread applications of traffic conflict techniques. Some researchers thought that the need for this type of validity is overly exaggerated and even unnecessary (Brown and Cooper 1990; Chin and Quek 1997; Archer 2005; Gstalter and Fastenmeier 2007). An important reason is that safety is more about the absence of crashes. Traffic conflict techniques could be a useful tool to analyze road user behavior and give a good insight in potential safety problems rather than to predict crashes (van der Horst 2007; Jong et al. 2007). Recently, traffic conflicts have been employed as the only measure to evaluate road safety, especially in the before–after studies (Oh et al. 2010; Ismail et al. 2010; Rojas and Garcia 2010; Salamati et al. 2011; Autey et al. 2012; Sacchi et al. 2013).

The investigation of the link between traffic conflicts and crashes will remain as an important practical demand. This is despite that some reviewed studies dismissed the need to prove such link, did not validate the traffic conflict techniques, or acknowledged its practical difficulty. The demand for investigating such link is valid as much as a reliable laboratory test should be linked to illness.

4.2. Models to relate traffic conflicts to crashes

To investigate the relationship between traffic conflicts and crashes, many efforts have been made. Some of the efforts focused on establishing models that depend on the crash counts, while others proposed some non-crash-based models. The details of these models follow.

4.2.1. Crash-based models

4.2.1.1. Traditional regression model

Given the traffic conflict counts and crash counts, their relationship can be established directly by regression techniques. In this vein, traffic conflicts are taken as crash opportunities, some of which actually lead to crashes. Hauer and Garder (1986) suggested the form of this relationship was as follows:

\[
\lambda = \sum_{i} \pi_i c_i
\]

where, \(c_i\) is the number of observed conflicts of severity level \(i\), and \(\pi_i\) is the crash-to-conflict ratio for conflicts of severity level \(i\). The authors emphasized that the usefulness of eq. (1) depended on the stability of \(\pi\) across different locations and times. Based on this form of relationship, various regression techniques can be used to estimate the crash-to-conflict ratio (Lord 1996; Sayed and Zein 1999; Lord and Mannering 2010).

The most appealing points of traditional regression models are that they are easy to apply and researchers have good knowledge about these regression techniques. But the required stability of crash-to-conflict ratio is difficult to ensure, especially when mixing with varied severity levels because the boundaries to distinguish them are not well determined. The inclusion of crash data in the models also suffers from the availability and quality problems of crash records.

4.2.1.2. Two-phase model

The two-phase model proposed by El-Basyouny and Sayed (2013) is a further extension of traditional regression models. The model, which uses estimated conflicts to predict crashes, includes two phases. The first phase is to use lognormal model to predict conflicts by taking traffic volume, area type, and some geometric-related variables as covariates. The second phase is to use negative binomial model to predict crashes based on the estimated conflicts.

The two-phase model is expected to have a wider application when the traffic conflicts can be automatically extracted. The consistent relationship between conflicts and crashes means that identifying the factors that have an influence on conflicts will help to reduce collisions. However, the influence of various road-, traffic-, and environment-related factors on traffic conflicts is complex, let alone relating conflicts to driver-behavior-related factors that are not well-understood to this point in time.

4.2.2. Non-crash-based models

4.2.2.1. Extreme value theory model

The extreme value theory is to quantify the stochastic behavior of a process at unusually large or small levels and the underlying mechanism is that the process being modeled is smooth enough to enable extrapolation to unobserved levels. This is in line with the objective to use more frequent traffic conflicts to predict less frequent crashes. The extreme value theory model takes interactions between road users as risky events and estimates the risk of crash conditional on such an event based on observed values of conflict measures (Songchitruksa and Tarko 2004, 2006; Tarko 2012). The basic form of the model is given as

\[
R(C) = R(H)R(C \mid H)
\]

where \(R(C)\) is the estimated number of crashes for the road entity, \(R(H)\) is the number of observed conflicts for the road entity, and \(R(C \mid H)\) is the risk of crash estimated with the fitted extreme value distributions given the conflict \(H\) of the road entity.

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The most significant advantage of extreme value models is that they abandon the assumption of fixed crash-to-surrogate ratio and do not rely on the crashes anymore. Besides, extreme value theory models use a single dimension to measure the severity of traffic events and to identify crashes, which fits well within the safety continuum. Issues like subjectivity in determining sample size, serial dependency, and non-stationarity should be further investigated when using the extreme value theory models for road safety analysis.

### 4.2.2.2. Causal model

The causal model is established based on a counterfactual test stated in the conflict definitions (see section 2), where if the movements of involved road users had remained unchanged a collision would probably have resulted. In this case, whether an encounter ends up as a crash is determined by its initial conditions and the evasive actions. The conditional independence structure can also be described by a causal model as

\[
P(x, y, u) = P(y | x, u)P(x | u)P(u)
\]

where \( u \) denotes variables describing initiating conditions, \( x \) denotes the variable describing the evasive action, and \( y \) is a crash-related outcome; \( P(u) \) is a probability distribution over the values taken on the initial variables, \( P(x | u) \) is a conditional probability distribution for the evasive action, \( P(y | x, u) \) is a conditional probability distribution for the evasive action and the initial variables, and \( P(x, y, u) \) is the probability distribution of crash-related outcome. An important assumption in the model is that the crash-related outcome \( y(x, u) \) is monotonic in evasive action \( x \). Given the observed traffic conflicts of a road entity, once the probabilities for each of a set of events are calculated, the expected number of crashes based on this set of conflicts can be obtained by summing the probabilities (Davis et al. 2011).

The causal model is deemed as a mathematical statement of ideas that have been presented in the evasive action based traffic conflict definition. But this model is still in an experimental stage, and its further application is somewhat hampered because of lacking understanding of detailed knowledge of the evasive action mechanism.

### 4.2.2.3. Probabilistic framework based on all possible collision points

The probabilistic framework calculates the probability of collision between two interacted road users at a given instant by summing the collision probability over all possible motions that lead to a collision. An important component of the model is to predict the road users’ future positions with associated possibilities. With the movement extrapolation, the probability of collision can be described as

\[
P(\text{collision}|A_1, A_2) = \sum_{i,j} P(H_i | Q_{1,2,5,5})P(H_j | Q_{2,2,5,5})e^{-\frac{\Delta t}{2\sigma^2}}
\]

where \( P(\text{collision}|A_1, A_2) | Q_{1,2,5,5} \) is the probability of collision; \( P(H_i | Q_{1,2,5,5}) \) is the probability of road user \( A_1 \) moving according to extrapolation hypothesis \( H_i \) (with the same for \( A_2 \) and \( H_j \)); \( \Delta t = t_{f,i} - t_{p,i} \); \( t_{p,i} \) is the time to collision at the first instant of road user’s acting; \( t_{f,i} \) is the time at the measurement; and \( \sigma \) is a constant and suggested to take the value of average reaction time (Saunier and Sayed 2008; Saunier et al. 2010).

This probabilistic framework is suitable for an automated traffic conflict detection system that can extract individual road user trajectory information. But the movement extrapolation relying on learning the distribution of previously observed road user’s trajectories imposes restrictions on the transferability of the model, especially to intersections where little or no observations are available. This is primarily due to the absence of an explicit model for road user movements. In addition, the relationship between the computed probability of collision and safety still needs to validate.

### 5. Directions for future research

The aforementioned discussions show that significant research efforts have been allocated to the development of traffic conflict techniques. With these efforts, traffic conflict techniques have become the most prominent surrogate measures of safety, the development of which has been identified as one of the three most promising research directions (Tarko et al. 2009). Notwithstanding remarkable works, whether the theoretical nor the operational frameworks of current traffic conflict techniques are thoroughly well-founded. The following subsections discuss important long-term research directions to enable traffic conflict techniques to be a mainstream measure of safety.

#### 5.1. Developing unified standards for traffic conflict techniques

Various versions of traffic conflict techniques have been proposed and applied. These techniques have some basic elements in common but are also at much variance. For example, the STCT uses the TA conflicting speed as a conflict measure which can only be measured with a collision course, while the DOCTOR includes the situations with as well as without a collision course. Both the USTCT and STCT rely on the appearance of evasive actions while the German traffic conflict technique concerns more the “driver error” and incorporates it into the safety continuum (Gstalter and Fastenmeier 2007). These variances make it difficult to cross-validate and generalize the findings from different research works and also pose a challenge to the development of unified traffic conflict techniques. During early developmental phases, the use of different traffic conflict techniques can help to expand the application domain of traffic conflicts. But it can be expected that, with a better understanding of the traffic conflicts, these paths will eventually merge. The achievement of this goal undoubtedly requires global cooperation of researchers and practical engineers, with focus on developing universally standards for traffic conflicts and objectively measuring them.

Developing unified traffic conflict technique also needs to extend the scope of current traffic conflict techniques. As described in section 2, the statements in traffic conflict definitions determine the study subjects are “two or more road users”. It appears that a vast majority of previous studies focus on the conflict between two road users, and only few studies mentioned single-road-user conflicts or multi-road-user conflicts (Laureshn et al. 2010; Tarko 2012). Therefore, when addressing these issues, there are many open questions that remain unanswered. For example, how to determine the single-road-user conflict and how to measure it? How to describe a conflict involving almost simultaneously three or more road users? And what is the mechanism of dealing with one conflict affecting the other adjacent road user such as secondary conflicts? It is believed that answering these questions will give a more comprehensive safety analysis of road entities.

#### 5.2. Using the safety continuum instead of only traffic conflicts

A conflict is commonly counted based on its severity, either the intensity of evasive actions or the value of proximity measure. However, there are some questions related to the conflict severity, regarding what threshold to distinguish conflicts from other events should be selected, how severity can be quantified, and which approach is more accurate in predicting safety. Therefore, an alternative approach which takes all traffic events as a safety continuum and without separates conflicts from other events is...
recommended. Although there are some research efforts suggesting the use of the whole safety continuum or all nonzero risk non-crash events instead of only traffic conflicts (Swenson and Hydén 2006; Davis et al. 2011; Laureshyn et al. 2010; Zheng et al. 2014b), much additional work is needed. First of all, the severity measures of traffic events should be objectively and clearly defined. A good measure fitting within the safety continuum should reflect the risk of collision and the potential consequence of a potential crash. Then, it is more promising to use the shape of safety hierarchy than only use the conflict counts or the traffic event counts of different severity levels. An important reason is that the required stability of crash-to-conflict ratio (see eq. (1)) is difficult to ensure when relating these traffic events to crashes, and also the thresholds to distinguish different severity levels are difficult to be objectively determined. A further step is to develop a parametric model to describe the shape of safety hierarchy, and this will significantly facilitate the use of safety continuum.

An important premise of using the safety continuum is to prove this continuum does exist, and this needs more convincing proof as provided by Hydén (1987). A potential solution is to make better use of the naturalistic driving data, which provide information about the normal situations, conflict situations, and rare crash situations.

5.3. Determining thresholds to distinguish conflicts and normal events

In spite of aforementioned challenges, the use of traffic conflict counts for safety prediction will likely be an important part of future research. If traffic conflict counts are to be used, sensitivity to threshold selection should be examined. The study of Peesapati et al. (2013) made an effort and showed that the correlation between conflicts and crashes was sensitive with different post encroachment time (PET) thresholds. Thus, the selection of a proper threshold is a big challenge on the use of traffic conflict counts.

One possible attempt that can be made is to do the same as Peesapati et al. (2013), which is to test the correlation between crashes and conflicts along the range of all possible thresholds and then select the one that produces the highest correlation as the fixed threshold. This is based on the assumption that there is a fixed threshold to distinguish conflicts and normal events and requires large size of reliable conflict and crash data. The other way is to allow the threshold to change and to be determined by exogenous variables. Example of this method is to determine thresholds within an exceedance statistical framework (Tarko 2012; Zheng et al. 2014b). Future works are needed to select the effective exogenous variables or to explore new methods.

5.4. Employing multidimensional definition of severity

Traditionally, severity of traffic conflicts is measured along the dimension of proximity. The closer the conflict is to a crash, the more severe it is. While several objective measures are proposed to quantify proximity, it is important to note other contexts within which two conflicts of the same proximity may have different severity assessment. Two conflicts with identical TTC one involving a pedestrian and a truck and the second involving a pedestrian and a bike should have different severities. Subjective assessment of severity, with all its reliability and repeatability shortcomings, may enable the measurement of severity along several dimensions (Shinar 1984). The consequences of a potential conflict can be quantified and integrated as a second dimension of severity assessment. Furthermore, it can be argued that two conflicts with identical TTC and identical pairs of road users may have various prospects for avoiding a collision as reflected in the causal model (Davis et al. 2011) and the extreme value theory model (Songchitruksa and Tarko 2006). Depending on the ambient traffic and angle of approach, drivers may have variable chance of success if attempting to avoid a collision. Therefore, the likelihood of an observed evasive action can be another dimension of measuring severity. Therefore, the severity hierarchy model can be constructed in several dimensions, instead of the classic single abstract severity dimension. Crashes can therefore be modeled as multivariate extremes of the process generating traffic events. Whether all these added dimensions will accept and differentiate all traffic events, including crashes and conflicts, is an important open question and future research direction.

5.5. Further testing the correlation between conflicts and crashes

Although many research works have begun to directly use traffic conflicts as a safety evaluation measure, investigating the correlation between traffic conflicts and crashes is still a challenging but worthwhile work. This is particularly true because the predictive validity of traffic conflict techniques not only increases our confidence of accepting traffic conflicts as a safety measure but also helps to better understand the mechanisms leading to crash occurrence. Some research efforts based on modern statistical and modeling methods (e.g., extreme value theory, causal theory, and probabilistic framework based on all possible collision points) offer an appealing theoretical foundation. These methods rely on modeling all traffic events, including conflicts and crashes, along different severity dimensions. However, these models still need to be further validated with more conflict data and crash data. For example, conflict data from longer observation periods, conflict data with detailed description of evasive actions, and crash data that characterizes a traffic process leading to a crash. The exploration of new methods to validate the traffic conflict techniques is also an area of research potential.

6. Summary and conclusions

It is found that although remarkable previous works have been done, answering all these open questions is still a formidable challenge and will require focused research effort. First of all, the ambiguity and inconsistency in traffic conflict framework are fundamental issues. These issues on their own within a specific study may not be so distinct, as many studies with different traffic conflict techniques got acceptable results, but the difficulty in cross-validating and generalizing the findings from different studies hinders the development of traffic conflict techniques to some extent. Research directions as developing unified standards, using the safety continuum, determining proper thresholds, and employing multidimensional definition of severity have significant potential to further address these issues. Secondly, from the perspective of traffic conflict data collection, methods with modern techniques as computer vision technique and naturalistic driving hold great potential in developing large-scale automated methods for traffic conflict data collection. Another challenge is on the long-standing topic of validity of traffic conflict techniques. To relate traffic conflicts to crashes, many crash-based and non-crash based models have been developed, and further work is still needed.

Overall, this review study shed some light on the strengths and weakness of state-of-the-art of the current traffic conflict techniques and provided some insights on future research directions. Hopefully, it has provided interested readers with a general view of traffic conflict techniques, has presented some future and potentially long-term research objectives, and will stimulate much more interest to work towards improving traffic conflict techniques.

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