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

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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.

Résumé : Le développement d'outils pour mesurer les non-collisions en sécurité routière a suscité beaucoup d'intérêt de recherche au cours des cinq dernières décennies. Les techniques de conflit de circulation, qui analysent les situations de sécurité d'un point de vue d'événements de circulation puisqu'on en observe plus que les collisions, sont les techniques dominantes à ce jour. La présente étude fournit une revue complète des recherches précédentes sur les techniques de conflit de circulation en essayant de répondre aux questions ouvertes suivantes : Qu'est-ce qu'un conflit de circulation? Comment colliger les données sur les conflits de circulation? Et sur quelles bases peut-on affirmer que les conflits de circulation sont de bons substituts aux collisions? Les forces et les faiblesses des réponses disponibles à ces questions sont évaluées d'un point de vue méthodologique et empirique. Des directions pour les recherches futures sont identifiées et soulignées. Nous croyons que les directions futures recommandées devraient offrir des réponses convaincantes aux questions ouvertes identifiées. [Traduit par la Rédaction]

Mots-clés : sécurité routière, technique de conflit de circulation, collecte de données de conflit, validité, revue de la literature.

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 Mannering 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

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Table 1. Summary of existing traffic conflict measures.

Type	Traffic conflict measures
Temporal proximity	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 (Minderhoud and Bovy 2001), time integrated time-to-collision (Minderhoud and Bovy 2001), time to line crossing (Vogel 2003*a*), gap time (Gettman and Head 2003), initially attempted post encroachment time (Gettman and Head 2003), encroachment time (Gettman and Head 2003), headway (Vogel 2003*b*), time advantage (Laureshyn et al. 2010), time to departure (Tarko 2012), braking time (Lu et al. 2012)
Spatial proximity	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)

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 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. 2006*a*; 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; Garder 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 a link between the two sets of events, conflicts and crashes, while this link is the one used to support the claim of predictive validity of traffic conflict techniques.

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 2013*a*). 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 (2013*a*) 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 unchanged 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 statistics provides a promising framework to determine the thresholds according to the exogenous variables (Tarko 2012; Zheng et al. 2014*a*). Peesapati et al. (2013) also suggested to test different thresholds and selected the one that produced the best correlation between conflicts and crashes, and this is applicable providing the reliable historical crash records.

The severity hierarchy models, such as distribution in terms of nearness to collisions (Glauz and Migletz 1980), pyramid hierarchy model (Hydén 1987), diamond-shaped hierarchy model (Svensson 1998), rank all the traffic events according to their severity and frequency and provide visual representations of safety continuum. These models strive to give a clearer description of the relationships among different groups of events, but the inconsistency problem still remains since the boundaries to distinguish different groups of events are not clearly defined (Chin and Quek 1997). A promising method to eliminate the inconsistency problem is to incorporate all the traffic events in the safety continuum and analyze the safety situations based on the shape of the hierarchy models (Svensson and Hydén 2006; Laureshyn et al. 2010). Nevertheless, the limited development of parametric models to describe the safety hierarchy restrains the further use of this approach. Another limitation of these safety hierarchy models is the difficulty in defining an objective severity dimension along which both conflicts and crashes can be measured and juxtaposed. Severity defined by proximity measures is not a complete dimension and is not measurable in a meaningful way in the case of crashes. For example, TTC is zero (or very close to zero due to measurement errors) no matter the corresponding event is a property damage only, injury or fatal crash. This kind of proximity measure can only reflect the risk of collision but not the severity of crashes, which is typically differentiated based on consequences of the crash not proximity.

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.

Table 2. Summary of methods for collecting conflict data.

Method	Advantages	Disadvantages	Related research
Field observation	Easy to apply; More valid than many objective measures	Intra- and inter-observer variability; high cost; labor intensive	Hauer (1978); Glauz and Migletz (1980); Nel (1989); Parker and Zegeer (1989); Almqvist and Ekman (2001)
Computer vision technique	Automatically detect traffic conflicts; cost-effective; reliable and efficient	High requirement about the quality of video; still under development	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)
Naturalistic driving	Allow to study rare safety situations as conflict and crash situations	Limited data size; data is protected and not fully available for research community; event screening is time-consuming	Dingus et al. (2006*a*); Dingus et al. (2006*b*); McLaughlin et al. (2008); Guo et al. (2010); Uchida et al. (2010); Dozza and González (2012); Wu and Jovanis (2012); Bagdadi (2013*a*); Bagdadi (2013*b*); Habibovic et al. (2013); Dozza and González (2013) in press; Jonasson and Rootzén (2014) in press; Valero-Mora et al. (2013)

3.2. Computer vision technique

The use of computer vision technique for collecting traffic conflict data relies on computer algorithms to track moving objects and detect traffic conflicts from videos. The videos should be recorded 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 module for detecting and tracking objects and an interpretation module 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 deployed or relatively inexpensive to deploy for traffic monitoring purposes. Ideally, the traffic conflicts in the recorded video can be detected automatically to enable relatively large-scale analysis (e.g., Songchitruksa and Tarko 2006; Saunier et al. 2010). But so far, using computer vision technique for conflict data collection 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 frameworks 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 observations (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, naturalistic driving studies yield unique records of longitudinal traffic conflict data. In naturalistic driving studies, participating vehicles are equipped with advanced data acquisition system including cameras and various sensors, which continuously and inconspicuously 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 information are valuable for safety analysis (Guo et al. 2010; Uchida et al. 2010; Wu and Jovanis 2012; Bagdadi 2013*b*; 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 knowledge about the most relevant conflict measures for crashes. Compared to the on-site observation methods, the longitudinal data of naturalistic driving can also significantly improve the understanding 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 to the research community because of legal and ethical issues. In addition, the extraction of traffic conflicts from the naturalistic driving data are a complex task due to the vast size of the naturalistic driving data which includes years of records. On the other hand, identifying events based on kinematic triggers may also lead to selection bias because some crashes involved no reaction from the drivers and thus no significant kinematic changes (Guo et al. 2010). Lastly, the validation of traffic conflict techniques based on naturalistic driving data are precariously dependent on recording a crash by a participating vehicle. Selection bias is also a potential challenge because a random driver may be more reluctant to participate in a detailed monitoring survey of their own vehicle.

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 statistical 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 conflicts to crashes since then.

4.1. Arguments on the predictive validity of traffic conflict techniques

Arguments on the predictive validity of traffic conflict techniques examine whether there is a relationship between traffic 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 1977; Zimolong 1979; Muhlrad 1982). Besides, the discrepancy 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 (Brow 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 García 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:

$$\lambda = \sum_i \pi_i c_i \tag{1}$$

where, c_i is the number of observed conflicts of severity level *i*, and π_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 π_i 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

$$F(C) = F(H)R(C \mid H) \tag{2}$$

where $F(C)$ is the estimated number of crashes for the road entity, $F(H)$ 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.

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

$$P(x, y, u) = P(y \mid x, u)P(x \mid u)P(u) \tag{3}$$

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, $P(x \mid u)$ is a conditional probability distribution for the evasive action, $P(y \mid x, u)$ 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 $y(u, x)$ 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

$$P[\text{collision}(A_1, A_2) \mid Q_{1,t\le t_0}, Q_{2,t\le t_0}] = \sum_{i,j} P(H_i \mid Q_{1,t\le t_0})P(H_j \mid Q_{2,t\le t_0})e^{-\frac{\Delta_{i,j}^2}{2\sigma^2}} \tag{4}$$

where $P(\text{collision}(A_1, A_2) \mid Q_{1,t\le t_0}, Q_{2,t\le t_0})$ is the probability of collision; $P(H_i \mid Q_{1,t\le t_0})$ is the probability of road user A_1 moving according to extrapolation hypothesis H_i (with the same for A_2 and H_j); $\Delta_{i,j} = t_{i,j} - t_0$; $t_{i,j}$ is the predicted time to collision at the first instant of road user's acting; t_0 is the time at the measurement; and σ 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, neither 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 (Laureshyn 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 (Svensson and Hydén 2006; Davis et al. 2011; Laureshyn et al. 2010; Zheng et al. 2014*b*), 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 convictive 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. 2014*a*). 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 collision 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.

References

Shariat-Mohaymany, A., Tavakoli-Kashani, A., Nosrati, H., and Ranjbari, A. 2011. Identifying significant predictors of head-on conflicts on two-lane rural roads using inductive loop detectors data. Traffic Injury Prevention, **12**(6): 636–641. doi:10.1080/15389588.2011.621472. PMID:22133341.

Allen, B.L., Shin, B.T., and Cooper, P.J. 1978. Analysis of traffic conflicts and collisions. Report No. TRR 667, Transportation Research Board, Washington, D.C.

Almqvist, S., and Ekman, L. 2001. The Swedish traffic conflict technique: Observer's manual. Department of Technology and Society Traffic Engineering, Lund University.

Amundsen, F.H., and Hydén, C. 1977. Proceedings of the 1st Workshop on Traffic Conflicts, Oslo, Norway.

Amundsen, F.H., and Larsen, O.E. 1977. Traffic conflicts technique-status in Norway. Proceedings of 1st Workshop on Traffic Conflicts, Olso, Norway.

Archer, J. 2005. Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling: A Study of urban and suburban intersections. Dissertation, Lund University.

Autey, J., Sayed, T., and Zaki, M.H. 2012. Safety evaluation of right-turn smart channels using automated traffic conflict analysis. Accident Analysis and Prevention, **45**: 120–130. doi:10.1016/j.aap.2011.11.015. PMID:22269493.

Bagdadi, O. 2013*a*. Estimation of the severity of safety critical events. Accident Analysis and Prevention, **50**: 167–174. doi:10.1016/j.aap.2012.04.007. PMID: 22621710.

Bagdadi, O. 2013*b*. Assessing safety critical braking events in naturalistic driving studies. Transportation Research Part F, **16**: 117–126. doi:10.1016/j.trf.2012.08.006.

Berthelot, A., Tamke, A., Dang, T., and Breuel, G. 2012. A novel approach for the probabilistic computation of time-to-collision. IEEE Intelligent Vehicles Symposium IV, 1173–1178.

Brow, G.R. 1994. Traffic conflicts for road user safety studies. Canadian Journal of Civil Engineering, **21**(1): 1–15. doi:10.1139/l94-001.

Brown, G.R., and Cooper, P.J. 1990. Role of conflicts in traffic analysis. Proceedings of 3rd Workshop of International Cooperation on Theories and Concepts in Traffic Safety, Cracow, pp. 116–123.

Campbell, R.E., and King, L.E. 1970. The traffic conflicts technique applied to rural intersections. Accident Analysis and Prevention, **2**(3): 202–221.

Chin, H., and Quek, S. 1997. Measurement of traffic conflicts. Safety Science, **26**: 169–185. doi:10.1016/S0925-7535(97)00041-6.

Cooper, P.J. 1977. State of the art report on traffic conflict research in Canada. Proceedings of 1st Workshop on Traffic Conflicts, Olso, Norway, pp. 22–33.

Cooper, P.J. 1984. Experience with traffic conflicts in Canada with emphasis on post encroachment time techniques. International Calibration Study of Traffic Conflicts, NATA ASI Series F5, pp. 75–96.

Davis, G.A., Hourdos, J., Xiong, H., and Chatterjee, I. 2011. Outline for a causal model of traffic conflicts and crashes. Accident Analysis and Prevention, **43**: 1907–1919. doi:10.1016/j.aap.2011.05.001. PMID:21819818.

Dingus, T.A., Klauer, S.G., Neale, V.L., and Petersen, A.D. 2006*a*. The 100-car naturalistic driving study, phase II - results of the 100-car field experiment. Report No. DOT HS 810 593, National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, D.C.

Dingus, T.A., Neale, V.L., Klauer, S.G., Petersen, A.D., and Carroll, R.J. 2006*b*. The development of a naturalistic data collection system to perform critical incident analysis: An investigation of safety and fatigue issues in long-haul trucking. Accident Analysis and Prevention, **38**: 1127–1136. doi:10.1016/j.aap.2006.05.001. PMID:16806028.

Dozza, M., and González, N.P. 2012. Recognizing safety-critical events from naturalistic driving data. Procedia-Social and Behavioral Sciences, **48**: 505–515. doi:10.1016/j.sbspro.2012.06.1029.

Dozza, M., and González, N.P. 2013. Recognising safety critical events: Can automatic video processing improve naturalistic data analyses? Accident Analysis and Prevention, **60**: 298–304. doi:10.1016/j.aap.2013.02.014. PMID:23489911.

El-Basyouny, K., and Sayed, T. 2013. Safety performance functions using traffic conflicts. Safety Science, **51**: 160–164. doi:10.1016/j.ssci.2012.04.015.

Engel, U. 1985. To what extent do conflict studies replace accident analysis: validation of conflict studies, an international review. Organisme national de securite routiere. Proceedings "Evaluation 85", Paris, France, 2, pp. 324–343.

Evans, L. 2001. Causal influence of car mass and size on driver fatality risk. American Journal of Public Health, **91**(7): 1076–1081. doi:10.2105/AJPH.91.7.1076. PMID:11441734.

Garder, P. 1989. Occurrence of evasive manoeuvres prior to accidents. Proceedings of 2nd Workshop of International Cooperation on Theories and Concepts in Traffic Safety, Munich, pp. 29–38.

Gettman, D., and Head, L. 2003. Surrogate safety measures from traffic simulation models. Report No. FHWA-RD-03-050, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Glauz, W.D., and Migletz, D.J. 1980. Application of traffic conflict analysis at intersections. Report No. HS-028882, Transportation Research Board, Washington, D.C.

Glauz, W.D., Bauer, K.M., and Migletz, D.J. 1985. Expected traffic conflict rates and their use in predicting accidents. Transportation Research Record 1026, pp. 1–12.

Grayson, G.B., Hydén, C., Kraay, J.H., Muhlrad, N., and Oppe, S. 1984. The Malmo study: A calibration of traffic conflict techniques. Report No. R-84-12, Institute for Road Safety Research, Leidschendam.

Gstalter, H., and Fastenmeier, W. 2007. Thirty years of traffic safety research: A personal retrospective of concepts and methods. Proceedings of 20th Workshop of International Cooperation on Theories and Concepts in Traffic Safety, Valencia, Spain.

Guido, G., Saccomanno, F., Vitale, A., Astarita, V., and Festa, D. 2011. Comparing safety performance measures obtained from video capture data. ASCE Journal of Transportation Engineering, **137**(7): 481–491. doi:10.1061/(ASCE)TE.1943-5436.0000230.

Guo, F., Klauer, S.G., Hankey, J.M., and Dingus, T.A. 2010. Near crashes as crash surrogate for naturalistic driving study. Transportation Research Record: Journal of the Transportation Research Board, **2147**: 66–74. doi:10.3141/2147-09.

Güttinger, V.A. 1982. From accidents to conflicts: Alternative safety measurement. Proceedings of the 3rd International Workshop on Traffic Conflicts Techniques, Leidschendam, the Netherlands, pp. 14–25.

Habibovic, A., Tivesten, E., Uchida, N., Bärgman, J., and Aust, M.L. 2013. Driver behavior in car-to-pedestrian incidents: An application of the Driving Reliability and Error Analysis Method (DREAM). Accident Analysis and Prevention, **50**: 554–565. doi:10.1016/j.aap.2012.05.034. PMID:22749319.

Hauer, E. 1978. Traffic conflict surveys: some study design considerations. TRRL Supp Report 352, Transport and Road Research Laboratory, Berkshire, England.

Hauer, E., and Garder, P. 1986. Research into validity of traffic conflicts technique. Accident Analysis and Prevention, **18**: 471–481. doi:10.1016/0001-4575(86)90020-5. PMID:3801121.

Hayward, J.C. 1971. Near misses as a measure of safety at urban intersections. Dissertation, The Pennsylvania State University.

Huang, F., Liu, P., Yu, H., and Wang, W. 2013. Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. Accident Analysis and Prevention, **50**: 1014–1024. doi:10.1016/j.aap.2012.08.018. PMID:23000074.

Hutchinson, T.P. 1977. Intra-accident correlations of driver injury and their application to the effect of mass ratio on injury severity. Accident Analysis and Prevention, **9**(3): 217–227. doi:10.1016/0001-4575(77)90023-9.

Hydén, C. 1987. The development of a method for traffic safety evaluation: the Swedish traffic conflicts technique. Lund Institute of Technology, Lund.

Hydén, C., Garder, P., and Linderholm, L. 1982. An updating of the use and further development of the traffic conflicts technique. Proceedings of the 3rd International Workshop on Traffic Conflicts Techniques, Leidschendam, the Netherlands, pp. 42–49.

Ismail, K., Sayed, T., Saunier, N., and Lim, C. 2009. Automated analysis of pedestrian-vehicle conflicts using video data. Transportation Research Record: Journal of the Transportation Research Board, **2140**: 44–54. doi:10.3141/2140-05.

Ismail, K., Sayed, T., and Saunier, N. 2010. Automated analysis of pedestrian-vehicle conflicts: Context for before-and-after Studies. Transportation Research Record: Journal of the Transportation Research Board, **2198**: 52–64. doi:10.3141/2198-07.

Ismail, K., Sayed, T., and Saunier, N. 2011. Methodologies for aggregating indicators of traffic conflict. Transportation Research Record: Journal of the Transportation Research Board, **2237**: 10–19. doi:10.3141/2237-02.

Jonasson, J.K., and Rootzén, H. 2014. Internal validation of near-crashes in naturalistic driving studies: a continuous and multivariate approach. Accident Analysis and Prevention, **62**: 102–109. doi:10.1016/j.aap.2013.09.013. PMID: 24144495.

Jong, M., Gysen, G., Daniels, S., and Petermans, A. 2007. Conflict observations in Genk, Belgium: a pilot project. Proceedings of 20th Workshop of International Cooperation on Theories and Concepts in Traffic Safety, Valencia, Spain.

Kaparias, I., Bell, M.G.H., Greensted, J., Cheng, S., Miri, A., Taylor, C., and Mount, B. 2010. Development and implementation of a vehicle-pedestrian conflicts analysis method: Adaptation of a vehicle-vehicle technique. Transportation Research Record: Journal of the Transportation Research Board, **2198**: 75–82. doi:10.3141/2198-09.

Kruysse, H.W. 1991. The subjective evaluation of traffic conflicts based on an internal concept of dangerousness. Accident Analysis and Prevention, **23**: 53–65. doi:10.1016/0001-4575(91)90035-4. PMID:2021404.

Kulmala, R. 1982. Traffic conflict studies in Finland. Proceedings of 3rd International Workshop on Traffic Conflict Techniques, Leidschendam, the Netherlands, pp. 50–59.

Laureshyn, A., Svensson, A., and Hydén, C. 2010. Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation. Accident Analysis and Prevention, **42**: 1637–1646. doi:10.1016/j.aap.2010.03.021. PMID:20728612.

Lord, D. 1996. Analysis of pedestrian conflicts with left-turning traffic. Transportation Research Record: Journal of the Transportation Research Board, **1538**: 61–67. doi:10.3141/1538-08.

Lord, D., and Mannering, F. 2010. The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. Transportation Research Part A, **44**(5): 291–305.

Lu, G., Liu, M., Wang, Y., and Yu, G. 2012. Quantifying the severity of traffic conflict by assuming moving elements as rectangles at intersection. Social and Behavioral Sciences, **43**: 255–264.

Malaterre, G., and Muhlrad, N. 1977. A conflict technique. Proceedings of 1st Workshop on Traffic Conflicts, Olso, Norway.

McLaughlin, S.B., Hankey, J.M., and Dingus, T.A. 2008. A method for evaluating collision avoidance systems using naturalistic driving data. Accident Analysis and Prevention, **40**: 8–16. doi:10.1016/j.aap.2007.03.016. PMID:18215527.

Migletz, D.J., Glauz, W.D., and Bauer, K.M. 1985. Relationship between traffic conflicts and accidents. Report No. FHWA/RD-84/042, Federal Highway Administration, Virginia.

Minderhoud, M.M., and Bovy, P.H. 2001. Extended time-to-collision measures for road traffic safety assessment. Accident Analysis and Prevention, **33**: 89–97. doi:10.1016/S0001-4575(00)00019-1. PMID:11189125.

Muhlrad, N. 1982. The French traffic conflict technique. Proceedings of 3rd International Workshop on Traffic Conflict Techniques, Leidschendam, The Netherlands, pp. 62–69.

Najm, W., and Smith, D. 2004. Modeling driver response to lead vehicle decelerating. SAE 2004-01-0171. Society of Automotive Engineers.

Nel, W.P. 1989. Traffic conflict measuring techniques: a user's manual. South African Council for Scientific and Industrial Research.

Oh, J., Min, J., Kim, M., and Cho, H. 2009. Development of an automatic traffic conflict detection system based on image tracking technology. Transportation Research Record: Journal of the Transportation Research Board, **2129**: 42–54.

Oh, J., Kim, E., Kim, M., and Choo, S. 2010. Development of conflict techniques for left-turn and cross-traffic at protected left-turn signalized intersections. Safety Science, **48**: 460–468. doi:10.1016/j.ssci.2009.12.011.

Oppe, S. 1977. What task is a traffic conflict technique intended for? Proceedings of 1st Workshop on Traffic Conflicts, Olso, Norway, pp. 111–116.

Ozbay, K., Yang, H., Bartin, B., and Mudigonda, S. 2008. Derivation and validation of new simulation-based surrogate safety measure. Transportation Research Record: Journal of the Transportation Research Board, **2083**: 105–113. doi:10.3141/2083-12.

Parker, M.R., and Zegeer, C.V. 1989. Traffic conflict techniques for safety and operations-observers manual. Publication No. FHWA-IP-88-027, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Peesapati, L., Hunter, N., Michael, P., and Rodgers, M.O. 2013. Evaluation of post encroachment time as a surrogate for opposing left-turn crashes. The 92nd Annual Meeting of TRB, No. 0839, Washington, D.C.

Perkins, R.S., and Harris, J.I. 1968. Traffic conflict characteristics-Accident potential at intersections. Highway Research Record No. 224 35-43.

Phillips, R.O., Bjørnskau, T., Hagman, R., and Sagberg, F. 2011. Reduction in car-bicycle conflict at a road-cycle path intersection: Evidence of road user adaptation? Transportation Research Part F, **14**(2): 87–95. doi:10.1016/j.trf.2010.11.003.

Rajesh, T. 1995. Towards theory for describing accepted time gap in interactions between pedestrians and vehicles. Bulletin 133. Department of Traffic Planning and Engineering, Lund University, Lund, Sweden.

Rojas, M.A.R., and García, A.G. 2010. Deceleration lane length evaluation based on a new conflict indicator. Proceedings of 4th International Symposium on Highway Geometric Design, Valencia, Spain.

Sacchi, E., Sayed, T., and deLeur, P. 2013. A comparison of collision-based and conflict-based safety evaluations: The case of right-turn smart channels. Accident Analysis and Prevention, **59**: 260–266. doi:10.1016/j.aap.2013.06.002. PMID:23831452.

Salamati, K., Schroeder, B., Rouphail, N.M., Cunningham, C., Long, R., and Barlow, J. 2011. Development and implementation of conflict-based assessment of pedestrian safety to evaluate accessibility of complex intersections. Transportation Research Record: Journal of the Transportation Research Board, **2264**: 148–155. doi:10.3141/2264-17.

Saunier, N., and Sayed, T. 2007. Automated analysis of road safety with video data. Transportation Research Record: Journal of the Transportation Research Board, **2019**: 57–64. doi:10.3141/2019-08.

Saunier, N., and Sayed, T. 2008. Probabilistic framework for automated analysis of exposure to road collisions. Transportation Research Record: Journal of the Transportation Research Board, **2083**: 96–104. doi:10.3141/2083-11.

Saunier, N., Sayed, T., and Ismail, K. 2010. Large-scale automated analysis of vehicle interactions and collisions. Transportation Research Record: Journal of the Transportation Research Board, **2147**: 42–50. doi:10.3141/2147-06.

Saunier, N., Mourji, N., and Agard, B. 2011. Mining microscopic data of vehicle conflicts and collisions to investigate collision factors. Transportation Research Record: Journal of the Transportation Research Board, **0117**: 41–50.

Savolainen, P.T., Mannering, F., Lord, D., and Quddus, M.A. 2011. The statistical analysis of highway crash-injury severities: A review and assessment of methodological alternatives. Accident Analysis and Prevention, **43**: 1666–1676. doi:10.1016/j.aap.2011.03.025. PMID:21658493.

Sayed, T., and Zein, S. 1999. Traffic conflict standards for intersections. Transportation Planning and Technology, **22**(4): 309–323. doi:10.1080/03081069908717634.

Sayed, T., Ismail, K., Zaki, M.H., and Autey, J. 2012. Feasibility of computer vision-based safety evaluations: Case study of a signalized right-turn safety treatment. Transportation Research Record: Journal of the Transportation Research Board, **2280**: 18–27. doi:10.3141/2280-03.

Sayed, T., Zaki, M.H., and Autey, J. 2013. Automated safety diagnosis of vehicle-bicycle interactions using computer vision analysis. Safety Science, **59**: 163–172. doi:10.1016/j.ssci.2013.05.009.

Schagen, I., and Sagberg, F. 2012. The potential benefits of naturalistic driving for road safety research: Theoretical and empirical considerations and challenges for the future. Procedia-Social and Behavioral Sciences, **48**: 692–701. doi:10.1016/j.sbspro.2012.06.1047.

Shinar, D. 1984. The traffic conflict technique: A subjective vs. objective approach. Journal of Safety Research, **15**: 153–157. doi:10.1016/0022-4375(84)90046-X.

Songchitruksa, P., and Tarko, A.P. 2004. Using imaging technology to evaluate highway safety. Publication FHWA/IN/JTRP-2004/27. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Songchitruksa, P., and Tarko, A.P. 2006. The extreme value theory approach to safety estimation. Accident Analysis and Prevention, **28**: 811–822.

Svensson, Å. 1998. A method for analysing the traffic process in a safety perspective. Dissertation, Lund University.

Svensson, Å., and Hydén, C. 2006. Estimating the severity of safety related behavior. Accident Analysis and Prevention, **38**: 379–385. doi:10.1016/j.aap.2005.10.009. PMID:16337136.

Tarko, A.P. 2012. Use of crash surrogates and exceedance statistics to estimate road safety. Accident Analysis and Prevention, **45**: 230–240. doi:10.1016/j.aap.2011.07.008. PMID:22269505.

Tarko, A.P., Davis, G., Saunier, N., Sayed, T., and Washington, S. 2009. Surrogate measures of safety -a white paper. Transportation Research Board, Washington, D.C.

Tiwari, G., Mohan, G., and Fazio, J. 1998. Conflict analysis for prediction of fatal crash locations in mixed traffic streams. Accident Analysis and Prevention, **30**: 207–215. doi:10.1016/S0001-4575(97)00082-1. PMID:9450124.

Topp, H.H. (Ed.) 1998. Traffic safety work with video-processing. University Kaiserslautern. Transportation Department, 1998, Green Series No.43.

Uchida, N., Kawakoshi, M., Tagawa, T., and Mochida, T. 2010. An investigation of factors contributing to major crash types in Japan based on naturalistic driving data. IATSS research, **34**: 22–30. doi:10.1016/j.iatssr.2010.07.002.

Valero-Mora, P.M., Tontsch, A., Welsh, R., Morris, A., Reed, S., Touliou, K., and Margaritis, D. 2013. Is naturalistic driving research possible with highly instrumented cars? Lessons learnt in three research centres. Accident Analysis and Prevention, **58**: 187–194. doi:10.1016/j.aap.2012.12.025. PMID:23332021.

van der Horst, A.R.A. 1990. A time-based analysis of road user behavior in normal and critical encounter. Dissertation, Delft University of Technology.

van der Horst, A.R.A. 2007. Video-recorded accidents, conflicts and road user behaviour: a step forward. Proceedings of 20th Workshop of International Cooperation on Theories and Concepts in Traffic Safety, Valencia, Spain.

van der Horst, A.R.A., de Goede, M., de Hair-Buijssen, S., and Methorst, R. 2014. Traffic conflicts on bicycle paths: A systematic observation of behaviour from video. Accident Analysis and Prevention, **62**: 358–368. doi:10.1016/j.aap.2013.04.005. PMID:23642307.

Vogel, K. 2003*a*. Modelling driver behaviour-A control theory based approach. Dissertation, University of Linköping.

Vogel, K. 2003*b*. A comparison of headway and time to collision as safety indicators. Accident Analysis and Prevention, **35**: 427–433. doi:10.1016/S0001-4575(02)00022-2. PMID:12643960.

Wakabayashi, H., and Renge, K. 2002. Vehicle tracking system using digital VCR and its application to traffic conflict analysis for ITS-assist traffic safety. Proceedings of The 9th Meeting of the Euro Working Group Transportation "Intermodality, Sustainability and Intelligent Transportation Systems", pp. 356–362.

Williams, M.J. 1981. Validity of the traffic conflict techniques. Accident Analysis and Prevention, **13**: 133–145. doi:10.1016/0001-4575(81)90025-7.

Wu, K.F., and Jovanis, P.P. 2012. Crashes and crash-surrogate events: Exploratory modeling with naturalistic driving data. Accident Analysis and Prevention, **45**: 507–516. doi:10.1016/j.aap.2011.09.002. PMID:22269536.

Zheng, L., Ismail, K., and Meng, X.H. 2014*a*. Freeway safety estimation using extreme value theory approaches: a comparative study. Accident Analysis and Prevention, **62**: 32–41. doi:10.1016/j.aap.2013.09.006. PMID:24129319.

Zheng, L., Ismail, K., and Meng, X.H. 2014*b*. Shifted Gamma-Generalized Pareto Distribution model to map the safety continuum and estimate crashes. Safety Science, **64**: 155–162. doi:10.1016/j.ssci.2013.12.003.

Zimolong, B. 1979. Traffic conflict at urban junctions. Proceedings of 2nd International Traffic Conflict Technique Workshop, Paris, France, pp. 111–116.

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1. Nicolette Formosa, Mohammed Quddus, Stephen Ison, Mohamed Abdel-Aty, Jinghui Yuan. 2020. Predicting real-time traffic conflicts using deep learning. *Accident Analysis & Prevention* **136**, 105429. [Crossref]
2. Lu Xing, Jie He, Ye Li, Yina Wu, Jinghui Yuan, Xin Gu. 2020. Comparison of different models for evaluating vehicle collision risks at upstream diverging area of toll plaza. *Accident Analysis & Prevention* **135**, 105343. [Crossref]
3. Christine Chaloupka, Ralf Risser, Elisabeth Füssl. Evaluation of Technologies That Help to Identify Hazards for Cyclists in Cities 155-171. [Crossref]
4. Andrew P. Tarko. Traffic conflicts as crash surrogates 31-45. [Crossref]
5. Raghad Zeki Abdul-Majeed, Hussein A. Ewadh. Serious Conflicts: A Safety Performance Measure at Signalized Intersections 291-306. [Crossref]
6. Lai Zheng, Tarek Sayed. 2019. Bayesian hierarchical modeling of traffic conflict extremes for crash estimation: A non-stationary peak over threshold approach. *Analytic Methods in Accident Research* **24**, 100106. [Crossref]
7. S.M. Sohel Mahmud, Luis Ferreira, Md. Shamsul Hoque, Ahmad Tavassoli. 2019. Using a surrogate safety approach to prioritize hazardous segments in a rural highway in a developing country. *IATSS Research* . [Crossref]
8. Lai Zheng, Tarek Sayed. 2019. A full Bayes approach for traffic conflict-based before–after safety evaluation using extreme value theory. *Accident Analysis & Prevention* **131**, 308-315. [Crossref]
9. Chen Chai, Xianming Zeng, Xiangbin Wu, Xuesong Wang. Safety Evaluation of Responsibility-Sensitive Safety (RSS) on Autonomous Car-Following Maneuvers Based on Surrogate Safety Measurements 175-180. [Crossref]
10. Lai Zheng, Tarek Sayed, Mohamed Essa, Yanyong Guo. Do Simulated Traffic Conflicts Predict Crashes? An Investigation Using the Extreme Value Approach * 631-636. [Crossref]
11. Madhumita Paul, Indrajit Ghosh. 2019. Post encroachment time threshold identification for right-turn related crashes at unsignalized intersections on intercity highways under mixed traffic. *International Journal of Injury Control and Safety Promotion* **21**, 1-15. [Crossref]
12. Lai Zheng, Tarek Sayed, Mohamed Essa. 2019. Bayesian hierarchical modeling of the non-stationary traffic conflict extremes for crash estimation. *Analytic Methods in Accident Research* **23**, 100100. [Crossref]
13. Madhumita Paul, Indrajit Ghosh. 2019. Influence of green signal countdown timer on severe crash types at signalized intersections due to red light violations. *Transportation Letters* **93**, 1-12. [Crossref]
14. Xiupeng Shi, Yiik Diew Wong, Michael Zhi-Feng Li, Chandrasekar Palanisamy, Chen Chai. 2019. A feature learning approach based on XGBoost for driving assessment and risk prediction. *Accident Analysis & Prevention* **129**, 170-179. [Crossref]
15. Vittorio Astarita, Vincenzo Pasquale Giofré. 2019. From traffic conflict simulation to traffic crash simulation: Introducing traffic safety indicators based on the explicit simulation of potential driver errors. *Simulation Modelling Practice and Theory* **94**, 215-236. [Crossref]
16. Ziaur Rahman, Stephen P. Mattingly, Rahul Kawadgave, Dian Nostikasari, Nicole Roeglin, Colleen Casey, Taylor Johnson. 2019. Using crowd sourcing to locate and characterize conflicts for vulnerable modes. *Accident Analysis & Prevention* **128**, 32-39. [Crossref]
17. Tiantian Chen, Lu Bai, N.N. Sze. Factors affecting the severity of rear-end conflicts: a driving simulator study 1182-1187. [Crossref]
18. Jiří Ambros, Jaroslav Altmann, Chris Jurewicz, Anna Chevalier. 2019. Proactive assessment of road curve safety using floating car data: An exploratory study. *Archives of Transport* **50**:2, 7-15. [Crossref]
19. Lai Zheng, Tarek Sayed. 2019. From univariate to bivariate extreme value models: Approaches to integrate traffic conflict indicators for crash estimation. *Transportation Research Part C: Emerging Technologies* **103**, 211-225. [Crossref]
20. Lai Zheng, Tarek Sayed. 2019. Comparison of Traffic Conflict Indicators for Crash Estimation using Peak Over Threshold Approach. *Transportation Research Record: Journal of the Transportation Research Board* **2673**:5, 493-502. [Crossref]
21. S.M. Sohel Mahmud, Luis Ferreira, Md. Shamsul Hoque, Ahmad Tavassoli. 2019. Micro-simulation modelling for traffic safety: A review and potential application to heterogeneous traffic environment. *IATSS Research* **43**:1, 27-36. [Crossref]
22. Lai Zheng, Tarek Sayed. 2019. Application of Extreme Value Theory for Before-After Road Safety Analysis. *Transportation Research Record: Journal of the Transportation Research Board* **2673**:4, 1001-1010. [Crossref]
23. Lai Zheng, Tarek Sayed, Mohamed Essa. 2019. Validating the bivariate extreme value modeling approach for road safety estimation with different traffic conflict indicators. *Accident Analysis & Prevention* **123**, 314-323. [Crossref]

24. Kentaro Yamada, Manabu Kuroki. 2019. New Traffic Conflict Measure Based on a Potential Outcome Model. *Journal of Causal Inference*, ahead of print. [Crossref]
25. Petr Pokorny, Kelly Pitera. 2019. Observations of truck-bicycle encounters: A case study of conflicts and behaviour in Trondheim, Norway. *Transportation Research Part F: Traffic Psychology and Behaviour* **60**, 700-711. [Crossref]
26. Po-Ruey Lei. 2019. Mining maritime traffic conflict trajectories from a massive AIS data. *Knowledge and Information Systems* . [Crossref]
27. Madhumita Paul. Safety Assessment at Unsignalized Intersections Using Post-Encroachment Time's Threshold—A Sustainable Solution for Developing Countries 117-131. [Crossref]
28. Elhashemi M. Ali, Mohamed M. Ahmed, Shaun S. Wulff. 2019. Detection of critical safety events on freeways in clear and rainy weather using SHRP2 naturalistic driving data: Parametric and non-parametric techniques. *Safety Science* . [Crossref]
29. Lai Zheng, Tarek Sayed, Ahmed Tageldin. 2018. Before-after safety analysis using extreme value theory: A case of left-turn bay extension. *Accident Analysis & Prevention* **121**, 258-267. [Crossref]
30. Carl Johnsson, Aliaksei Laureshyn, Tim De Ceunynck. 2018. In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators. *Transport Reviews* **38**:6, 765-785. [Crossref]
31. Ahmed Tageldin, Tarek Sayed, Karim Ismail. 2018. Evaluating the safety and operational impacts of left-turn bay extension at signalized intersections using automated video analysis. *Accident Analysis & Prevention* **120**, 13-27. [Crossref]
32. Lai Zheng, Karim Ismail, Tarek Sayed, Tazeen Fatema. 2018. Bivariate extreme value modeling for road safety estimation. *Accident Analysis & Prevention* **120**, 83-91. [Crossref]
33. Yanyong Guo, Tarek Sayed, Mohamed H. Zaki. 2018. Exploring Evasive Action–Based Indicators for PTW Conflicts in Shared Traffic Facility Environments. *Journal of Transportation Engineering, Part A: Systems* **144**:11, 04018065. [Crossref]
34. X. Shi, Y.D. Wong, M.Z.F. Li, C. Chai. 2018. Key risk indicators for accident assessment conditioned on pre-crash vehicle trajectory. *Accident Analysis & Prevention* **117**, 346-356. [Crossref]
35. S. M. Sohel Mahmud, Luis Ferreira, Md. Shamsul Hoque, Ahmad Tavassoli. 2018. Surrogate Measures for Traffic Safety Evaluation in Developing Countries: An Application Toward Sustainable Safety. *Advances in Civil Engineering Materials* **7**:3, 20170105. [Crossref]
36. Andrew P. Tarko. Chapter 17. Surrogate Measures of Safety 383-405. [Crossref]
37. Andrew P. Tarko. 2018. Estimating the expected number of crashes with traffic conflicts and the Lomax Distribution – A theoretical and numerical exploration. *Accident Analysis & Prevention* **113**, 63-73. [Crossref]
38. Kun-Feng Wu, Muhammad Nashir Ardiansyah, Wei-Jyun Ye. 2018. An evaluation scheme for assessing the effectiveness of intersection movement assist (IMA) on improving traffic safety. *Traffic Injury Prevention* **19**:2, 179-183. [Crossref]
39. S. M. Sohel Mahmud, Luis Ferreira, Shamsul Hoque, Ahmad Tavassoli. Application of Traffic Conflict Techniques as Surrogate Safety Measures: A Sustainable Solution for Developing Countries 88-105. [Crossref]
40. S.M. Sohel Mahmud, Luis Ferreira, Md. Shamsul Hoque, Ahmad Tavassoli. 2017. Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs. *IATSS Research* **41**:4, 153-163. [Crossref]
41. Rasa Ušpalytė-Vitkūnienė, Aliaksei Laureshyn. 2017. PERSPECTIVES FOR SURROGATE SAFETY STUDIES IN EAST-EUROPEAN COUNTRIES. *The Baltic Journal of Road and Bridge Engineering* **12**:3, 161-166. [Crossref]
42. Wei Yuanyuan, Zhang Cunbao, Zhou Bin, Chen Feng, Zhang Hualong. The mobile phone use behavior and its effect on pedestrian safety at signalized intersections in China 225-231. [Crossref]
43. Marie-Soleil Cloutier, Ugo Lachapelle, Andrée-Anne d'Amours-Ouellet, Jacques Bergeron, Sébastien Lord, Juan Torres. 2017. "Outta my way!" Individual and environmental correlates of interactions between pedestrians and vehicles during street crossings. *Accident Analysis & Prevention* **104**, 36-45. [Crossref]
44. Xinguo Jiang, Guopeng Zhang, Yue Zhou, Liang Xia, Zhenggang He. 2017. Safety assessment of signalized intersections with through-movement waiting area in China. *Safety Science* **95**, 28-37. [Crossref]
45. Lai Zheng, Karim Ismail. 2017. A generalized exponential link function to map a conflict indicator into severity index within safety continuum framework. *Accident Analysis & Prevention* **102**, 23-30. [Crossref]
46. R.G. Poulos, J. Hatfield, C. Rissel, L.K. Flack, L. Shaw, R. Grzebieta, A.S. McIntosh. 2017. Near miss experiences of transport and recreational cyclists in New South Wales, Australia. Findings from a prospective cohort study. *Accident Analysis & Prevention* **101**, 143-153. [Crossref]

47. Tim De Ceunynck, Bert Dorleman, Stijn Daniels, Aliaksei Laureshyn, Tom Brijs, Elke Hermans, Geert Wets. 2017. Sharing is (s)caring? Interactions between buses and bicyclists on bus lanes shared with bicyclists. *Transportation Research Part F: Traffic Psychology and Behaviour* **46**, 301-315. [Crossref]

48. Aliaksei Laureshyn, Tim De Ceunynck, Christoffer Karlsson, Åse Svensson, Stijn Daniels. 2017. In search of the severity dimension of traffic events: Extended Delta-V as a traffic conflict indicator. *Accident Analysis & Prevention* **98**, 46-56. [Crossref]

49. Salvatore Cafiso, Alessandro Di Graziano, Giuseppina Pappalardo. 2017. In-vehicle stereo vision system for identification of traffic conflicts between bus and pedestrian. *Journal of Traffic and Transportation Engineering (English Edition)* . [Crossref]

50. Yifan Guo, Qiaojun Xiang, Shen Li, Ting Zhang, Rao Yao. 2017. Impacts of Large Vehicles on Traffic Safety in Freeway Interchange Merging Areas and Improvement Measures. *MATEC Web of Conferences* **124**, 04004. [Crossref]

51. Rolla Almodfer, Shengwu Xiong, Zhixiang Fang, Xiangzhen Kong, Senwen Zheng. 2016. Quantitative analysis of lane-based pedestrian-vehicle conflict at a non-signalized marked crosswalk. *Transportation Research Part F: Traffic Psychology and Behaviour* **42**, 468-478. [Crossref]

52. Kentaro Yamada, Manabu Kuroki. 2016. New Traffic Conflict Measures Using Potential Outcome Models. *Japanese journal of applied statistics* **45**:1-2, 1-24. [Crossref]

53. Adrian C. Lorion, Bhagwant Persaud. 2015. Investigation of surrogate measures for safety assessment of urban two-way stop controlled intersections. *Canadian Journal of Civil Engineering* **42**:12, 987-992. [Abstract] [Full Text] [PDF] [PDF Plus]

54. Calvin Pin, Tarek Sayed, Mohamed H. Zaki. 2015. Assessing Safety Improvements to Pedestrian Crossings Using Automated Conflict Analysis. *Transportation Research Record: Journal of the Transportation Research Board* **2514**:1, 58-67. [Crossref]

55. Bixiang Li, Shengwu Xiong, Xiaohong Li, Mianfang Liu, Xiaohong Zhang. 2015. The Behavior Analysis of Pedestrian-cyclist Interaction at Non-signalized Intersection on Campus: Conflict and Interference. *Procedia Manufacturing* **3**, 3345-3352. [Crossref]