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Review article

Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs

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ABSTRACT

Although there have been a number of recent reviews on the use of traffic conflict techniques (TCTs), none have focused on the use of proximal surrogate indicators. This paper comprehensively reviews the development and application of proximal surrogate safety indicators to address this gap. There is a particular focus on more recent advancements in the application of such indicators. For each of the main indicators reviewed, the paper provides a synthesis of the main guiding principles, as well as the most prominent features, including critical or threshold values used in the past. In addition, the main advantages and disadvantages of the reviewed indicators are highlighted. Finally, a number of research gaps are identified together with recommendations for potentially useful avenues of future research.

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1. Introduction

The application of Traffic Conflict Techniques (TCTs) for analysing traffic safety problems has seen considerable research interest, having gained acceptance as a proactive surrogate approach [1–3]. TCTs, which address several issues associated with traditional approaches, can improve our understanding into the failure mechanism and chain of events which leads to road traffic collisions and resulting consequences [4]. The most appealing aspect of conflict indicators is their ability to capture severity of collision data objectively within a shorter time period compared to the use of accident data. Hence, the effectiveness of any safety program can also be assessed in a more timely manner [5]. Moreover, the ethical problems associated with the need for the collection of long accident history data will also be avoided.

Several comprehensive reviews have been undertaken on the application of TCTs for diagnosing traffic safety problems. Those reviews mainly deal with the reliability and validity of TCTs and methodological approaches to data collection [3,5]. None of those reviews specially focused on the use of proximal surrogate indicators. This paper provides a comprehensive review on the development and application of such indicators to address those gaps. For this purpose, relevant articles were identified and gathered from various online and offline databases, including Google Scholar; Research Gate; Science Direct; Transport Research International Documentation; and Engineering Village. For each indicator reviewed, there has been a focus on the principles, important features, as well as advantages and disadvantages. Particular effort has been made to identify the relevant articles which focused on recent advancements in the application of surrogate safety measures.

The current review has identified 38 major proximal indicators, divided into two major groups, namely temporal and non-temporal. The non-temporal measures are also sub-divided into three categories based on measuring attributes, such as distance, deceleration and others. The following sections of the paper synthesize the major indicators with a view to provide a state-of-art review of the development and use of those indicators. For each indicator, review mainly focuses on the recent advancements in the application, computational equations, advantages and disadvantages. Finally, a summary of the main indicators is provided, followed by a set of research gaps and future research directions.

2. Temporal (and/or spatial) proximity based conflict indicators

Temporal (and/or spatial) proximity based conflict indicators have been developed under the assumption that the closer vehicles are to each other, the nearer they are to a collision. One of the major advantages in the traditional definition is that all collisions will be preceded by conflicts. The quantitative measurement is relatively objective and provides an interpretable measure in terms of closeness to collision. Moreover, a time or space proximity definition is easily understood and it is appreciated by both drivers, as well as conflict observers.

In order to apply the concept in practice, many proximal measures have been proposed, broadly categorized into temporal and non-temporal. The latter are also grouped according to distance, deceleration and other criteria. Indicators based on temporal proximity are the most popular measures because they integrate both the spatial proximity and speed. Using the values of traffic movement parameters in a specified equation, traffic conflicts are recorded when the output is less than a predetermined threshold [1,6,7]. A brief description of each type of proximal surrogate indicators is given in the following sub-sections. Computation equations of the major indicators are provided in Appendix A.

2.1. Temporal proximal indicators

Temporal proximal indicators are the most prominent and widely used indicators. A total of 18 temporal proximal indicators have been found and a summaryis shown in Table 1. The latter also addresses the main limitations, advantages, and suitability for evaluating particular crash types.

2.1.1. Time to collision (TTC)

TTC at an instant t is defined as '*the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained*' [8]. TTC at the onset of braking (TTC_{br}), represents the available manoeuvring space at the moment the evasive action starts. The minimum TTC (TTC_{min}) has reached during the approach of two vehicles on a collision course is taken as an indicator for the severity of an encounter. In principle, the lower the TTC_{min} is, the higher the level of a collision will be [9].

2.1.1.1. Approaches for determining time-to-collision values.
In earlier studies, two widely used approaches have been found to determine TTC values for safety assessments. One deals with TTC values of vehicles passing a cross-section of a roadway. This method is usually used in empirical traffic flow studies. The other approach focuses on drivers driving either during a certain time period or over a specific route in real-life traffic conditions; or on a driving simulator in a controlled environment. The minimum TTC values are ascertained using the subsequent vehicle positions and speeds [10].Recently, microscopic traffic simulation modelling approach for safety evaluation has gained popularity. In this approach, TTC is mainly calculated by extrapolating position and

Table 1
Summary of temporal proximal based indicators.

Indicator	Definition	Limitations	Advantages	Suitability for collision type
Time-to-Collision (TTC) or Time-Measured-to-Collision (TMTC)	The time until a collision between the vehicles would occur if they continued on their present course at their present rates.	Assume consecutive vehicles will keep constant speeds; Ignore many potential conflicts due to acceleration or deceleration discrepancies; Can provide the magnitude of crashes but not their severity; Collision course must exists, TTC index cannot be estimated in a finite number where the leading vehicle is faster than following.	TTC is far more frequently used in practice than PET or TA due to theoretical issues; TTC was more informative than PET; Many automobile collision avoidance systems or driver assistance systems have used TTC as an important warning criterion; Applicable for Work Zone safety analysis, Applicable in post-processor such as SSAM	Rear-end, turning/weaving, hit objects/parked vehicle, crossing and hit pedestrian.
Time Exposed Time-to-Collision (TET)	Summation of all moments (over the considered time period) that a driver approaches a front vehicle with a TTC-value below the threshold value TTC*.[a]	Does not provide the variation severity levels of different TTC values below the threshold value; If TTC-value is lower than the threshold, does not affect the TET indicator value; Highly data-intensive and attainable only in a simulation environment.	Can be calculated separately for per user class, Can be applied in the comparison of a do-nothing case with an adapted situation; Suited for application in microscopic simulation studies of traffic; Easy to include small TTC value due to including of time-dependent TTC values of all subjects.	Same as TTC.
Time Integrated Time-to-Collision (TIT)	Integral of the TTC-profile during the time it is below the threshold	Difficult to interpret its meaning for complexity to determine; Not preferable to use in comparative studies in which simulation tools are applied to generate trajectories; Benefits is small due to the uncertainties in driver behaviour.	Level of safety of collision can be derived; Can be applied in the comparison of a do-nothing case with an adapted situation; suitable for microscopic simulation studies of traffic; Easy to include small TTC value due to including of time-dependent TTC values of all subjects.	Same as TTC.
Modified Time-to-Collision (MTTC)	Modified models which considered all of the potential longitudinal conflict scenarios due to acceleration or deceleration discrepancies.	Obtaining the field speed of both users and the distance gap in an evolution process is difficult and has to rely on other approaches; Not fit for lane changing or head-on collision; Does not reflect the severity of collision	More advance than TTC; Consider driving discrepancies; Severity of the collision could be weighted using CI indicators.	Vehicle-vehicle crash same as TTC
Crash Index (CI)	Influence of speed on kinetic energy involved in collisions.	Describes only the safety information about two vehicles at a certain time and place. Not fit for lane changing or head-on collision, has to rely on other approaches for data collection	Reflect the severity of a potential crash; describe the influence of speed on kinetic energy involved in collisions; Consider the elapsed time before the conflict occurred; Severity and the likelihood of a potential conflict could be interpreted.	Same as MTTC.
Headway (H)	The elapsed time between the front of the lead vehicle passing a point on the roadway and the front of the following vehicle passing the same point	Mainly applicable in conflicts related to follow up manoeuvre i.e. for read-end collision in lane based traffic environment; Do not take into account conflicts due to lateral movement particularly during lane changing or overtaking.	Easy to measure; Level of safety could be distinguished.	Rear-end mainly, other such as turning and hit objects/parked vehicle.
Time-to-Accident (TA)	Time-to-Accident (TA) is the time that remains to an accident from the moment that one of the road users starts an evasive action if they had continued with unchanged speed and directions	Often criticized for relying heavily on the subjective judgement of speed and distance. Mainly rely on the evasive action. Other same as TTC	Widely used; Easy to measure; Can be done by both manually or by Video analysis, Couple of manuals have been developed in different countries.	Same as TTC.
Post-Encroachment Time (PET)	The time between the moment that a road user (vehicle) leaves the area of potential collision and the other road user arrives collision area.	Only useful in the case of transversal (i.e. crossing) trajectories (Right angle collision); Cannot reflect changes with the dynamics of safety-critical events over a larger area; Levels of severity as well as impact of a conflict are not taken into account;	PET is more appropriate than TTC for intersecting conflicts; PET can be easily extracted; PETs can be easily estimated using photometric analysis in video or simulated environment; PET represents the driver behaviours.	Mainly for right angle or crossing crash, hit pedestrian. Merging/diverging, head on (to a certain extent).

[a] *Threshold value.

speed of the vehicle from trajectories of vehicle e.g. Essa and Sayed [11], Caliendo and Guida [12], Ambros et al. [13].

2.1.1.2. Critical time-to-collision value. In applying the improved safety indicators, a critical or *threshold value* should be chosen to distinguish between relatively safe and critical encounters. Generally, TTC lower than the perception and reaction time should be considered unsafe. The value of TTC in various situations in which traffic conflicts frequently happen has been studied by many authors (e.g. Sayed et al. [1], Shariat-Mohaymany et al. [6], Van der Horst [9], Vogel [14], Sayed et al. [15], Van der Horst [16]. Table 2 presents some reported minimum and desirable critical threshold TTC values.

Table 2
Minimum and desirable TTC threshold values indicated by different studies.

Reference	Minimum (s)	Desirable (s)	Condition
Van der Horst [16]	1	1.5	Approaches at intersections
Sayed et al. [15]	1.6	2.0	Low level of conflict
	00	0.9	High level of conflict
Hogema and Janssen [17]	–	3.5	Non-supported drivers
Hogema and Janssen [17]	–	2.6	Supported drivers
Vogel [14]	1	2	Approaches at intersections
Meng and Qu [18]	2	4	Urban Road Tunnel (rear end crash)
Huang et al. [7]		1.6	Signalized Intersection
Sayed et al. [1]		3	Signalized Intersection
AASHTO [19]; Farah et al. [20] & Hegeman [21]		3	For 2-lane rural roads

2.1.2. Extended Time to Collision (TET, TIT)

Minderhoud and Bovy [10] have proposed two new proximal indicators based on the time-to-collision (TTC) notion. The first of these, Time Exposed Time to Collision (TET) represents a measure of the length of time a TTC-event remains below a designated TTC-threshold. The second indicator, Time Integrated TTC (TIT), represents a measure of the integral of the TTC-profile during the time it is below the threshold.

2.1.3. Time Exposed Time-to-Collision (TET) indicator

TET expresses the total time spent in safety-critical situations, characterized by a TTC value below the threshold value TTC*. For calculation purposes, it is assumed that TTC, at an instant t, is kept constant for a small time step τ_{sc} (e.g. 0.1 s). For the considered time period, H, there are $T = H/\tau_{sc}$ time instantst taken into account in the calculation (t = 0….T) to which the summation is extended while calculating the TET value.

2.1.4. Time Integrated Time-to-Collision (TIT) indicator

The probability of collision will vary with the value of TTC. TIT indicator has been developed taking into account the impact of the different TTC values. This indicator expresses the level of safety, or relative probability of conflict, using the integral of the time-to-collision profile of drivers (in s^2).

A comparative analysis by Minderhoud and Bovy [10] has shown that the TET value is useful to distinguish the difference of scenarios. Although, the TIT indicator is theoretically more appealing, it becomes difficult to interpret its meaning for more complex situations. In addition, the TET is preferable for use in comparative studies, particularly when simulation tools are applied to generate trajectories. Overall, the additional benefit of the more complex TIT approach appears to be small due to the simplifications and uncertainties in modelled driver behaviour.

2.1.5. Modified TTC (MTTC)

Time to Collision (TTC) surrogate indicators are mainly based on the assumption that consecutive vehicles will keep constant speeds until the collision occurs. In addition, the definition of TTC means that the collision will take place only if the speed of the following vehicle is greater than that of the leading vehicle. These assumptions ignore many potential conflicts due to different inconsistencies of driver behaviour including acceleration or deceleration discrepancies. To overcome this, Ozbay et al. [22] proposed a modified traffic to collision and Yang et al. [23] further validates this indicator. The modified indicator presented all of the potential longitudinal conflict scenarios as summarized in Table 3. In the latter, V_F, V_L, a_F, and a_L are the speed and acceleration of the following and leading vehicles, respectively.

The consideration of the occurrence of a conflict is mainly based on the trajectory parameters of the two consecutive vehicles, including their relative distance, speed and acceleration. It is also applicable for the lane changing, merging and diverging conflicts analysis, see [24]. For identifying the potential conflict probability (CP) under different traffic conditions, the study adopted an exponential decay function. Another collision probability for two and multiple road users is described by Saunier and Sayed [25]. This takes into account all of the probable extrapolation hypotheses, which can automatically analyse the level of safety by continuously computing the conflict probability.

2.1.6. Crash Index (CI)

By comparing an MTTC value with the threshold, it is possible to identify if a vehicle is in a potential collision situation. However, MTTC by itself cannot give enough indication of the level of severity of a conflict. This is because two probable colliding vehicles might have the same MTTC for different combinations of speeds and relative distances. Therefore, a new Crash Index (CI) has been proposed by Ozbay et al. [22] to incorporate additional factors reflecting the level of severity of a probable crash. This new approach describes the influence of speed on kinetic energy involved in collisions. It also considers the elapsed time before the conflict, to interpret the severity and the likelihood of a probable conflict [22].

2.1.7. Time-to-Accident (TA)

Time-to-Accident (TA) is defined as 'the time that remains to an accident from the moment that one of the road users starts an evasive action, if they had continued with unchanged speed and directions' [26,27]. This definition is also valid for situations with only one road user. When more than two road users are involved, the situation is regarded as a number of different conflicts. Therefore, TA is seen as a special value of the TTC, based on evasive action undertaken by any of the road user to avoid collision [28].

The concept of this indicator was first proposed by Hydén [26] for Sweden road safety evaluation. From that time, it is generally known as "the Swedish Traffic Conflicts Technique". Given the approaching speed of the following road user, assuming that user can successfully stop just at the collision point, the minimal TA is calculated to come to stop just at the collision point for a car with maximum braking. Hydén [26] has drawn a uniform severity level of TA with respect of speed considering road friction. The uniform severity level is adjusted by Lund University by adding the additional fixed safety margin by 0.5 s. From this level, parallel lines have been drawn for graphically represent on how the severity increases from non-serious conflict to serious conflict. Svensson [27] further advanced the concept of a severity hierarchy by dividing levels of severity into subgroups.

2.1.7.1. Threshold values.
Based on threshold TA values, the scale of conflict seriousness can be determined [29]. The boundary between a serious and a slight conflict is based on the "Optimal Braking Time" (OBT) for an average vehicle that comes safely to a halt with locked brakes on normal dry asphalt, just before the point of collision, plus an extra safety margin of 0.5 s. A single TA value of 1.5 s was initially used to distinguish serious conflict and slight conflict [30]. All conflicts to the left of the boundary "Optimal Braking Time" (OBT) are termed as "serious conflicts". Shbeeb [31] indicated that the 1.5 s limit appeared to work well in

Table 3
Description of possible scenarios between two vehicles one following the other.
Source: [24]

V	$V_F > V_L$			$V_F \leq V_L$		
a	$a_L > 0$	$a_L > 0$	$a_L > 0$	$a_L > 0$	$a_L > 0$	$a_L > 0$
$a_F > 0$	P	C	C	P	C	P
$a_F < 0$	P	P	P	I	P	I
$a_F = 0$	P	C	C	I	C	I

Note: C-Conflict occurs; P-Possible Conflict; I-Impossible conflict with each other.

Table 4
Desired threshold of TA proposed.

Reference	TA (S)	Critical situation
Hydén [26]	1.5	Serious conflict
Shbeeb [31]	1.5	Well in urban areas intersection
Shbeeb [31]	<1.5	Rural areas where speed is higher

urban areas when the speed was rather low, but not in rural areas where speed is higher. A summary of threshold values used in different studies are given in Table 4.

2.1.8. Time headway (H)

H is one of the indicators used to estimate the criticality of a certain traffic situation. H is measured by taking the time that passes between two vehicles' reaching the same location.

2.1.8.1. Threshold values. In the US, it has been found that it is impossible to follow a vehicle safely with a headway of <2 s [32]. In Germany, the recommended minimum distance is "half the speedometer", which means, a car travelling at 80 km/h should keep a distance of at least 40 m. This rule translates to a recommended time headway of 1.8 s. In Sweden, time headway of 3 s in rural areas is recommended by the National Road Administration. However, many road administrations in European countries recommend a safe headway of 2 s [14]. Table 5 summarizes some of the proposed critical headway.

2.1.9. Post-Encroachment Time (PET)

The concept of Post-Encroachment Time (PET) was first introduced by Allen et al. [36]. PET was defined as 'the time difference between the moment an "offending" vehicle passes out of the area of potential collision and the moment of arrival at the potential collision point by the "conflicted" vehicle possessing the right of-way' [37]. Typically, it is assumed that the threshold value < 1.0 or 1.5 s are considered critical [8,29]. Songchitruksa and Tarko [38] defined PET the time it takes from the end of the right-of-way infringement of the first vehicle for the second vehicle to reach the conflict spot, measured from the rear bumper of the first vehicle to the front bumper of the second vehicle. To measure PET, one needs to know only two points in time: when the first vehicle leaves the right-of-way infringement zone and when the second vehicle enters the right-of-way infringement zone.' [38]. The latter study found that a 6.5 s threshold value gives the best-fitted model for site aggregated crash count.

Two other concepts are related to the PET found is literature, namely, Encroachment Time (ET) and Initially Attempted Post Encroachment Time (IAPT). ET reflects "the period that the "offending" vehicle occupies the conflict area therefore infringing the right-of-way of the vehicle in the major approach". If it is considered that the major approach vehicles having constant speeds, ET would be a better measure of conflicts. IAPT is similar to PET, except that it uses the estimated arrival time at the conflict area of the vehicle of major approach with respect to the moment the encroachment has ended [39].

Table 5
Proposed desirable headways.

Reference	Headway (s)	Critical situation
Ohta [33]	Between 1.1 and 1.7	Comfortable
Ohta [33]	>0.6	Danger
Taieb-Maimon and Shinar [34]	0.7	Minimum safe
Evans [35] & Michael et al. [32]	>2.0	Should not be considered safe enough to prevent possible conflicts

2.2. Distance based proximal indicators

The main attribute for conflict determination under this category is the distance available to avoid a collision. Table 6 provides a summary of major distance based proximal indicators.

2.2.1. Potential Index for Collision with Urgent Deceleration (PICUD)

This index, which has been proposed by Iida et al. [40], evaluates the possibility that two consecutive vehicles might collide, assuming that the leading vehicle applies its emergency brake, particularly during lane changing. PICUD is defined as the distance between the two vehicles considered when they completely stop. Estimation of PICUD requires two predetermined parameters, namely: reaction time and deceleration rate. Uno et al. [41] assumed that the vehicle deceleration rate is 3.3 (m/s^2) and the reaction time is 1.0 s in their study.

2.2.2. Proportion of Stopping Distance (PSD)

Allen et al. [36] proposed the use of Proportion of Stopping Distance (PSD). The latter has been defined as the ratio between the remaining distance to the potential point of collision and the minimum acceptable stopping distance. Further details on this indicator can be seen in the Guido et al. [42], Astarita et al. [43].

2.2.3. Margin to Collision (MTC)

MTC was first proposed by Kitajima et al. [44] based on a similar perspective to Stopping Distance. The index also represents the possibility of collision in a case where the preceding vehicle and the following vehicle decelerate abruptly at the same time (the abrupt deceleration is assumed to be 0.7 [G] (=6.9 [m/s^2])).An MTC of <1 indicates a high likelihood of collision in a case where the preceding vehicle decelerates abruptly, even if the following vehicle at the same time also decelerates abruptly.

2.2.4. Difference of Space distance and Stopping distance (DSS)

DSS is difference between the space and stopping distances. Here, the space distance is calculated by the sum of differences between the leading and following vehicles. The braking distance of the leading vehicle and the stopping distance is calculated by the sum of the brake reaction distance and the braking distance of the following vehicle. When the leading vehicle brakes suddenly, and subsequently the following vehicle also brakes to avoid conflict, DSS shows the freeze position of the two vehicles.

When DSS is less than zero, it is defined that the vehicle is unsafe. In this indicator, the calculation formula and dangerous threshold values are comparatively simple. However, an evaluation method using this indicator does not consider the level of severity, as well as the duration conflict [45].

2.2.5. Time Integrated DSS (TIDSS)

To overcome the DSS shortcoming, TIDSS was proposed by Okamura, M. et al. [45]. This indicator evaluates the safety of traffic flow by the total value of the time integrated value gap between DSS and the dangerous threshold value.

2.2.6. Unsafe Density (UD)

Unsafe Density was first presented by Barceló et al. [46] for car-following situations using micro-simulation based on vehicle speeds, relative position between the lead and the following vehicle and the reaction time of the following driver.

The unsafe parameter does not give a global situation of the safety in a network or part of it. To assess the safety level of different links of the network over time, an "unsafe" density parameter was calculated using the summation of the "unsafety" parameter for all the vehicles in the simulation normalized with respect to section length (L) and total time period considered in the analysis (T).

Table 6
Summary of distance based proximal indicators.

Indicator	Definition	Limitations	Advantages	Suitability for collision type
Potential Index for Collision with Urgent Deceleration (PICUD)	Distance between the two vehicles considered when they completely stop.	Mainly applicable in lane changing condition when leading vehicle apply emergency break; Threshold value yet to be sated up; Do not take into account lateral conflicts.	PICUD is more suitable than TTC for evaluating the danger of collision of the consecutive vehicles with similar speeds. PICUD might detect the change in traffic condition and conflicts more sensitively than TTC.	Same as TTC.
Proportion of Stopping Distance (PSD)	Ratio between the remaining distance to the potential point of collision and the minimum acceptable stopping distance.	Based on evasive actions; PSD provide higher percentage of vehicles interaction and time exposure to conflict than TTC and DRAC, hence less focus on specific safety problem.	Single vehicle conflict with fixed or unfixed objects can be evaluated; Easy for observation and calculation.	Hit object (on road or road side), overturning.
Margin to Collision (MTC)	Ratio of the summation of the inter-vehicular distance and the stopping distance of the preceding vehicle divided by the stopping distance the following vehicle.	Same as Stopping distance. In addition, it does not consider a response delay of the following vehicle. A non-dimensional parameter.	Same as Stopping distance. It also provides the possibility of conflict when the preceding and following vehicle at the same time decelerate abruptly.	Same as Stopping distance.
Unsafe Density (UD)	Level of "unsafe" in the relation between two consecutive vehicles on the road for a determined simulation step.	The value of this parameter doesn't really have a sense in itself and must be used only for comparison purposes; fit for only rear-end collision analysis (identical trajectory); Applicable only for lane based traffic situation.	Gives more accurate information than typical micro-simulation outputs; Comparative study between link can be done.	Rear-end, merging and diverging or lane changing.
Difference of Space distance and Stopping distance (DSS)	DSS is defined by the difference of the space and stopping distance.	Provide information on the number of unsafe vehicle but cannot consider the degree of danger as well as the duration.	The calculation formula and dangerous threshold value are simple and clear.	Rear-end, hit object and turning.
Time Integrated DSS (TIDSS)	Total value of the time integrated value gap between DSS and the dangerous threshold value.	Mainly suitable for rear-end conflict.	Consider the degree and the duration of danger.	Same as DSS

2.3. Deceleration based indicators

Dangerous situations are defined using the rate deceleration during emergency. Seven applied indicators are categorized under this category and the most important are summarized in the Table 7.

2.3.1. Deceleration Rate to Avoid a Crash (DRAC)

DRAC was first defined by Almqvist et al. [47]considering the role of speed differentials and deceleration in potential crash occurrence. DRAC is the differential speed between a following/response vehicle and its corresponding subject/lead vehicle (SV), divided by their closing time. The SV is responsible for the initial action (i.e. braking for a traffic light or stop sign and changing lanes and/or accepting a gap), and the RV is the vehicle immediately affected by SV action and must respond to avoid dangerous interactions.

Many researchers have explicitly recognized the relevance of DRAC as a safety–performance indicator as it explicitly considers the role of differential speeds and decelerations in traffic flow (see [42,43,48,49]. However, many researchers have argued that the traditional DRAC fails to accurately identify the potential traffic conflict situation because it does not consider many important factors that play a major role in the

braking process, especially in critical situations like the vehicle braking capability over time for prevailing road and traffic conditions [39,50, 51]. Therefore, it is desirable that a modified safety indicator would be introduced that will consider both required deceleration rates and braking capabilities for individual vehicles.

2.3.1.1. Threshold values. AASHTO [52] recommends a slightly higher threshold of 3:40 m/s^2 for most drivers. Archer [33] suggests that a given vehicle is in traffic conflict if its DRAC exceeds a threshold braking value of 3:35 m/s^2. Guido et al. [42] also considered this threshold value in their study to highlight higher risk vehicle interactions. DRAC provides a better measure to represent both frequency and severity of high risk vehicle interactions.

2.3.2. Crash Potential Index (CPI)

To deal with the problems associated with DRAC, Cunto and Saccomanno [53] introduced the concept of Crash Potential Index (CPI). The Crash Potential Index (CPI) is defined as the probability that a given vehicle DRAC exceeds its maximum available deceleration rate (MADR) during a given time interval [39].

For a given vehicle, CPI is estimated as the ratio between the sum of time increments for which DRAC > MADR and the total time (Ti) that

Table 7
Summary of deceleration based indicators.

Indicator	Definition	Limitations	Advantages	Suitability for collision type
Deceleration Rate to Avoid the Crash (DRAC)	Differential speed between a following/response vehicle and its corresponding subject/lead vehicle (SV) divided by their closing time.	Fails to accurately identify the potential traffic conflict situation; Not suitable for lateral movement.	Explicitly considers the role of differential speeds and decelerations in traffic flow.	Rear-end, Hit object/parked vehicle, Hit pedestrian, Merging and diverging manoeuvres.
Crash Potential Index (CPI)	Probability that a given vehicle DRAC exceeds its maximum available deceleration rate (MADR) during a given time interval.	Not suitable for lateral movement; mainly applicable at intersection.	Address some of the issues found in DRAC like vehicle braking capability for prevailing road and traffic conditions.	Same as DRAC.
Criticality Index Function (CIF)	Multiplication of vehicle speed with the required deceleration	Like TTC, it considers constant speed of consecutive vehicle; Further evaluation is needed using additional field date for validation.	Chance of occurrence and severity could be measured.	Turning accident, Right angle

vehicle, *i*, occupies the time-space domain. On the basis of the CPI measure, a vehicle is assumed to be in traffic conflict if its DRAC exceeds its assigned MADR [42].

This measure captures three important aspects of vehicle interactions, namely the following or response vehicle braking requirements to avoid the crash, the maximum available FV braking power and the time exposed to the interaction. The FV braking requirements during a vehicle interaction is represented by the deceleration rate to avoid the crash (DRAC) estimated using Newtonian physics for every time interval.

2.3.3. Criticality Index Function (CIF)

In the CIF, proposed by Chan [54], two hypotheses are considered for estimating a probable incident and the severity of a potential vehicular collision as follows:

(1) The higher the collision speed, the more severe the resulting consequences will be; and.
(2) The longer time available for evasive manoeuvre, the more likely a collision can be avoided.

The potential collision severity is proportional to the speed squared of the involved vehicle and inversely proportional to the time to conflict (TTC).

The proposed index could be a meaningful surrogate safety indicator by assessing the safety level involved in traffic conditions in terms of evaluating probability and severity of collision. However, further evaluation is needed using additional field date collected from different roadway condition.

2.4. Other indicators

2.4.1. Jerks

The term Jerks is a composite of g-force and speed or a derivative of acceleration first used by Wåhlberg [55]. The latter evaluated the relationship between the left/right, accelerate/decelerate and composite g-force and mean speed and the frequency of accidents. This study was done only for bus drivers during different time-periods. Results showed a weak tendency for left/right g-force and mean speed to predict bus accidents.

Bagdadi and Várhelyi [56] compare the jerkiness derived from naturalistic driving data from 166 passenger cars to develop a relationship between jerky driving and accident proneness. They also proposed a new method for detecting jerks in safety critical events considering acceleration profiles [57]. More recently, Zaki et al. [58] have shown that using jerk profile is preferable in finding undetected conflicts, compared to the use of conventional indicators. However, the study only considered breaking as an evasive action. Other actions, such as swerving to avoid conflict, may not be applicable for the proposed approach.

2.4.2. J-value

J-value is an accumulative safety indicator related to the accumulation of risk of vehicles inside a platoon. It was first proposed by ARON et al. [59]. Parameters values of this indicator are obtained from individual vehicle data, e.g. time gap between two consecutive vehicles, and vehicular speed [60].

2.4.3. Standard Deviation of Lateral Position (SDLP)

This indicator has been described by Vogel [61]. This measure is similar in nature to the degree of vehicular control a driver exerts in any particular driving situation and is allegedly related to the probability of running-off the road [61]. This indicator is mainly suitable for driving simulator or instrumented vehicle studies i.e. naturalistic driving approach. Therefore, it is not preferable in a static field measurement as an indicator of safety.

Finally, there are several other safety indicators that are less widely used, such as Critical Gap [62], Gap Time (GT) [36],Time to Intersection (TTI) [16], Time to Stop Line (TSL) [63], Time to Line Crossing (TLC) [61], Predicted Minimum Distance (PMD) ([64]); ODCA &PDCA, [65], Potential Energy (PE) [66] etc. Most of those indicators have not an established statistical relationship to accident frequency and outcome severity. There is also lack of sufficient experimentation and scientific investigation to allow for the widespread adoption of those indicators.

3. Discussion

Using the values of traffic movement parameters in a specified equation, traffic conflicts can be recorded once the output is less than a predetermined threshold [1,6]. Indicators based on temporal proximal indicators are popular because they integrate both the spatial proximity and speed.

Among those indicators, Time to Collision (TTC) is frequently used in practice in preference to many other established measures, for theoretical and reliability reasons. However, TTC is not an appropriate surrogate safety indicator for the measurement of lane changing conflicts, as it has been developed using the concept of point conflict. Time to Accident (TA) is an evasive action based indicator by which vehicle to vehicle conflicts, single and multi-vehicle conflicts can be evaluated. The TTC and TA indicators are suitable for measuring different type of conflicts such as rear-end, head-on, and hitting a fixed-object/parked vehicle, hit pedestrian and collision during turning. Time headway (H) is another indicator used to estimate the criticality of a follow-up traffic situation, which is applicable in all traffic environments.

Post-Encroachment Time (PET) is more appropriate for conflicts assessment at intersections. A number of studies have used these indicators such as, Hydén [8], Van der Horst [16], Archer [29], Allen et al. [36], Gettman and Head [48]. Moreover, TET (Time Exposed Time-to-Collision) and TIT (Time Integrated Time-to-collision) extended from TTC could be useful for evaluating probability and level of severity of crashes. Another extension of TTC is Modified Time to Collision (MTTC) proposed by Yang [24], which considers driving discrepancies and is also applicable in a developing country context. Crash Index (CI) is useful for weighting severity of the collision.

In addition, some non-temporal indicators that explain spatial or kinematic characteristics of vehicle interactions such as PICUD, PSD, DSS, DRAC have the potential to be applied in developing countries. Potential Index for Collision with Urgent Deceleration (PICUD) is more suitable than TTC for evaluating the danger of collision of the consecutive vehicles with similar speeds. Many researchers have explicitly recognized the relevance of DRAC as a safety–performance indicator, as it explicitly considers the role of differential speeds and decelerations in traffic flow; e.g. Archer [29], Guido et al. [42], Astarita et al. [43], Gettman and Head [48], Qu et al. [49]. Difference of the Space and Stopping Distance (DSS) is a simple but useful measure to calculate rear-end collision, which is potentially applicable for different traffic environments. Using Proportion of Stopping Distance (PSD) indicator, single vehicle conflicts with fixed or moving objects can be evaluated. It is relatively easier for observation and calculation.

However, there are still some challenging issues for the wider application of the proximal indicators for safety evaluation. The main issues identified are discussed in the next session.

3.1. Resultant issues and recent advancements

Whilst conflict measures based on proximity do not rely on evasive actions, the definition may still have limitations, since the distinction between a conflict and a non-conflict situation remains unclear in practice.

Although many indicators have been used, no consensus has been reached on what indicators should be given preference. Various indicators are different in nature and preferred application conditions are

different. Therefore, some researchers suggested the combined use of various indicators i.e. Laureshyn et al. [67], Ismail et al. [68], Salamati et al. [69], Kaparias et al. [70].

Amost all of the indicators are limited to the estimation of crash risk. The level of severity and the possible consequences of a potential crash are usually not accounted for [67,71]. Due to this limitation, two dimensions have been raised on severity, namely 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). Therefore, it is difficult to distinguish the consequences in terms of severity when all traffic events in a safety continuum are considered.

Many of the indicators assume the "unchanged speed and direction" for predicting probable conflict.Some experiments assumed unchanged directions and constant acceleration or decelerations. However, due to the complexity in traffic behaviour, in many cases, these simple assumptions and extrapolation may not be realistic. Therefore, consideration of all the possible options for road users have been suggested,i.e. Saunier and Sayed [25], Saunier et al. [72], Berthelot et al. [73].

Most of the indicators have been used to study safety problems in urban roads and intersections in developed countries. There are very few studies where these techniques have been applied in rural road environments, such as Shariat-Mohaymany et al. [6], Farah et al. [74]. Therefore, there is a question, to what extent these measures would be applicable in the non-lane base heterogeneous and/or rural roads traffic environment.

Most of indicators have focused on read-end or right-angle collisions. Some studies has been considered merging and diverging collisions, particularly in motorway/freeway of developed countries i.e.Yang et al. [23], Uno et al. [41], Bin et al. [75], St-Aubin [76]. Application of this conflict measure for head-on collision measurement is very rare. It is not known the extent to which these conflict indicators would be useful for the evaluation of probability of head-on or overturning conflicts in rural road environments.

Many of these indicators have not been validated for conditions in developing countries where, very often, complex and unique road and geometric characteristics and traffic behaviour applies. Local peculiarities include some special types of single vehicle crashes, such as overturn induced by pothole; shoulder drops and bridge approach drops, tyre burst induced by over loading and over use of tyres. In addition, numbers of crashes in developing countries are triggered by road hazards, including road side encroachment, road side activities by local users. Addressing these issues in traffic conflict techniques remain a challenge.

The validity and reliability of the application of proximal indicators continues to pose research questions. Validity is examined on the basis of whether there is correlation between a traffic conflict and a real crash record. Some studies also consider the validity as the potentiality of traffic conflict counts for the prediction of expected number of crashes, such as, Zheng et al. [3], Chin and Quek [5]. Some earlier studies showed that the correlation between a conflict and a crash is not statistically significant, e.g. Glennon et al. [77]. However, a number of studies showed a strong relationship between traffic conflicts and actual crashes. Several recent studies have used advanced data collection techniques, including automated observation through computer vision, and have shown a strong relationship between traffic conflict and crashes (e.g. Sayed et al. [1], Ozbay et al. [22], Yang [24], Archer [29], Songchitruksa and Tarko [38], El-Basyouny and Sayed [78], Peesapati et al. [79].

The reliability of indicators is another concern which is mainly related to the method of conflict measurement. Video analysis has been introduced to improve the reliability of data collection. Issues related to camera adjustment, coverage of camera, transformation of image from three to two dimensions, and dependency on human observations in extracting data from video, are still major constraints to obtain accurate data [24,29]. Therefore, for automatic description of conflict without human observer dependency, researchers are now using video sensors and computer vision techniques, i.e. Sayed et al. [1], Saunier et al. [72], Saunier and Sayed [80], Ismail et al. [81], Ismail et al. [82]. The main conclusions indicate that the application of computer vision techniques, coupled with automatic discrimination techniques, could provide improved results.

The application of micro simulation modelling for safety evaluation has opened a new spectrum for improving reliability of conflict studies [24,39]. Using a post-processor for analysing simulation model outputs is also a recent development. The FHWA [83] developed a Surrogate Safety Assessment Model as a post processor to determine the number and severity of conflicts obtained from simulation packages. More recently, integrated traffic simulation packages have been developed to accommodate the limitation of generating realistic vehicle trajectories with high precision by the existing microscopic simulation software [84,85]. Integration of advanced machine vision technique with micro-simulation modelling has the potential to establish a better theoretical and operational foundation for understanding the most concerning traffic safety problems.

3.2. Future research directions

Further research is needed to address the issues discussed above, as well as to fulfil some other research questions, namely:

3.2.1. Definition of standard threshold values for different traffic environments

Application of proximal indicator for defining conflict is threshold sensitive, as conflicts and levels of severity vary with the threshold value. However, no standard value has not been determined yet to distinguish conflict and normal events. There is scope for future research on the selection of an appropriate threshold values for different standard indicators, as those values might be dependent on the driver, the road and the traffic environment.

3.2.2. Setting-up common standardsof proximal indicatorsfor conflict evatuation

As described in this paper, a number of proximal indicators have been developed and applied in a discrete manner in different areas. Different approaches are used for evaluating conflict, calibrating and validating those indicators. Although, there are some similarities in basic attributes and methodological approaches, there remains a very diverse range of assumptions and approaches. It has been argued that such diversity makes practical application difficult on reliability and validity grounds [3]. Therefore, setting up a generalized standard for conflict evaluation could be a potential research avenue to enable improved level of applicability confidence.

3.2.3. Development of relationships between traffic conflicts and crashes for different traffic environments

Some statistical models, such as traditional regression model, two-phase model, extreme value theory, causal theory, and probabilistic framework, have been developed to relate traffic conflicts to crashes [3]. Although, these models are providing an appealing theoretical foundation, they still need to be further tested and validated. New methods or models could be explored for heterogeneous traffic environments in developing countries to validate different proximal indicators.

3.2.4. Incorporating road and vehilce factors in the indicators

Proximal indicators are mainly based on operational attributes i.e. time, speed, acceleration and deceleration. Many of the road crashes are happening due to road or vehicle factors. Future research is needed for the incorporation of these atributes with the proximal indicators.

3.2.5. Application in non-lane base heterogeneous rural traffic environments

The concept of surrogate safety measures as a traffic safety evaluation tools is still mainly confined to the lane based homogeneous traffic condition in developed counties. The extent, to which these indicators would be applicable in such environments, has not yet been proven. Therefore, more research and application in non-lane base heterogeneous rural traffic environment will offer a wider perspective in understanding and application of proximity for safety evaluation.

Recently developed advanced computer image processing systems and video technology have already been tested for conflict studies. The application of such new approaches to traffic environments in developing countries may lead to advances in traffic conflict studies and hence reduce the high crash rates in those countries.

3.2.6. Indicator for single or more than two vehicle crash

Past research has focussed on the two user conflicts. Only a few studies have focused on single or multi-vehicles conflicts such as, Laureshyn et al. [67], Tarko [86]. Therefore, there is a research gap on how to determine and validate conflicts involving single vehicles, for example, overturning crash or multi-vehicles.

3.2.7. Indicator for evaluating overtaking conflict

The majority of past research has focussed on rear-end or right angle conflicts, except some collisions with pedestrian and bicyclist. With the exception of Shariat-Mohaymany et al. [6], there is no evidence on the use of surrogate safety indicator for evaluating risk during overtaking manoeuvre.

3.2.8. Development of micro-simulation models specifically using traffic safety indicators for developing counties

Simulation base safety studies have mainly focused on developed countries. Real life testing is more difficult in developing countries due to lack of expertise and resources. Research on the development of traffic safety micro-simulation models is therefore more critical in developing counties.

4. Conclusions

The use of proximal surrogate safety indicators for safety evaluation has had a long history with a wide range of such indicators having been used for different settings. This paper presents a review of the state-of-the-art of proximal surrogate safety indicators. The paper provides an inclusive analysis on principles, applications, advantages, disadvantages and application suitability for different type of conflict evaluation using proximal surrogate indicators. Mathematical formulations and data requirements are also given in Appendix A.

Finally, in spite of significant research, development of number of proximal indicators and application in different perspectives, there are still significant opportunities to improve the application of such approaches. This is particularly the case for the evaluation of single or multi-vehicle conflicts; defining standard thresholds for different traffic conditions; setting of common standards; incorporating road and vehicle factors; and application in non-lane based heterogeneous traffic environments in developing countries. Highlighting the resultant applicability issues in developing countries was followed by a discussion of some of the future research directions aimed at stimulating wider application of these techniques with increased accuracy and reliability.

Appendix A. Computational equations for major surrogate indicators

Indicator	Computation	Notations
Temporal proximal Time-to-Collision (TTC) [8] or Time-Measured-to-Collision (TMTC) [14]	$TTC_i(t) = \frac{X_{i-1}(t) - X_i(t) - l_i}{V_i(t) - V_{i-1}(t)}$	V: Vehicle speed X: Vehicle position l: Subject vehicle's length $X_{i-1}(t) - X_i(t)$: Relative distance $V_i(t) - V_{i-1}(t)$: Relative speed
Time Exposed Time-to-Collision (TET) [10]	$TET_i^* = \sum_{t=0}^{T}(i(t) \cdot sc)$	τ_{sc}: Small time step δ: Switching variable (0 or 1)
Time Integrated Time-to-Collision (TIT) [10]	$TIT_i^* = \sum_{t=0}^{T}[TTC^* - TTC_i(t)] \cdot sc$	$\forall \ 0 \leq TTC_i(t) \leq TTC^*$ TTC^*: TTC value below the threshold value. $TTC_i(t)$: TTC subject vehicle
Modified Time-to-Collision (MTTC) [22–24] Crash Index (CI) [22,24]	$MTTC = \frac{-\Delta V \pm \sqrt{V^2 + 2\Delta a D}}{\Delta a}$ $CI = \frac{(V_F + a_F \cdot MTTC)^2 - (V_L + a_L \cdot MTTC)^2}{2} \times \frac{1}{MTTC}$	V_F: Following vehicle's speed (m/s); V_L: Leading vehicle's speed (m/s); a_F: Vehicle's acceleration (m/s^2); a_L: Leading vehicle's acceleration (m/s^2); ΔV: Relative speed (m/s) Δa: Relative Acceleration (m/s^2) D: Initial relative space gap (m);
Headway (H) [14,32]	$H = t_i - t_{i-1}$	t_i: Time (vehicle i passes a certain location) t_{i-1}: Time (vehicle ahead of vehicle i passes the same location).
Time-to-Accident (TA) [26,87]	$TA = 1.5 \times \frac{V_i}{16.7 \times \exp(-0.0306 \times 0.5 V_m)}$	V_i: initial speed V_m: Mean speed.
Post-Encroachment Time (PET) [36]	$PET = t_2 - t_1$	t_2: Coming time at conflict point t_1: Leaving time of conflict point.
Non-temporal proximal indicators Potential Index for Collision with Urgent Deceleration (PICUD) [40,41]	$PICUD(m) = \frac{V_1^2 - V_2^2}{2\alpha} + S_0 - V_2 \Delta t$	V_1, V_2: Velocity of leading car 1 and following car 2, respectively S_0: Distance between car 1 and 2 Δt: Driver's reaction time 1 α: Deceleration rate to stop
Proportion of Stopping Distance (PSD) [36,43]	$PSD = \frac{RD}{MSD}$	RD: Remaining distance to the potential point of collision (m) MSD: Minimum acceptable stopping distance (m).

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Indicator	Computation	Notations
Unsafe Density (UD) [46,88]	$\text{unsafety} = \Delta S \cdot S \cdot R_b$ $\text{Unsafety Density} = \frac{\sum_{S=1}^{S_t} \sum_{V=1}^{V_t} \text{unsafety}_{v,s} \cdot d}{T \cdot L}$	S: Speed of the follower vehicle ΔS: Difference of speed at collision time R_b: unsafe parameter V_t: nb of vehicles in the link S_t: nb of simulation steps within aggregation period d: simulation step duration [s] T: aggregation period duration [s] L: section length [m]
Difference of Space distance and Stopping distance (DSS) [45]	$\text{DSS} = \left(\frac{v_1^2}{2\mu g} + d_2\right) - \left(v^2 \Delta t + \frac{v_2^2}{2\mu g}\right)$	S: Space distance (m) Stop: Stop distance (m) v_1: Velocity of following vehicle (m/s); v_2: Velocity of leading vehicle (m/s) μ: Friction coefficient g: Gravity acceleration (m/s^2) d_2: Distance between leading vehicle and following vehicle (m) Δt: Reaction time X: Position of the vehicle (m)
Deceleration Rate to Avoid the Crash (DRAC) [43,47,51]	$\text{DRAC}_{FV,t+1}^{REAR} = \frac{(V_{FV,t} - V_{SV,t})^2}{(X_{SV,t} - X_{FV,t}) - L_{SV,t}}$	L = vehicle length (m) V = velocity (m/s)
Crash Potential Index (CPI) [42,51]	$\text{CPI}_i = \frac{\sum_{t=t_i}^{tf_i} P(\text{MADR}^{(a_1,a_2,\cdots,a_n)} \le \text{DRAC}_{i,t}) \cdot \Delta t \cdot b}{T_i}$	DRAC$_{i,t}$: Deceleration rate to avoid the crash (m/s^2) MADR$^{(a_1,a_2,\cdots,a_n)}$: Random variable following normal distribution for a given set of traffic and environmental attributes (a$_1$, a$_2$, ..., a$_n$) (m/s^2) t$_i$: Initial simulated time interval for vehicle i tf$_i$: Final simulated time interval for vehicle i Δt: Simulation time interval T$_i$: Total travel time for vehicle i b: A binary state variable, 1 if a vehicle interaction exists and 0 otherwise.
Criticality Index Function (CIF) [54]	Criticality Index $= V^2$ / TTC (Time to Conflict)	V: Velocity (m/s)

References

[1] T. Sayed, M.H. Zaki, J. Autey, Automated safety diagnosis of vehicle–bicycle interactions using computer vision analysis, Saf. Sci. 59 (2013) 163–172.

[2] M. Zaki, et al., Application of computer vision to diagnosis of pedestrian safety issues, J. Transp. Res. Board 2393 (2013) 75–84.

[3] L. Zheng, K. Ismail, X.H. Meng, Traffic conflict techniques for road safety analysis: open questions and some insights, Can. J. Civ. Eng. 41 (7) (2014) 633–641.

[4] T. Sayed, S. Zein, Traffic conflict standards for intersections, Transp. Plan. Technol. 22 (4) (1999) 309–323.

[5] H.-C. Chin, S.-T. Quek, Measurement of traffic conflicts, Saf. Sci. 26 (3) (1997) 169–185.

[6] A. Shariat-Mohaymany, et al., Identifying significant predictors of head-on conflicts on two-lane rural roads using inductive loop detectors data, Traffic Inj. Prev. 12 (6) (2011) 636–641.

[7] F. Huang, et al., Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections, Accid. Anal. Prev. 50 (2013) 1014–1024.

[8] C. Hydén, Traffic conflicts technique: state-of-the-art, Traffic Safety Work with Video-processing, Green Series, 43, University Kaiserlauten. Transportation Department, 1996.

[9] A. Van der Horst, A time-based analysis of road user behaviour at intersectionsICTCT Conference Proceedings (Krakow), 1990.

[10] M.M. Minderhoud, P.H. Bovy, Extended time-to-collision measures for road traffic safety assessment, Accid. Anal. Prev. 33 (1) (2001) 89–97.

[11] M. Essa, T. Sayed, Simulated traffic conflicts: do they accurately represent field-measured conflicts? J. Transp. Res. Board 2514 (2015) 48–57.

[12] C. Caliendo, M. Guida, Microsimulation approach for predicting crashes at unsignalized intersections using traffic conflicts, J. Transp. Eng. 138 (12) (2012) 1453–1467.

[13] J. Ambros, R. Turek, J. Paukrt, Road safety evaluation using traffic conflicts: pilot comparison of micro-simulation and observationProc. International Conference on Traffic and Transport Engineering, 2014.

[14] K. Vogel, A comparison of headway and time to collision as safety indicators, Accid. Anal. Prev. 35 (3) (2003) 427–433.

[15] T. Sayed, G. Brown, F. Navin, Simulation of traffic conflicts at unsignalized intersections with TSC-Sim, Accid. Anal. Prev. 26 (5) (1994) 593–607.

[16] A. Van der Horst, A Time-based Analysis of Road User Behaviour in Normal and Critical Encounters, TU Delft, Delft University of Technology, 1990.

[17] J. Hogema, W. Janssen, Effects of Intelligent Cruise Control on Driving Behaviour: a Simulator Study, 1996.

[18] Q. Meng, X. Qu, Estimation of rear-end vehicle crash frequencies in urban road tunnels, Accid. Anal. Prev. 48 (2012) 254–263.

[19] AASHTO, A Policy on Geometric Design of Highways and Streets, 2011, American Association of State Highway Transportation Officials (AASHTO), 2011.

[20] H. Farah, et al., A model for passing decisions on two-lane rural highways, Transportation Research Board 87th Annual Meeting, 2008.

[21] G. Hegeman, Assisted Overtaking: an Assessment of Overtaking on Two-lane Rural Roads, TU Delft, Delft University of Technology, 2008.

[22] K. Ozbay, et al., Derivation and validation of new simulation-based surrogate safety measure, J. Transp. Res. Board 2083 (2008) 105–113.

[23] H. Yang, K. Ozbay, B. Bartin, Application of simulation-based traffic conflict analysis for highway safety evaluation, Proceedings of the 12th WCTR, 2010 (Lisbon, Portugal).

[24] H. Yang, Simulation-based Evaluation of Traffic Safety Performance Using Surrogate Safety Measures, Rutgers University-Graduate School, New Brunswick, 2012.

[25] N. Saunier, T. Sayed, Probabilistic framework for automated analysis of exposure to road collisions, J. Transp. Res. Board 2083 (2008) 96–104.

[26] C. Hydén, The development of a method for traffic safety evaluation, The Swedish Traffic Conflicts Technique, Lund University, Department of Traffic Planning and Engineering, 1987.

[27] Å. Svensson, A Method for Analysing the Traffic Process in a Safety Perspective, Lund University, 1998.

[28] A. Petermans, et al., Handbook Swedish Traffic Conflict Measuring Technique, Policy Research Centre Traffic Safety, UHasselt, Wetenschapspark 5 B 3590 Diepenbeek, 2009.

[29] J. Archer, Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling, A Study of Urban and Suburban Intersections, Royal Institute of Technology, Stockholm, Sweden, 2005.

[30] F. Amundson, C. Hyden, Proceedings of First Workshop on Traffic Conflicts, Institute of Economics, Oslo, 1977.

[31] L. Shbeeb, Development of traffic conflicts technique for different environments, A Comparative Study of Pedestrian Conflicts in Sweden and Jordan, Lund University, 2000.

[32] P.G. Michael, F.C. Leeming, W.O. Dwyer, Headway on urban streets: observational data and an intervention to decrease tailgating, Transport. Res. F: Traffic Psychol. Behav. 3 (2) (2000) 55–64.

[33] H. Ohta, Individual differences in driving distance headway, Vision in Vehicles, 4, 1993, pp. 91–100.

[34] M. Taieb-Maimon, D. Shinar, Minimum and comfortable driving headways: reality versus perception, J. Hum. Factors Ergon. Soc. 43 (1) (2001) 159–172.

[35] L. Evans, Traffic Safety and the Driver, van Nostrand Reinhold, New York, 1991.

[36] B.L. Allen, B.T. Shin, P.J. Cooper, Analysis of traffic conflicts and collisions, Transp. Res. Board (667) (1978) 67–74.

[37] P. Cooper, Experience with traffic conflicts in Canada with emphasis on "post encroachment time" techniques, International Calibration Study of Traffic Conflict Techniques, Springer 1984, pp. 75–96.

[38] P. Songchitruksa, A. Tarko, Practical method for estimating frequency of right-angle collisions at traffic signals, J. Transp. Res. Board 2006 (1953) 89–97.

[39] F.J.C. Cunto, Assessing Safety Performance of Transportation Systems Using Microscopic Simulation, University of Waterloo, 2008.

[40] Y. Iida, et al., Traffic conflict analysis and modeling of lane-changing behavior at weaving section, Proceedings of Infrastructure Planning, 2001.

[41] N. Uno, et al., A microscopic analysis of traffic conflict caused by lane-changing vehicle at weaving section, Proceedings of The 13th Mini-Euro Conference Handling Uncertainty in Transportation Analysis of Traffic and Transportation Systems, 2002.

[42] G. Guido, et al., Comparing safety performance measures obtained from video capture data, J. Transp. Eng. 137 (7) (2010) 481–491.
[43] V. Astarita, et al., A new microsimulation model for the evaluation of traffic safety performances, Transp. Eur. 51 (2012) 1–16.
[44] S. Kitajima, et al., Estimation of driver's dangerous states of rear-end collision based on driver video recorder data and ordinary driving data, Proceedings of Automotive Engineers of Japan, 97–09, 2009, pp. 89–97.
[45] M. Okamura, et al., Impact evaluation of a driving support system on traffic flow by microscopic traffic simulation, Adv. Transp. Stud. (2011) (Special Issue 2011).
[46] B. Jaime Barceló, et al., Safety Indicators for Microsimulation-based Assessments, Transportation Research Board, Washington, D.C., 2003
[47] S. Almqvist, C. Hyden, R. Risser, Use of speed limiters in cars for increased safety and a better environment, Transp. Res. Rec. 1318 (1991).
[48] D. Gettman, L. Head, Surrogate safety measures from traffic simulation models, J. Transp. Res. Board 2003 (1840) 104–115.
[49] X. Qu, et al., Safety evaluation for expressways: a comparative study for macroscopic and microscopic indicators, Traffic Inj. Prev. 15 (1) (2014) 89–93.
[50] Q. Meng, J. Weng, Evaluation of rear-end crash risk at work zone using work zone traffic data, Accid. Anal. Prev. 43 (4) (2011) 1291–1300.
[51] F. Cunto, F.F. Saccomanno, Simulated safety performance of rear-end and angled vehicle interactions at isolated intersections, Can. J. Civ. Eng. 36 (11) (2009) 1794–1803.
[52] AASHTO, in: AASHTO (Ed.), A policy on geometric design of highways and streets, fifth ed.American Association of State Highway Transportation Officials (AASHTO) 2004, pp. 263–266.
[53] F.J.C. Cunto, F.F. Saccomanno, Microlevel traffic simulation method for assessing crash potential at intersections, Transportation Research Board 86th Annual Meeting, 2007.
[54] C.-Y. Chan, Defining safety performance measures of driver-assistance systems for intersection left-turn conflicts, Intelligent Vehicles Symposium, 2006 IEEEIEEE, 2006.
[55] A.E.a. Wåhlberg, The relation of acceleration force to traffic accident frequency: a pilot study, Transport. Res. F: Traffic Psychol. Behav. 3 (1) (2000) 29–38.
[56] O. Bagdadi, A. Várhelyi, Jerky driving—an indicator of accident proneness? Accid. Anal. Prev. 43 (4) (2011) 1359–1363.
[57] O. Bagdadi, A. Várhelyi, Development of a method for detecting jerks in safety critical events, Accid. Anal. Prev. 50 (2013) 83–91.
[58] M. Zaki, T. Sayed, K. Shaaban, Use of drivers' jerk profiles in computer vision-based traffic safety evaluations, J. Transp. Res. Board 2434 (2014) 103–112.
[59] M. Aron, M. Biecheler, J. Peytavin, Temps intervehiculaires et vitesses: Quels enjeux de securite sur les routes de Normandie? Premiere etape: Realisation du recueil de donnees et description des indicateurs, rapport sur convention inrets/dscr, 2002.
[60] M.-H. Pham, et al., Applicability of road safety indicators to assess driving risks under Swiss road conditions, Proceedings of the 7th STRC Swiss Transport Research, 2007.
[61] K. Vogel, Modelling driver behaviour–a control theory based approach, Linköping Studies in Science and Technology, 751, Institute of Technology, University of Linköping, 2002 (Dissertation).
[62] X. Cao, et al., Automatic discrimination of traffic conflicts during lane changing manoeuvresARRB Conference, 26th, 2014, Sydney, New South Wales, Australia, 2014.
[63] D. Harwood, et al., Safety effectiveness of intersection left-and right-turn lanes, J. Transp. Res. Board 1840 (2003) 131–139.
[64] A. Polychronopoulos, et al., Dynamic situation and threat assessment for collision warning systems: the EUCLIDE approach, Intelligent Vehicles Symposium, 2004 IEEE, IEEE, 2004.
[65] T. Hiraoka, et al., Collision risk evaluation index based on deceleration for collision avoidance(first report), Rev. Automot. Eng. 30 (4) (2009) 429–437.
[66] H. Suzuki, T. Nakatsuji, Effect of adaptive cruise control (ACC) on traffic throughout-a numerical example on actual freeway corridor, Trans. Soc. Automot. Eng. Jpn 35 (1) (2004) 239–245.
[67] A. Laureshyn, Å. Svensson, C. Hydén, Evaluation of traffic safety, based on micro-level behavioural data: theoretical framework and first implementation, Accid. Anal. Prev. 42 (6) (2010) 1637–1646.
[68] K. Ismail, T. Sayed, N. Saunier, Methodologies for aggregating indicators of traffic conflict, Transp. Res. Rec. 2237 (2011) 10–19.
[69] K. Salamati, et al., Development and implementation of conflict-based assessment of pedestrian safety to evaluate accessibility of complex intersections, J. Transp. Res. Board 2264 (2011) 148–155.
[70] I. Kaparias, et al., Development and implementation of a vehicle-pedestrian conflict analysis method: adaptation of a vehicle-vehicle technique, J. Transp. Res. Board 2198 (2010) 75–82.
[71] O. Bagdadi, Estimation of the severity of safety critical events, Accid. Anal. Prev. 50 (2013) 167–174.
[72] N. Saunier, T. Sayed, K. Ismail, Large-scale automated analysis of vehicle interactions and collisions, J. Transp. Res. Board 2147 (2010) 42–50.
[73] A. Berthelot, et al., A novel approach for the probabilistic computation of time-to-collision, Intelligent Vehicles Symposium (IV), 2012 IEEE, IEEE, 2012.
[74] H. Farah, S. Bekhor, A. Polus, Risk evaluation by modeling of passing behavior on two-lane rural highways, Accid. Anal. Prev. 41 (4) (2009) 887–894.
[75] M. Bin, N. Uno, Y. Iida, A study of lane-changing behavior model at weaving section considering conflicts, J. East. Asia Soc. Transp. Stud. 5 (2003) 2039–2052.
[76] P.G. St-Aubin, Traffic safety analysis for urban highway ramps and lane-change bans using accident data and video-based surrogate safety measures, Masters Abstracts International, 2012.
[77] J.C. Glennon, et al., Critique of the traffic conflict technique, J. Transp. Res. Board 630 (1977) 32–38.
[78] K. El-Basyouny, T. Sayed, Safety performance functions using traffic conflicts, Saf. Sci. 51 (1) (2013) 160–164.
[79] L. Peesapati, M. Hunter, M. Rodgers, Evaluation of postencroachment time as surrogate for opposing left-turn crashes, J. Transp. Res. Board 2386 (2013) 42–51.
[80] N. Saunier, T. Sayed, Automated analysis of road safety with video data, J. Transp. Res. Board 2019 (2007) 57–64.
[81] K. Ismail, T. Sayed, N. Saunier, Camera calibration for urban traffic scenes: practical issues and a robust approach, 89th Annual Meeting of the Transportation Research Board, Washington, DC, 2010.
[82] K. Ismail, T. Sayed, N. Saunier, Automated analysis of pedestrian-vehicle: conflicts context for before-and-after studies, J. Transp. Res. Board 2198 (2010) 52–64.
[83] FHWA, Surrogate Safety Assessment Model and Validation: Final Report, 2008 (Publication No. FHWA-HRT-08-051).
[84] J.J. So, B.B. Park, I. Yun, Classification modeling approach for vehicle dynamics model-integrated traffic simulation assessing surrogate safety, J. Adv. Transp. 49 (3) (2015) 416–433.
[85] J. So, et al., Development and validation of a vehicle dynamics integrated traffic simulation environment assessing surrogate safety, J. Comput. Civ. Eng. 29 (5) (2014) 04014080.
[86] A.P. Tarko, Use of crash surrogates and exceedance statistics to estimate road safety, Accid. Anal. Prev. 45 (2012) 230–240.
[87] Å. Svensson, C. Hydén, Estimating the severity of safety related behaviour, Accid. Anal. Prev. 38 (2) (2006) 379–385.
[88] A. Torday, D. Baumann, A.-G. Dumont, Indicator for microsimulation-based safety evaluation, Proceedings of the 3rd STRC Swiss Transport Research, 2003.