Simulation based validation of time to collision as a safety performance surrogate

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Abstract

Traffic crashes are the ultimate measure of safety for a highway location. However, the collection of data from actual traffic crashes involves the requirement of a lengthy and resource-demanding effort in order to minimize the randomness associated with crash occurrence.

The purpose of this study is to determine if the surrogate measure of conflict as represented by "time to collision" can adequately describe the occurrence of inter-vehicle crashes on an Interstate highway. A part of an urban Interstate highway in Northern Virginia was used as the test site. Crashes were treated as unintended collisions between two or more motor vehicles. Crashes for a 6-year period were collected. The same network was designed and simulated using a stochastic, microscopic, behaviour-based simulation program (PARAMICS). An application was coded to extract conflicts through the program. The counted conflicts were then compared to the observed crashes in order to validate a correlation of the two. Two different definitions of time to collision as well as several different threshold values (emulating severity) were used as crash surrogates in order to determine the best fit.

The results of this study indicated that there is a statistically significant correlation between crashes and the proposed surrogates. A sensitivity analysis determined the best threshold values. Models were developed relating the number of crashes and conflicts.
Keywords: conflict, crashes, time to collision, micro simulation.

1 Introduction

Traffic crashes are the ultimate measure of safety for a highway location [1]. However, there are many reasons why crashes are not a convenient measurement

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for describing traffic safety conditions. One of the problems is that the number of crashes at a specific site is usually small. Small crash numbers are inevitably associated with large random variations. Many years have to be included to get an objective picture of the situation (usually 3 years or more). This means that several external factors might change during the period of observation. Another problem is that many crashes are never reported to the police. A third problem is that often a countermeasure is introduced at a site because of the high number of reported crashes. A drop in the number of crashes soon after the implementation of a safety countermeasure may be attributed either to a successful effect of the countermeasure or to a randomly high number of crashes occurring during the period before the measure was introduced (regression to the mean). For all these reasons, other indicators or measures with a higher occurrence frequency (crash surrogates) are desirable. Conflict is one of those measures.

A conflict can be defined as: "an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged" [1]. The technique was 'invented' by General Motors. The car manufacturer wanted to use it for evaluating details of vehicle design's influence on risks. There are several proposals on how to record a conflict [1–3] (i.e. how to distinguish a severe conflict from a non-severe conflict), one of which is time to collision (TTC). Serious conflicts are similar to traffic crashes in that they occur as the result of a breakdown in the interaction between the road user, the environment and the vehicle. Traffic conflicts do not always cause crashes, but they are probably an aftermath of the same causal factors that cause crashes. In a sense, "a two-vehicle crash can be described as a conflict where the evasive action was unsuccessful" [2]. Validation of their actual correlation with traffic crashes and usefulness in assessing safety is the next step.

2 Previous work

Traffic simulation programs are designed to emulate operational and traffic control strategies. However, an opportunity of assessing the safety of an actual network is given by modifying the core program in order to enable it to record conflicts or other surrogates (given the fact that actual crashes do not occur in general purpose simulation programs). Of course, the above statement is only valid if the program algorithms adequately emulate the actual behaviour of both vehicles and drivers. Unfortunately, this is not yet the case since existing simulation programs do not require detailed information on the behaviour of the road user. However, it is possible that this deficiency can be alleviated to some extent through model calibration. A well-calibrated micro-simulation program can greatly reduce data collection costs and eliminate the problem of a subjective count of a conflict by each observer. Those two advantages can enable safety assessment on a bigger scale. FHWA, in an attempt to promote the idea of deriving safety data through the recording of surrogate measures issued a paper [4] which assessed the features and attributes of certain general purpose microscopic simulation products. In the report, the processes associated with computing safety indicator measures, and extracting and analyzing simulation output data are structured in a framework termed a Surrogate Safety Assessment Methodology (SSAM). That paper also proposed specific algorithms for recording conflicts using various micro-simulation tools. A modified version of those algorithms was used in this study.

It is highly desirable that a general purpose micro-simulation program (in contrast to a program designed specifically for tracking safety surrogates) be used in recording conflicts. This enables a more holistic view (and assessment) of the network, providing all types of data simultaneously (safety, throughput and capacity data). For example, most recently, Garber and Liu [5] have used TTC as a measure gathered from models run through the Paramics micro-simulation suite as the safety measures to identify the impact of different truck restriction strategies. However, the validity of such results relies in the ability of the software used to accurately report conflicts.

This notion triggered several attempts to determine whether modified versions of micro-simulation models can accurately depict and detect conflicts. However, the focus has been to relate actual with simulated conflicts [6, 7]. Those attempts have revealed many of the problems and limitations of the conflict technique, including the need for extensive calibration and overestimation or underestimation of conflicts for certain network layouts. The approach has also proved its overall potential by yielding acceptable levels of consistency.

Few attempts have been made to relate these measures quantitatively to observed crash frequencies. One of those introduced a new surrogate, named crash index density (CID), which incorporates TTC and also takes into account the "kinetic energy" of the vehicles [8]. This surrogate is expected to have a more accurate depiction of conflicts, and can also take severity into account. Paramics was used as the simulation program. The CID indicator as well as TTC was tested using a calibrated simulation model of the New Jersey Turnpike. A 6.67 mile section was chosen as the validation section. This section has three lanes and a posted speed of 65 mph with no on-ramps or off-ramps within the section. Real crash records between 1996 and 2005 for this section were used. The results showed a strong positive correlation between actual crashes and both a modified version of TTC and CID (0.918 and 0.912 respectively) was observed. However, CID failed to yield a better correlation than TTC. The study, however, has its limitations: it only examined one segment of a road with no ramps and data were aggregated, thus producing only 24 (hourly) points in the accident-conflict spectrum. Furthermore, no sensitivity analysis was done in order to determine if the proposed threshold used to count conflicts is the most appropriate.

3 Methodology

The scope of this study was to determine whether the measure of conflict could adequately describe the occurrence of inter-vehicle crashes on an Interstate highway with truck lane restrictions. The goal was to determine if significant correlation between crash and conflict existed and, as a second step, to find out if the surrogate of TTC can effectively be used as an adequate measure of safety.

The procedure followed incorporated the following tasks:

- site selection
- collection and analysis of crash data
- collection and analysis of operational data
- running the simulation program
- determining the relationship between actual crashes and simulated conflicts

3.1 Site selection

After a comprehensive analysis of the information available, a 7.6-mile long section of Interstate 66 in Northern Virginia was chosen between interchanges 55 and 64 but not including interchanges 55 and 64. It included three interchanges (grade separated junctions). This was the longest stretch that could be obtained for which all the required data were readily available. After further research on this site it was determined that no changes were made to the geometrical characteristics of the facility during the period for which data were obtained for this study.

High occupancy lanes (HOV-2) as well as shoulder utilization strategies are implemented in the system during certain peak-hours. Since it is very difficult to obtain accurate data about the volumes as well as simulated interactions between vehicles moving through HOV/shoulder and regular lanes as well as occupancy rates on those lanes it was decided to exclude the period that the HOV and shoulder use strategies were implemented from the analysis of this study.

3.2 Collection of crash data

In this study, crashes were treated as unintended collisions between two or more motor vehicles, thus single vehicle crashes were excluded from the data collection procedure. The reason for this choice is that there is no way to simulate single-vehicle crashes through micro-simulation software (crashes do not occur in these programs; there is only a possibility to extract surrogate measures through monitoring the interactions between vehicles). Only crashes reported to the police were used into building the crash database to be used. This approach certainly has an adversary effect on the produced results since many property damage only (PDO) crashes may not have been reported to the police. However, there was no easy solution to overcome this deficiency.

In order to improve the accuracy of the results and mitigate the effect of preponderance of zero crashes in certain parts of the segment it was crucial that crash data be obtained for a long period of time. Consistent crash data were kept since January 2000 for the selected site. Data were obtained from January 1st 2002 until December 31st 2007, a 6-year span. Only crashes occurring during weekdays were collected. This is because a typical weekday will be used during the simulation.

Moreover, crashes whose causal factors were sleet, ice, oil or low visibility were also excluded because those conditions could not be simulated in the program. Crash severity was also not taken into account. A total of 1235 crash events were gathered.

The whole segment was divided into 30 homogeneous sections (15 in each direction). Each of those sections had the same geometric characteristics (curvature, number of lanes, presence of acceleration/ deceleration lane). This fragmentation ensured the existence of several data points. After obtaining the crash data, they were classified according to hour and segment of the road that they occurred in a pivot-table format.

3.3 Collection of operational data

It was decided that the simulation program be run for 24 hours of a typical weekday to facilitate the direct comparison of the simulated results with the week weekday crash data. Traffic data (hourly volumes and vehicle classification data) were obtained using both the VDOT database and the Archived Data Management System (ADMS) Virginia database.

Hourly volumes were extracted to ensure that volume data corresponded to the hourly crash data previously obtained and the vehicles classified into the following four different categories:

- Passenger Cars – All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers.
- Other Two-Axle, Four-Tire Single Unit Vehicles – All two-axle, four-tire, vehicles, other than passenger cars.
- Buses – All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses are considered to be trucks.
- Trucks: All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two or more axles. Trucks with a tractor were also classified in this category due to the small percentage of the total volume that they represent. The percentage of motorcycles (all two or three-wheeled motorized vehicle with saddle type seats and are steed by handlebars rather than steering wheels) was minimal so their numbers were combined to the ones of passenger cars.

For each of the selected sites that did not have continuous count data available, the researchers obtained data through spot studies from the respective jurisdiction

3.4 Micro-simulation

Before the simulated network could be used to examine the route diversion strategy, the network was first calibrated and then validated. The calibration procedure involved tweaking built-in calibration parameters that define how the vehicles behave in the network in order to ensure that the simulated vehicles

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mimic vehicular behaviour in the field. The calibration process followed a Latin Hypercube Design (LHD) procedure proposed by a previous study conducted by Park and Qi [9]. This procedure employs the LHD algorithm to reduce the extremely large number of parameter combinations into a reasonable level while still reasonably covering the entire parameter surface. . Volume data were the input to the simulation, and the travel times were used as measure of effectiveness (MOE) for the calibration. Mean headway, Mean reaction time, Speed memory, Curve speed factor, Headway factor and Link speed were the calibrated parameters.

3.4.1 Conflict data collection

It should be noted that the simulation program did not provide exact transverse coordinates of a vehicle within a lane. This deficiency made recording of sideswipe collisions impossible. Also, having taken into account that there was a wide median on the selected site, which averted the existence of head-on conflicts, only three kinds of conflicts could be observed: Lane-changing conflict, defined as the conflict between the vehicle that made an abrupt lane-changing manoeuvre and the vehicle following immediately after it in the target lane. The merging conflict, defined as the conflict between the vehicle merging to the main road from a ramp and the vehicle following immediately after it in the target lane on the main road. The rear-end conflict, defined as the conflict between the vehicle that suddenly reduced its speed and the vehicle following immediately after it in the same lane and in the same direction.

The three types of conflicts defined above were essentially rear-end events, and they were categorized into the three types by the different triggering conditions. Also, merging and lane-changing conflicts were similar since the encroaching vehicles in both cases made a lane changing manoeuvre before the occurrence of a conflict. However, a fundamental difference between the two was that the vehicle negotiating a merging manoeuvre had to negotiate its merge by accepting a gap in a limited space defined by the length of the acceleration lane. In this study the counts of these three kinds of conflicts were aggregated to obtain the total conflicts. A more detailed approach (for example a comparison of lane-changing conflicts with crashes caused by a lane-changing manoeuvre) was decided not to be pursued due to the fact that a pre-crash manoeuvre description was not always available in the crash reports, thus a comparison with the corresponding conflicts was not feasible. When the TTC was less than a certain threshold value set in advance, a conflict of certain type was counted. A customized Application Programming Interface (API) that was incorporated within the Paramics software was used to obtain detailed parameters of the simulated vehicle trajectories, including time steps, speeds, accelerations, and position to numerically calculate the conflicts.

3.4.2 Computational algorithm for TTC

Certain algorithms were developed to count conflicts in the simulated network. In order to illustrate the logic behind the algorithms used, an example of the conflict count procedure for a merging conflict is given below. A timeline of a conflict line event for a vehicle making a lane change manoeuvre in front of a vehicle progressing in the same direction on the target lane is described in Figure 1. This timeline is adapted from the research report of FHWA-RD-03-050 (FHWA, 2003). The upper curve represents the time-space trajectory of the encroaching vehicle, while the lower curve represents the time-space trajectory of the evasive vehicle (which –in this example- follows the encroaching vehicle in the target lane). In this example, six time points from t_1 to t_6 are employed to describe the first two conflict points. In the simulation, the whole timeline ends at predefined maximum reference time (t6-t1 seconds after t1):

- At time t1, the encroaching vehicle makes a lane-change manoeuvre into the same lane as (and right in front of) the evasive vehicle.
- At time t2, the evasive vehicle begins braking to avoid the collision.
- At time t3, the next time step of the simulation is reached and state variables (position, speed, acceleration /deceleration) for each vehicle are updated.
- At time t4, the evasive vehicle would reach the first conflict point if it did not decelerate at t2.
- At time t5, the evasive vehicle would reach the second conflict point if it did not decelerate at t3.
- At time t6, the predefined maximum reference conflict time is reached (a possible conflict recorded after t6 will count as a rear-end conflict and not as a merging conflict).

The difference between time t_4 and t_1 is the TTC for the first conflict point. TTC (in this time frame) is the projected time the evasive vehicle needs to reach the position where the encroaching vehicle initiated a lane changing manoeuvre if the evasive vehicle's speed remains unchanged.

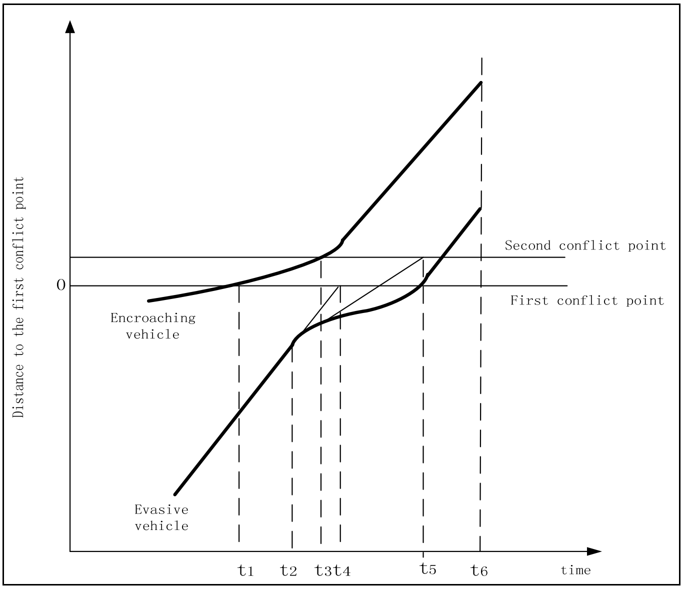

Figure 1: Conflict line of lane-changing conflict.

Similarly, the difference between the time t_5 and t_3 is the TTC for the second conflict point (i.e. for the updated states – position, speed, acceleration /deceleration) at the beginning of the next simulation time step. This time TTC is the projected time that the evasive vehicle needs to reach the position of the encroaching vehicle (that has already completed its lane changing manoeuvre) if its speed remains unchanged. If a conflict is recorded after t_6 it will count as a rear-end conflict and not as a merging conflict. The whole course of conflict event may of course end if the evasive vehicle makes a lane change to avoid the imminent collision or if the encroaching vehicle makes another lane change to get off the lane. This algorithm has the advantage of being fast (it only requires the distance between the two vehicles and the speed of the succeeding vehicle) but also has a deficiency. It does not directly take into account the speed of the leading vehicle. Under this algorithm, a conflict is counted if it takes the succeeding vehicle a time t_i which is less than a critical value ($t_{critical}$) to reach the point where the preceding vehicle was t_i seconds ago. However, reporting a conflict would still not directly factor the speed of the leading vehicle.

In order to factor the speed of the leading vehicle, a conflict is counted if it takes the succeeding vehicle time t_i (less than $t_{critical}$) to reach the place where the preceding vehicle was t_i seconds ago moving at a speed equal to the relative speed of the two vehicles. This algorithm translates the proposed FHWA definition of conflict: "the expected time for two vehicles to collide if they remain at their present speed and on the same path". A conflict line for mTTC at time t1 is illustrated in Figure 2. The arrow line indicates the calculated conflict time (for this time step) and is directly dependent on the difference between the actual speeds (differential speed) of the two vehicles. This definition of conflict counts will be named modified time to collision (mTTC) in this study. Two general triggering conditions for the count of a conflict were therefore defined; one based on absolute speed and one on relative speed. FHWA recommends a value of 0.5 seconds when absolute values are used and 1.5 seconds when relative speed is used. In this study, values of 0.1, 0.3, 0.5, 0.7, 0.9 and 1.1, 1.3, 1.5, 1.7, 1.9 were used respectively in order to determine which provides the best correlation with crashes. The smaller the interval the more "severe" the counted conflicts are. If the minimum TTC is less than a certain threshold set in advance, a conflict will be counted. A customized Application Programming Interface (API) that tracked detailed parameters of the simulated vehicle trajectories, such as time step, speed, acceleration, and position was used to obtain conflict counts and the locations where they occurred. Ten seeds were run for each case and the results were averaged in order to mitigate the effects of randomness.

A total number of 100 ((5+5)*10) 24-hour scenarios were therefore simulated. During the simulation, for each occurring conflict the following data were collected by the program: location (link) where the conflict occurred, time of day, corresponding highway occupancy of the link at that time. The results were then tabulated in and compared with actual crashes. Correlation factors reveal which critical time and which definition of conflict (using absolute or relative speeds) yielded the best results.

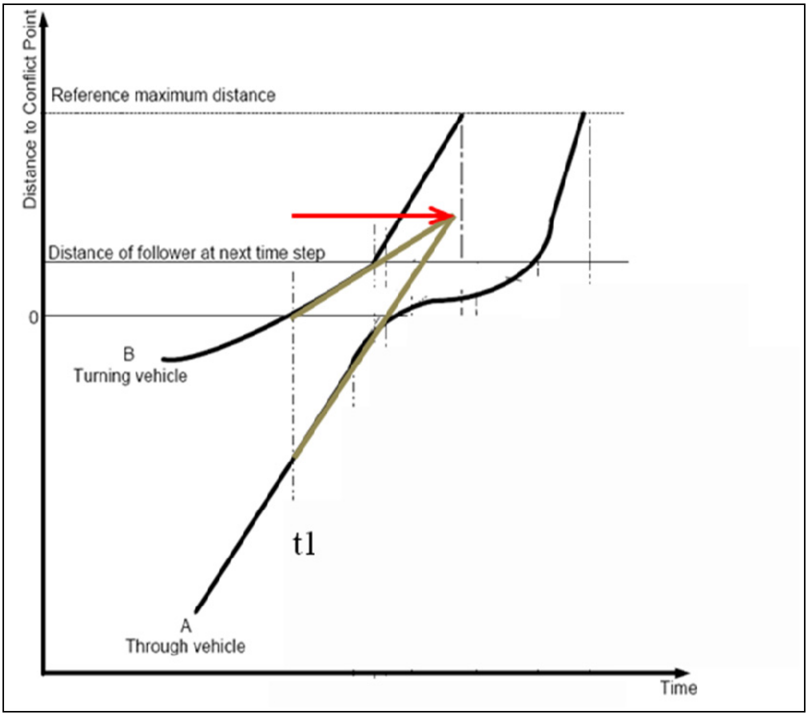

Figure 2: Conflict line of lane-changing conflict for mTTC.

4 Results

A view of multi-vehicle crashes (per hour per year) and conflicts (per hour for a TTC threshold of 0.5) fluctuation throughout the day for the whole network can be seen in Figure 3. It is apparent that crashes and conflicts follow a similar pattern. The shaded regions represent times of day that no data were collected due to the presence of transitory congestion mitigation measures (HOV lanes, use of shoulders for through traffic) whose simulation could not be accurately implemented for reasons stated in the methodology chapter.

Results revealed a positive correlation of conflicts (produced using time to collision and modified time to collision measures) and crashes. Table 1 also shows that TTC of 0.7 seconds and mTTC of 1.1 seconds are mostly with crashes. All thresholds yield a significant correlation at the 0.01 level.

4.1 Mathematical relationship between conflict and actual crashes

Different model types were used to describe the relationship of crashes per year (dependent variable) to conflicts (independent variable). These were Linear, Logarithmic, Inverse, Quadratic, Cubic, Compound, Power, S, Growth, Exponential and Logistic). The logarithmic models shown in Equations (1) and

(2) yielded the best results with R^2 values of 0.681 and 0.588 for the TCC and mTTC respectively. The p values for both coefficients were less than 0.05.

$$\text{Logarithmic model for TTC:} \quad Y=0.148*\ln(t) \tag{1}$$
$$\text{Logarithmic model for mTTC:} \quad Y=0.211*\mathrm{Ln}(t) \tag{2}$$

where

Y = the actual number of crashes per hour per year
t = the number of simulated conflicts for the same hour as that for Y

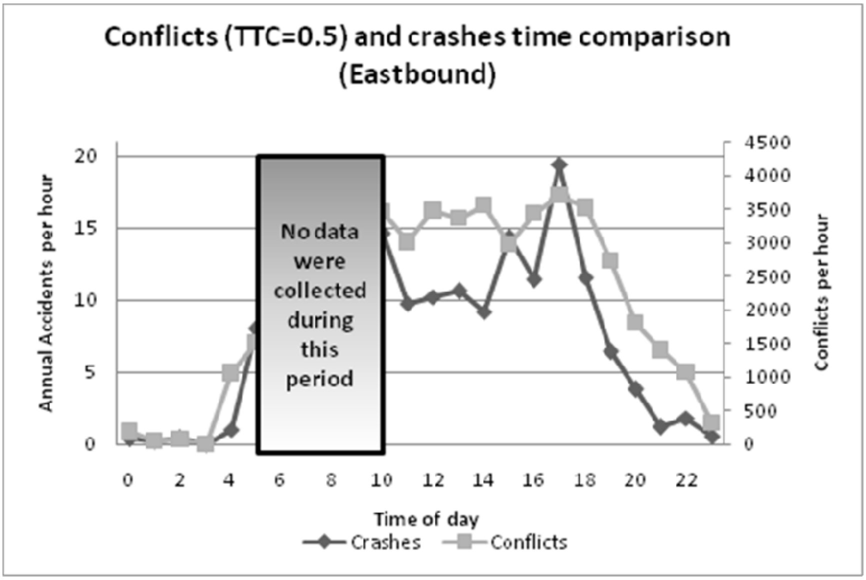

Figure 3: Comparison graphs of conflicts for simulated time to collision (0.5 sec) and crashes in a typical weekday (eastbound direction).

Table 1: Pearson correlation values for different values of TTC and mTTC.

Surrogate Type	Threshold Value of Surrogate (sec)	Pearson Correlation Factor
Time to collision (TTC)	0.1	0.373
	0.3	0.435
	0.5	0.489
	0.7	0.558
	0.9	0.494
Modified Time to Collision (mTTC)	1.1	0.578
	1.3	0.575
	1.5	0.540
	1.7	0.515
	1.9	0.498

It should be noted that although these equations describe the relationships between actual crashes and simulated conflicts at the site for the study, they may not necessarily apply to other sites with different traffic and geometric characteristics. They however illustrate the efficacy of using TTC and or mTTC as suitable surrogates for crashes at interstate highway segments.

Finally, a correlation analysis of volumes per lane and crashes gave a Pearson correlation factor of 0.181, which is a much lower value than those for conflicts shown in Table.

This verifies the notion that crashes are not linearly dependent to traffic volume. It can also be said that the proposed surrogates yield significantly better correlation results than volumes do, probably because the methodology on which they are based on takes into account several factors (such as speed limits, presence of intersections or curves, volumes of vehicles entering or exiting through the ramps etc) that cannot be expressed by volume alone.

5 Conclusions and recommendations

This study verified the relationship between simulated conflicts and crashes (for the examined network) in the mesoscopic scale. Data analysis revealed that significant correlation exists between two-vehicle crashes and the simulated surrogates. This correlation was evident for a wide spectrum of flows and throughout the day. Using the proposed modified definition of time to collision (that incorporates relative speed) resulted in the best correlation. The sensitivity analysis that was conducted revealed that threshold values of 0.7 and 1.1 for TTC and mTTC yielded the best correlation results (0.558 and 0.578 respectively).

Certain highway sections cannot be accurately emulated with the proposed methodology. Some limitations of this study have to be noted. The procedure used can accurately simulate only one of the three main aspects that define safety: infrastructure. Driver behaviour modification factors were limited and driver behaviour was considered to be constant throughout the day, even though several studies have proved this is not the case. Moreover, the effect of certain environmental factors could not be simulated. Also, the results of this study are based on two-vehicle crashes, thus total vehicle crashes cannot be estimated using the TTC conflict technique.

Two additional important aspects have to be mentioned. First, the consistency of the produced results is directly related to the quality of the input values. Some of them can be objectively defined (such as site's geometric characteristics, conflict recording procedure by the simulation program), others are subject to systematic or random errors (precision of volume or vehicle classification counts by the recording infrastructure), reliability of the subjective judgment and details provided by the reporting agencies (crash causal factor, crash location, environmental factors) Others are related to the consistency of the simulating process (how accurately the program emulates drivers' and vehicles' characteristics such as speed distribution, acceleration rates, queuing models etc).

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