Derivation and Validation of a New Simulation-based Surrogate Safety Measure

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ABSTRACT
Traffic safety evaluation is one of the most important processes in the analysis of transportation systems performance. Traditional methods like statistical models and before-after comparisons have many drawbacks such as limited time periods, sample size problems, and reporting errors. The advancement of the traffic conflict techniques combined with the micro-simulation offers a potentially innovative way for conducting safety assessment of traffic systems even before safety improvements are actually implemented. In this paper first simulation-based safety studies are reviewed, and then a modified simulation-based surrogate safety measure and a new simulation-based surrogate safety measure that can capture the probability of collisions as well as the severity of these potential collisions are proposed. Conceptual and computational logic of the proposed surrogate safety indicators are described in detail. These surrogate safety indices are initially proposed for link based analysis and should not be used for other purposes - such as intersection safety assessment - without further enhancements, and the use of these indices should be limited to the analysis of linear conflicts. In addition, these link-based indices are extended to be able to conduct aggregate network-wide safety assessments. The proposed indices are validated using a well-calibrated traffic simulation model of a section of the New Jersey Turnpike and real accident data from the same section. Preliminary results indicate that there is a strong relationship between the proposed surrogate safety measures and real accident data. Further research is needed to investigate these new surrogate safety indices under different locations and traffic conditions.
INTRODUCTION & MOTIVATION

Throughout the world more than one million people lose their lives in road traffic crashes each year (1). Obviously, it has become one of the world’s largest public health challenges, attracting extensive focus and awareness within the traffic engineering field. Many countermeasures and inventions are being introduced and put into practice across the world, aimed at reducing traffic accidents. Since these countermeasures have various advantages and disadvantages, it is important to conduct rigorous and reliable safety analyses before and after to make the most effective decisions.

Most of traditional analyses of traffic safety measures are carried out based on the observed accident data, using different types of statistical approaches; mainly before-after comparisons of observed data, and/or anticipatory estimation studies based on safety audits. However, several problems have been documented which use these methods (2) (3) (4) (5). One of the major concerns for these statistical models, like the Regression model or Bayesian estimation, is that they fail to consider driver behavior and a number of related variables that might influence the safety level, other than the AADT, speed, and V/C, etc. For comparisons, due to the rare and random occurrences of traffic accidents a relatively long observation period is necessary to gather the sufficient information needed to conduct the before-after comparisons. The use of safety audits to help make safety improvement decisions could potentially be a beneficial approach, but the level of their success will depend more heavily upon the auditors’ experience and individual preferences. Additional factors such as unreported accidents, length of the analysis period, and observation errors, may also negatively impact the accuracy and reliability of safety analyses.

Alternatively, far better surrogate safety measures have been proposed with the development of the traffic conflict technique (TCT). Previous research studies have shown that there is a high correlation between crash rates and conflicts, with the latter occurring at a much higher frequency, given the opportunities to capture the dynamic characteristics on road (6). Currently, some researchers have been paying increasing attention to the advancement of traffic micro-simulation models and their capabilities to support TCT for deriving surrogate safety measures within the same model used for operational performance analyses. Though there is still a limited amount of work conducted in this area, traffic micro-simulation models have been proven to be potential tools to achieve this goal, despite a number of well-known shortcomings of the underlying driving behavior models (7).

In this paper, after the review of current practice of simulation-based safety analysis studies, a modified crash index and a new crash index that can be calculated using micro-simulation models are proposed. Then, these proposed indices are validated using a well-calibrated real-world road segment and the observed accidents along this road, to explain some characteristics and the use of these proposed indicators.

LITERATURE REVIEW OF SIMULATION-BASED SAFETY ASSESSMENT STUDIES

Traffic safety analysis based on the micro-simulation approach, initially recognized by Darzentas et al. (1980) (8), has gained increasing attention in recent years. Archer et al. (2000a and 2000b) had also given a description of the potential of micro-simulation modeling for traffic safety assessment (7). In these studies Time-to-Collision (TTC) was mentioned as an indicator of safety measures. Considering
the limitation of traditional TTC indicator, Minderhoud et al. (2001) described TET (Time Exposed Time-to-collision) and TIT (Time Integrated Time-to-collision) based on time-to-collision (9). In the same study, they are shown to be useful safety measures in micro-simulation studies focusing on safety impacts. Furthermore, these two indicators are also integrated in a VISSIM model to analyze the improvement of performance of an improved incident reduction function for the driver’s dilemma in actuated signal control intersection (10). When comparing the safety performance of different route choice decisions in road networks, two network-wide safety measures, namely TExTIT and TInTVR, are obtained by dividing TET and TIT by the number of involved vehicles counted during the simulation period (11).

A recent Federal Highway Administration (FHWA)-sponsored research project investigated the potential for deriving surrogate measures of safety from existing traffic simulation models (12) (13), as an attempt to further advance this promising methodology. This FHWA project provides a relatively thorough framework and insightful fundamentals for new researches. For example, it reports that the Texas Transportation Institute (TTI) is in the process of investigating the use of the TTC in the VISSIM environment to test several corridors based on notions included in a FHWA report (14). Proof of concept for this test was initially illustrated by TTI in (15). Preliminary results of applying the TTC to the case studies and theoretical corridors are presented while extracting basic traffic performance indicators, which appears to be a promising method for the analysis of the conflict and safety impacts of access management for the corridors. Most recently, a study conducted by Garber and Liu (2007) also follows an approach similar to the process described in the FHWA report, in which TTC is gathered from Paramics models as the safety measures to identify the impact of different truck-restriction strategies. It concluded that simulation based safety measures are helpful for the analyses of different truck lane restriction strategies (16). Another research project at TNO in the Netherlands attempting to develop a demonstration of a test bed for the evaluation of safety performance measures based on the Multi-Agent Real-time Simulator (MARS) framework coupled with Paramics is currently under way (17).

Besides the above time-based researches, several other studies also proposed specific indicators in support of safety analyses through micro-simulation models. For instance, Possibility Index for Collision with Urgent Deceleration (PICUD) was proposed as a new index to evaluate the possibility that two consecutive vehicles might collide, assuming that the leading vehicle applied its emergency brake (18). The researchers who conducted this study concluded PICUD to be more suitable than TTC for evaluating the danger of collision of the consecutive vehicles with similar speeds, because it captures the effect of the dynamically changing distance between these two vehicles (19). This was also consistent with the results of a subsequent research study that indicates there is a possibility PICUD might better detect the change in traffic conditions and conflicts more sensitively than TTC (20). Also, European researchers proposed unsafe density (UD) parameter and applied in AIMSUN to obtain levels at which the links are unsafe (21). It is indicated that this parameter in itself is meaningless and should be used only for the comparisons of different countermeasures (22). UD is limited to the probability of linear collisions and it does not provide information about conflicting trajectories that are encountered at intersections.
Although great efforts are made towards deriving surrogate safety measures using microscopic simulation, most of these studies focused only on a typical case study. To determine the relationship of real crashes with the simulated indicators, more calibration and validation work is needed. Irrespective of the type of the safety measure that can be time-based, distance-based or speed-based indicators, further calibration and validation is needed to positively conclude that the simulated results are reasonable and consistent with the real traffic conditions. Calibration and validation aspects of the proposed surrogate measures using real-world accident have not yet been widely addressed by past studies. Our detailed review of the literature on micro-simulation-based surrogate safety measures found that VISSIM, Paramics and AIMSUN are identified as the most frequently used micro-simulation tools. However, there is no agreement about the suitability of any one simulator for safety analysis. It is safe to conclude that different simulators will have different strengths and weaknesses vis-a-vis the type of simulation-based safety analysis. Also, further model improvements will be needed to bring most of these tools to a point where safety analysis can be conducted at a certain level of confidence in the results.

MODEL DESCRIPTION

TTC in general can be defined as the time it would take a following vehicle to collide with a leading one, if the vehicles do not change their current movement characteristics. This can also be explained as the time needed to avoid a collision by taking certain countermeasures. FIGURE 1 illustrates a possible rear-end conflict if the following vehicle took no or improper countermeasures to respond to the leading vehicle’s deceleration.

<table>
<thead>
<tr>
<th>Time</th>
<th>Scenario Description</th>
<th>Symbolic Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>Normal Following</td>
<td>[Diagram 1]</td>
</tr>
<tr>
<td>T1</td>
<td>Leading Vehicle Deceleration</td>
<td>[Diagram 2]</td>
</tr>
<tr>
<td>T2</td>
<td>Following Vehicle Realized</td>
<td>[Diagram 3]</td>
</tr>
<tr>
<td>T3</td>
<td>Different results</td>
<td>[Diagram 4]</td>
</tr>
</tbody>
</table>

(1) Proper braking keeps safe

(2) No/ improper countermeasures result in collision

FIGURE 1 Typical Car-following and Rear-end Collision Scenario

For specific TTC calculation, former studies generally used the relative distance \( D \) between the two vehicles divided by their relative speed \( \Delta V \), and formulated TTC as follows:

\[
TTC = \frac{D}{\Delta V}
\]
Ozbay, K., Yang, H., Bartin, B., Mudigonda, S.

Where,

\[ D: \text{Relative distance (m)}; \]
\[ \Delta V: \text{Relative speed of two vehicles (m/s)}. \]

The equation above simply assumes that the following vehicle just keeps its speed while ignoring the actual acceleration or deceleration until the collision has occurred. This definition of TTC signifies that only if the speed of the following vehicle is larger than that of the leading vehicle, a collision will happen. However such an assumption would ignore many potential conflicts due to acceleration or deceleration discrepancies. TABLE 1 indicates all possible reasonable situations where potential conflicts will occur rather than just considering the prerequisite, as the cell marked grey in TABLE 1 shows. In the table, \( V_F, V_L, a_F, \) and \( a_L \) are the speed and acceleration of the following and leading vehicles, respectively.

**TABLE 1 A Description of possible scenarios between two vehicles one following the other**

<table>
<thead>
<tr>
<th>( V )</th>
<th>( V_F &gt; V_L )</th>
<th>( V_F \leq V_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>( a_L &gt; 0 )</td>
<td>( a_L &lt; 0 )</td>
</tr>
<tr>
<td>( a_F &gt; 0 )</td>
<td>P</td>
<td>C</td>
</tr>
<tr>
<td>( a_F &lt; 0 )</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>( a_F = 0 )</td>
<td>P</td>
<td>C</td>
</tr>
</tbody>
</table>

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

The judgment of whether a conflict could occur is totally based on the consideration of the trajectory parameters of the two vehicles, including their relative distance, relative speed and relative acceleration. This relationship is shown by the equations (2) and (3) that are used to determine if a conflict would occur.

\[
V_F t + \frac{1}{2} a_F t^2 \geq D + V_L t + \frac{1}{2} a_L t^2
\]  \( (2) \)

\[
\frac{1}{2} \Delta a t^2 + \Delta V t - D \geq 0
\]  \( (3) \)

Where,

\( V_F \): Following vehicle’s speed (m/s);
\( V_L \): Leading vehicle’s speed (m/s);
\( a_F \): Following vehicle’s acceleration (m/s²);
\( a_L \): Leading vehicle’s acceleration (m/s²);
\( \Delta V \): Relative speed (m/s), \( \Delta V = V_F - V_L \);
\( \Delta a \): Relative Acceleration (m/s²), \( \Delta a = a_F - a_L \);
\( D \): Initial relative Distance (m);
\( t \): Time (s).

In order to calculate the Time-to-Collision accurately, following logic that selects the specific expression for the TTC under different circumstances is proposed. Thus based
on the equations (4), (5) and, (6), a minimum TTC can be computed for a rear-end collision for each vehicle pairs. This modified surrogate safety measure is named as Modified Time-to-Collision (MTTC). It is clear from the discussion above that MTTC is better than the traditional definition of TTC.

\[
\begin{align*}
\text{If } (\Delta a \neq 0) \\
\{ t_1 = \frac{-\Delta V - \sqrt{\Delta V^2 + 2 \Delta a D}}{\Delta a} \} \quad t_2 = \frac{-\Delta V + \sqrt{\Delta V^2 + 2 \Delta a D}}{\Delta a}
\end{align*}
\]

\[
\begin{align*}
\text{If } (t_1 > 0 \text{ & } t_2 > 0) \\
\{ & \text{ If } (t_1 \geq t_2) \quad \{ \text{TTC} = t_2 \} \\
& \quad \text{Else If } (t_1 < t_2) \quad \{ \text{TTC} = t_1 \}
\}
\end{align*}
\]

\[
\begin{align*}
\text{Else If } (t_1 > 0 \text{ & } t_2 \leq 0) \\
\{ \text{TTC} = t_1 = \frac{-\Delta V - \sqrt{\Delta V^2 + 2 \Delta a D}}{\Delta a} \}
\end{align*}
\]

\[
\begin{align*}
\text{Else If } (t_1 \leq 0 \text{ & } t_2 > 0) \\
\{ \text{TTC} = t_2 = \frac{-\Delta V + \sqrt{\Delta V^2 + 2 \Delta a D}}{\Delta a} \}
\end{align*}
\]

\[
\begin{align*}
\text{If } (\Delta a = 0 \text{ & } \Delta V > 0) \{ \text{TTC} = \frac{D}{\Delta V} \}
\end{align*}
\]

Generally, if TTC is relatively short, a crash potential would arise because there might not be enough time for the driver of the following vehicle to respond and take evasive actions such as braking or changing lanes, to avoid the collision. However, it is difficult to determine how short the value of TTC actually is, since different drivers have different response times and they might also undertake different measures depending upon the vehicle’s performance, prevailing traffic conditions, and so on. This results in no definite TTC threshold value for different drivers facing a potential collision situation. Former studies also gave different suggestions for the selection of the TTC threshold value. For instance, Van der Horst (1991) (23), and Farber (1991) (24) suggested a TTC value of 4 seconds to distinguish between safe and uncomfortable situations on the roads. Hogema and Janssen (1996) (25) suggested a minimum TTC value of 3.5 seconds for drivers without an automatic cruise control system and 2.6 seconds for drivers with equipped vehicles. However impossible it is to set a standard, it is still necessary to use a reasonable threshold value. In this study, considering the simulation model still represents no accident environment, and the simulated drivers do not really suffer from distraction, misjudgment, and errors which would result in many accidents under real world conditions, a relatively longer TTC is deemed to be a reasonable choice. Four seconds is thus assumed as the threshold MTTC value in this study.

Given this threshold, whether a vehicle is in a potential collision situation can be deduced by comparing its instant MTTC with the threshold value. However, MTTC by itself does not give enough indication about the severity of the collision, since two
vehicles might have the same MTTC for various combinations of different speeds and relative distances. Therefore, a new crash index (CI) is proposed to incorporate additional factors to reflect the “severity” of a potential crash. This new approach is based on the idea borrowed from the kinetics to describe the influence of speed on kinetic energy involved in collisions. In addition it also considers the elapsed time before the conflict occurred, through which the severity and the likelihood of a potential conflict could be interpreted even though a collision had not actually occurred. The proposed index is given below:

\[ CI = \frac{(V_F + a_F \cdot MTTC)^2 - (V_L + a_L \cdot MTTC)^2}{2} \times \frac{1}{MTTC} \]

(7)

It also can be re-written as:

\[ CI = \frac{(\Delta V + \Delta a \cdot MTTC) \cdot [(V_F + V_L) + (a_F + a_L) \cdot MTTC]}{2} \times \frac{1}{MTTC} \]

(8)

If the weight of the paired vehicles was added to the numerator of equation (7) and (8), the first part of the formula can be explained as the kinetic energy transferred during the collision. Since the weight does not vary much between vehicles in the same category and that there are not many categories, assumed to be a constant, it is not included in the formula. The second part \( \frac{1}{MTTC} \) is the inverse of MTTC, which is used to determine the collision possibilities. The larger the MTTC is, the less the possibility of a crash, or vice versa. Now the dimension of CI (if equation (8) is multiplied by weight) indicates that CI is similar to the concept of “power” in physics, even it is not the real power that might have been transferred during the collision. Suppose in a normal car-following situation, two consecutive vehicles keep the same constant speed and do not accelerate; this would be a really safe scenario, and the CI value would be zero. While in a collision with high relative speed, the severity tends to be more serious, in which case the CI tends to have a high value. Hence CI could be used as an alternative indicator that reflects the severity and possibility of two consecutive vehicles involved in a potential conflict.

This indicator only describes the safety information about two vehicles at a certain time and place. But to compare different countermeasures, it should give a more general consideration of the complete road section or the network. Consequently, a crash index density (CID) is proposed as an aggregate measure to assess safety improvements. CID aggregates each paired-vehicle’s CI at each time step across a single link or the whole network. CID allows the safety level of different networks or scenarios to be comparable using the same scale. It could therefore be a beneficial indicator for safety evaluation studies. Equation (9) gives the expression of the proposed CID.

\[ CID = \sum \frac{CI_{ij} \cdot l_j}{T \cdot N \cdot L} \]

(9)

Where,

CID: Crash Index Density for the whole network or links;

\( CI_{ij} \): CI for the \( i \)th vehicle traveling on the \( j \)th link at the \( k \)th time step;
MODEL VALIDATION

Validation Methodology

To validate the Modified Time-to-Collision, MTTC and the proposed “Crash Index (CI)” a detailed comparison between simulation results and real accident records is conducted. The proposed CI indicator and MTTC are tested using a well-calibrated simulation model of the New Jersey Turnpike. In order to eliminate the negative impact of geometric features, the 6.67 mile section between Exits 7 and 7A (northbound) is 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 accident records between 1996 and 2005 for this section are used, comprising of more than 1000 records. The records consist of detailed information on each reported accident, including type, time, location, and other characteristics. Rear-end and sideswipe accident records are extracted from the data set. As proposed in the CI model, detailed information of a potential crash could be generated and used in prediction of occurrence and the degree of severity of an accident. So if this surrogate measure is effective and can be validated, it should have a strong relationship with real accidents in time and space. These criteria serve as the basis for the validation of CI.

FIGURE 2 gives the basic schematic diagram of the simulation model of the test section, the northbound roadway from Exit 7 to Exit 7A. Two traffic zones are connected to the 6.67 mile-long link by zone connectors, with traffic demand from zone 1 to zone 2 consisting of passenger cars, trucks, and buses. Real volumes of each hour, as well as the vehicular composition of traffic, are available through the data obtained from the available network wide vehicle transaction dataset of the facility for 2005. The average traffic flow for each hour throughout the whole year is used as the basic input for each simulation run, and the variation of real traffic flow is reflected in terms of standard deviations of hourly flow. For each simulation run, simulation time is taken as 24 hours to obtain MTTC and CI, based on 24-hour simulation data for comparison with real accidents for the same time period.
Simulation Tool & Data Collection

Former studies have given some insights about the strengths and weaknesses of various simulation software used to support safety analysis. However, there are still no definitive conclusions about the selection criteria of available traffic software packages specific to safety analysis. In the absence of this kind of guidance, Paramics is selected as the traffic simulation tool in this study since it provides a number of advanced modeling and data extraction features.

As a stochastic, microscopic, time step and behavior-based simulation model, Paramics allows the user to gather a representative average result. The small time step characteristics help researchers to explore the transitional behavior of individual drivers with specific attributes for various network traffic conditions, during various time periods. Two stochastic factors, aggression and awareness, which can be randomly assigned to the driver of each vehicle on a scale of 0-8, are observed to have an important influence on the way each vehicle behaves over time and space. Using correct values of these factors will provide the possibility to better capture the observed average driver behavior.

Paramics also provides a way to customize simulation models and variables through the Application Programming Interface (API), which is a significant advantage over most other similar simulators. A customized API that gathers detailed parameters about simulated vehicle trajectories such as time step, speed, acceleration, and position, is implemented into Paramics model to numerically calculate and output the proposed crash index (CI) and modified time-to-collision (MTTC). For data collection, considering the stochastic nature of the simulation model, a relatively large number of runs must be conducted in order to capture a more accurate representation of traffic conditions. To get statistically robust results from the simulation experiments, the number of simulation scenarios with different random seeds is identified to meet a stated objective. Based on these considerations, a sequential approach is used for determining the number of replications required in the simulation analysis. This statistical procedure aims at obtaining the mean \( \mu = E(X) \) of the selected measures of effectiveness (MOE) \( X \), within a specified precision. If we estimated \( \bar{X} \) such that \( |\bar{X} - \mu|/\mu = \gamma \), then \( \gamma \) is called the relative error of \( \bar{X} \). The specific objective of this approach is to obtain an estimated \( \mu \) with a relative error of \( \gamma \) and a confidence level of \( 100(1 - \alpha) \) percent. Denote the half-length of the confidence interval by \( \delta(n, \alpha) \). Further details about the approach are presented as follows (Law, A.M. & Kelton, W.D. 2000):

1. Make an initial number of \( n_0 \) replications of the simulation and set \( n = n_0 \), then calculate initial (crude) estimates \( \bar{X}(n) \) and \( s^2(n) \) from \( X_1, X_2, \ldots, X_n \);
2. Decide the size of allowable relative error \( \gamma = |\bar{X} - \mu|/\mu| \);
3. Calculate the adjusted relative error \( \gamma' = \gamma/(1 - \gamma) \);
4. Decide the level of significance \( \alpha \);
5. Calculate the half-length of the confidence interval
\[
\delta(n, \alpha) = t_{n-1, 1-\alpha/2} \sqrt{\frac{S^2(n)}{n}};
\]

6. If \( \delta(n, \alpha)/|\bar{X}(n)| \leq \gamma' \) use \( \bar{X}(n) \) as the point estimate for \( \mu \) and stop, else make one more replication and set \( n = n + 1 \), then go back to step 2.

This approach assumes identical, independent (IID) outcomes, but they need not be normally distributed. Thus the estimates of \( \bar{X}(n) \) and \( S^2(n) \) for the mean and variance, as well as the estimation of the confidence interval, become better with the incremental iteration.

Because more than one performance measure is used in the simulation analysis, relatively high replication values are chosen. In our case, 20 random seeds are used, and their average used for the comparison analysis. A relative error of \( \gamma = 0.05 \) and a confidence level of 95% are used to examine the effectiveness of replications. For each hour, the results of these 20 replications are all satisfied with the requirement of \( \delta(n, \alpha)/|\bar{X}(n)| \leq \gamma' \), where the adjusted relative error \( \gamma' = 0.048 \), and \( t_{19, 0.975} = 2.039 \). Thus, the results of these 20 replications are used for final analysis without any additional simulation seeds.

**VALIDATION RESULTS**

Initially, MTTC with a threshold value 4 seconds is used to identify the potential conflicts. The points below the threshold represented by the red line in FIGURE 3 (a) indicate potentially dangerous cases. It is hard to deduce if these dangerous cases will finally result in real accidents. Nevertheless, they provide useful indication as to higher probability of accidents.

Among these potential conflicts, it is better to know which ones are more serious than others. Based only on MTTC, however, it is hard to determine this type of information about the expected severity of conflicts. Thus, CI has been proposed as an improvement to MTTC, and is calculated to have a better picture of the expected severity of conflicts. In FIGURE 3 (b), when MTTCs are not changing for different cases (e.g. the green triangle pair), CI (e.g. blue circle pair) seems to be much better at representing the difference between these seemingly similar cases. In other words, even when two conflicts occur with the same probability, they could have different end results. For cases where MTTC is not very significant, the variation of CIs can capture the differences in terms of severity among potential conflicts. Thus, CI tends to better represent the safety level for different scenarios.
Different Results of Random Seeds

(a) A Random Selected Time Period (600s)

(b) Potential Conflict Cases Detected within a 30mins-Period

(c) Crash Index (CI) of Each Case

Threshold MTTC=4s
FIGURE 3 MTTC Characteristics over a Randomly Selected Period of 10 min. (Figure 3a), Comparison with Crash Index (Figure 3b), and Impact of Different Simulation Random Seeds (Figure 3c)

FIGURE 3 (c) illustrates the different results generated from each random seed. Total CIs (y-axis in the figure) of the road at different hours were collected. Totally, the simulation run is executed for 20 different seeds to satisfy our validation procedure, and the red line in the figure represents the mean value of these seeds. Simulation results reflect the impact of the variances of daily traffic flow. Apart from just using random simulation seeds, our API plug-in also generated the demand randomly based on the distribution of observed volumes over a period of 24 hours. This kind of approach that depends on the actual day-to-day changes in traffic demand makes the results more consistent with the real-world conditions.

Generally for a specific road, accidents along the road should have certain characteristics over time and space. There might be high accident risks at some special times. In our case, we first compared the simulation results and actual accidents on the New Jersey Turnpike assuming that there might be more accidents during the morning peak hours. However, after we checked statistical features of accidents for a number of sections, it was interestingly found that more accidents occurred in the afternoon rather than the morning rush hours. More importantly, accidents over different sections shared similar time distribution characteristics. We then concluded that, since the section is northbound (towards New York City), during morning rush hours there are regular commuters, who are more familiar with the roadway and driving conditions during these high volume periods. In the afternoon, there might be more users who are less familiar with the roadway and its driving conditions (since the more familiar drivers i.e. commuters would be on the southbound direction during the afternoon), and thus relatively less careful while driving under congested conditions. Thus, in order to get more reasonable simulation results, our model should reflect these driver characteristics. Paramics simulation tool provides two parameters, including aggression and awareness, to control driver behavior between different periods during the simulation. These two parameters are adjusted to simulate different kinds of driver groups during different time periods.

FIGURE 4 (a) shows the time distribution of actual accident records, MTTC, and proposed Crash Index (CI) for each hour. The number of actual accidents for each hour used in the figure is the total record of ten years (1996–2005) at that hour. It can be seen from FIGURE 4 that both MTTC and CI can capture the temporal distribution of accidents. The simulated CI and simulated MTTC match the trend of actual accidents in time. This is signified their positive correlation, 0.912 and 0.918 respectively (in FIGURE 4(b, c)). The higher the MTTC or CI is, the more real-world accidents are observed. This result validates temporal features of the MTTC and CI in direct comparison with real-world data.
There were no obvious discrepancies in terms of the geometric features of the complete study link and it is safe to assume that each small section should have had equal accident risk. The basic assumption is that accidents can randomly occur anywhere along the link as long as there are no geometric and other variations that might have a direct impact on the safety along the study link. The study section was then divided into a series of 300-meter sections. Historical accident records for the last ten years were associated with these shorter segments to test this hypothesis of random distribution of the real accidents over the entire study segment. FIGURE 5 shows that the accident frequencies of each segment are quite similar. The trend line is found to be almost horizontal, supporting our estimation of the random distribution of accidents over space.

The MTTC of each section was also found to have similar characteristics as shown in FIGURE 5 (a) suggesting that there is no real difference among the 300-meter long subsections. Therefore, MTTC is shown to be in complete agreement with the “observed safety” characteristics along this test segment. In the microscopic simulation model of the study section it was observed that the vehicle transfer from a curved link to a straight link was not smooth. In Paramics the vehicular flow at the transition between two links can be smoothened by adjusting the stop lines. It is, in the authors’ experience, sometimes very difficult to do this adjustment when one or both of the links are curved. Hence at two sections, which were the transitions between curved and straight links, the crash indices were found to be higher due to repeated acceleration and deceleration. Since it is apparent that the spatial distribution of accidents must be uniform over the study section, the average index of the two adjacent sections was used for the problematic section. Due to the same reason it can be observed from FIGURE 5 (b) that the trend in CI is affected to a greater extent since it considers the relative acceleration of the vehicles. It should be noted
here that the time distribution of the crash indices is an aggregate (over space) measure. Hence this does not have a major impact on the time distribution of crash indices.

CONCLUSIONS & FUTURE WORK

This paper describes and validates analytically derived Crash Index (CI) and Modified Time-to-Collision (MTTC) as new safety indicators based on the extension of the well-known TTC safety index. They are successfully applied it to a 6.67 mile section of the New Jersey Turnpike. Compared to the classical TTC-indicator, CI provides a more complete consideration of all possible conflicting cases, while providing an idea about the relative severity of different collision scenarios. The proposed computational logic is integrated into the Paramics micro-simulation model to acquire the data that is used for the
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evaluation of the proposed safety indicators namely, CI and MTTC. Results of a comprehensive simulation study and observed accident data are used as the validation approach, which considers day-to-day random fluctuations in demand, as well as within day fluctuations in driver behavior. As shown in FIGURE 4 and FIGURE 5, both temporal and spatial predictions of MTTC and CI for the study segment are validated in direct comparison with real-world accident data for the same highway section. This kind of validation using real-world accident data is very important since it shows that the proposed surrogate safety indices are capable of capturing real-world safety characteristics with a high level of confidence. It is important to mention that the proposed CI and MTTC are derived based on the information related to two directly interacting vehicles, mainly taking into account the potential rear-end conflicts, and is therefore useful for link or network-scale analyses of rear-end crashes. Further CI could provide better estimates of the accident severity as can be seen from the difference in the level of sensitivity over MTTC. More detailed data which includes accident severity needs to be used to validate the effectiveness of CI over TTC or MTTC to capture the severity of the accident aside from the accident frequency. For intersection analysis, CI has to be considerably modified. Moreover, CI should be used only for the comparison of alternatives not as an absolute indicator of safety. It has been shown in this study that CI can effectively model the temporal distribution of accidents to the same extent as MTTC. Moreover, a large scale validation study should be carried out to validate the soundness and feasibility of simulation-based surrogate safety measures for the comparison of various safety improvements at different locations. A critical threshold value for TTC also needs to be specified in accordance with observed field data.

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