Estimating Traffic Conflict Risk Associated with Merging Vehicles on a Highway Merge Section

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ABSTRACT
This study proposes a methodology for estimating rear-end conflict risk of merging vehicles on freeway merge sections as a probabilistic measure. The methodology consists of two major components. The first part estimates the merging probability of a vehicle given its position on a merge lane. Detailed vehicle trajectory data from Next Generation Simulation (NGSIM) program are used to find the underlying probability density function of merging decision. The second part derives the probabilistic risk of a merging vehicle conflicting with vehicles around it as a function of a surrogate safety measure, namely modified time-to-collision (MTTC). Combining these two parts together, an index is proposed to describe the conflict risk of each merging vehicle at each time step. By aggregating the conflict risk over time and space, a risk map for describing the level of conflict risk can be created. A case study demonstrates the implementation of the proposed method for traffic conflict analysis in detail. The result of this study can be used to evaluate the safety level of merge sections and develop real-time traffic control strategies to reduce conflicts associated with merging traffic.
INTRODUCTION
Highway vehicle collisions are one of the most important concerns for traffic systems all over the world. One major source of vehicle collisions is the merge sections. For instance, lane changing/merging collisions constituted about 4.0 percent of all police-reported collisions in 1991, and accounted for about 0.5 percent of all fatalities (1). The 1999 National Automotive Sampling System/General Estimates System (GES) crash database of the National Highway Traffic Safety Administration showed that 19,000 crashes occurred because of the merging (2). A merging vehicle is required to execute a mandatory lane-change maneuver along a limited length of a merge lane. By controlling the timing of merging, a merging vehicle either successfully resolves the unsafe conflict with other vehicles or gets involved in a collision.

Traffic engineers are looking for ways to redesign merge sections or control merging traffic to reduce collisions associated with merging vehicles. For instance, Cirillo (3) studied the accident experiences among 700 weaving sections in 20 states based on data gathered in the early 1960s, and determined that shorter acceleration lanes exhibited higher accident rates for merging traffic, and the effect of increasing the length of acceleration lanes appears to be substantial when the percent of merging traffic is greater than 6%. Some case studies of freeways in major U.S. cities have shown that ramp metering can reduce crash rate and more specifically rear-end and sideswipe crashes by regulating access of merging traffic to the mainline (4, 5). These historical crash-data-based studies have suggested some effective countermeasures. However, it is difficult to evaluate the effects of traffic safety countermeasures in terms of the change in the number of traffic crashes in many cases. For instance, it is difficult to evaluate safety performance of the new proposed facility designs or traffic control measures at initial operation stage. Traditional analysis method such as before-after comparison may not be implemented. One reason is that traffic crashes are rare events and may not be observed in a short time period (6). What’s more, the use of historical crash statistics as a measure of traffic safety requires a relatively long period for data accumulation and it is only a reactive approach (7). In addition, there are also concerns about the quantity and quality of the crash data (8, 9). Consequently, there is a need to develop alternative methods for identifying safety performance in a shorter time period and perhaps in a proactive manner.

Rather than exclusively relying on historical crash-data-based methods, traffic conflict technique (TCT) has been advocated as a promising alternative to analyze traffic safety. This technique was first applied in road traffic in the USA in the 1960s’ and was quickly transformed into a prevalent technical support tool to complement safety evaluations in various places (10). However, due to the observation and data extraction difficulties, its application was inhibited during last few decades. Recently, with the advent of advanced computer modeling techniques, more detailed conflict information can be generated based on new data collection tools, and therefore, researchers are paying attention to TCT again. One of the popular topics is the use of surrogate safety indicators in support of traffic safety studies (11, 12, 13, 14, 15). Although various studies on the use of surrogate safety measures have been made, limited efforts have been made to apply them for analysis of potential conflicts at highway merge sections.

The objective of this study is to develop a novel methodology for estimating the risk of traffic conflicts associated with merging vehicles on a highway merge section. The risk is estimated on the basis of investigating the potential conflicts caused by the mandatory lane-changes of merging vehicles. Either merging or not, merging vehicles interact with both vehicles on the merge and through lanes. Given the uncertainty of interactions, the merging decision is
described in a probabilistic manner. Risks of potential conflict scenarios under each merging
decision are then exploited by using a time-based surrogate safety indicator.

The methodology is presented in detail in the next section. A case study demonstrates the
application of the methodology in section 3. Section 4 summarizes the major findings and
suggests several research topics that require future study.

**PROPOSED METHODOLOGY**

Vehicles merging on a highway continuously interact with neighboring vehicles on the current
merge lane and adjacent through lane, which actually generate car-following and lane-changing
events. Based on driver’s judgment of its environment the subject vehicle either keeps traveling
on the merge lane or changes lane. FIGURE 1 indicates the typical situation of a merging vehicle
to be studied in this paper. As shown in FIGURE 1, the decision of the subject vehicle will lead
to four potential conflicts between the subject vehicle and its surroundings: conflict with the
preceding vehicle, conflict with the following vehicle on the merge lane, conflict with the
leading vehicle on the target lane, and conflict with the lagging vehicle on target lane. In order
for the subject vehicle to avoid these conflicts, it has to adjust its speed or position to interact
with others in a safe manner.

FIGURE 1 Merging vehicle and its potential conflicts with other vehicles.

FIGURE 2 presents the structure of estimating the conflict risk associated with the
subject vehicle under different conflicting scenarios shown in FIGURE 1. It consists of two
major parts: estimating the merging probability and estimating the potential risk under each
possible interaction scenario. For the first part, merging decision depends on many factors such
as gaps between vehicles, relative speed, and vehicle types, etc. A generalized model can be
presented as a probabilistic model (1) in which $X$ represents a class of factors and $f$ defines the
relational model on $X$ to predict merging probability.

$$Pr(Merge \mid X) = f(X)$$ (1)

One of the typical examples of such a model is the gap acceptance model in terms of a
binary logistic regression model similar to the one presented in (16). However, there is no unique
model that can be applied to all merging behaviors under different traffic conditions because the
influential factors in the model can vary from location to location. The approach of this study is
purely empirical and thus no attempt is made to develop or validate any existing analytical gap
acceptance model applicable to a merging process. Rather, emphasis is placed on the elementary
empirical analysis of merging probability based on the collected traffic data. This approach will
be demonstrated in the next case study section.

For the second part, in order to evaluate the risk of a traffic crash, the microscopic vehicle
behaviors are analyzed from the perspective of a traffic conflict. Though some research studies
(e.g., 17, 18) have suggested that there is only medium correlation between the number of traffic
accidents and the traffic conflicts, this study adopts the methodology to evaluate the risk of a
traffic collision due to the difficulty in observing the actual traffic collision itself.

![Diagram](image)

**FIGURE 2 Proposed structure for estimating conflict risk of merging vehicles.**

One of the frequently used indicators to characterize potential rear-end conflict is the
Time-To-Collision (TTC). This indicator is adopted in this study to analyze those four types of
conflicts in merging process. Originated from auto manufactures, TTC represents "the remained
time that would take a subject vehicle to collide with the tail of vehicle in front if the speed and
direction of the vehicles do not change" (19). This can also be explained as the time needed to
avoid a collision by taking certain countermeasures. Traditionally, TTC can be formulated as
follows:

$$TTC = D / \Delta V$$ (2)

Where $D$ is relative distance (ft), and $\Delta V$ is relative speed of two consecutive vehicles (ft/s).

The equation (2) above simply assumes that only if the speed of the subject vehicle is
larger than that of the preceding vehicle can a collision occur. In the case where the preceding
vehicle is faster than the subject vehicle, traditional TTC index cannot be computed as a
meaningful positive number. This is a practical weakness of the TTC indicator. It disregards many potential conflicts because of ignoring the discrepancies in acceleration or deceleration of the consecutive vehicles. Considering the impact of acceleration, Ozbay et al. (20) indicated all possible situations where the potential conflict may or may not occur. These scenarios are listed in TABLE 1, in which \( V_s \), \( V_p \), \( a_s \), and \( a_p \) are the speed and acceleration of the subject and its preceding vehicle, respectively.

<table>
<thead>
<tr>
<th>( V_s &gt; V_p )</th>
<th>( V_s \leq V_p )</th>
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<tbody>
<tr>
<td>( a_s &gt; 0 )</td>
<td>( a_p &gt; 0 )</td>
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<tr>
<td>( a_s &gt; 0 )</td>
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<td>( a_s &lt; 0 )</td>
<td>P</td>
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<tr>
<td>( a_s = 0 )</td>
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Note: C-Conflict occurs; P-Possible Conflict; I-Impossible conflict with each other.

Formulas (3) and (4) can be used to mathematically describe the underlying relationships which determine the occurrence of the conflict shown in TABLE 1. They are based on the trajectory projection of the two consecutive vehicles given their relative distance, speed and acceleration information. These formulas are proposed as a modification of equation (2) to capture extra potential conflict cases considering acceleration. By equating (3) or (4) and solving it, the modified TTC (hereafter called MTTC) for a rear-end conflict of the consecutive vehicles can be calculated.

\[
V_s t + \frac{1}{2} a_s t^2 \geq D_{SP} + V_p t + \frac{1}{2} a_p t^2
\]  
(3)

\[
\frac{1}{2} \Delta a t^2 + \Delta V t - D_{SP} \geq 0
\]  
(4)

Where \( V_s \) and \( V_p \) are speed of subject vehicle and preceding vehicle (ft/s), \( a_s \) and \( a_p \) acceleration of subject vehicle’s and preceding vehicle (ft/s²), \( \Delta V \) is relative speed (ft/s), \( \Delta V = V_s - V_p \), \( \Delta a \) is relative acceleration (m/s²), \( \Delta a = a_s - a_p \), \( D_{SP} \) is initial relative distance (ft) at each time step, and \( t \) is time (s).

Generally, if MTTC is relatively short, a crash potential would arise because there might not be enough time for the subject vehicle to respond and take certain measures, such as braking and changing lane, to avoid the collision. However, the question of “how short is really short” is difficult to determine since different drivers have different response times, and they also might take different actions depending upon the vehicle’s performance, prevailing traffic conditions, etc. Studies in the literature offered different suggestions for the selection of a threshold value for TTC to identify critical conflict. For instance, Van der Horst (21), and Farber (22) suggested a TTC value of 4 seconds to distinguish between safe and uncomfortable situations on the roads. On the other hand, Hogema and Janssen (23) 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. Arguably there is no unique threshold value of TTC below which all drivers facing a potential collision situation.

Considering the fact that the shorter MTTC is, the higher probability of conflict is, this study adopts an exponential decay function as an alternative of defining single threshold value to identify potential risk of the conflict. The function of the ith type of potential conflict probability \( (CP_i) \) associated with the subject vehicle is shown in equation (5) and it is a continuous...
monotone decreasing function of MTTC such that as MTTC \( \in [0, +\infty) \), CP \( \in [1, 0) \). When MTTC is 0, the two consecutive vehicles definitely conflict with each other. When MTTC is relative large, the conflict probability will be small. The same MTTCs may not indicate the same chance of conflict under different traffic conditions. So a parameter \( \lambda \) is used for adjusting the impact of MTTC at different cases such as freeway versus local road.

\[
CP_i = \Pr(\text{Conflict} \mid MTTC_i) = \exp\left(-\frac{MTTC_i}{\lambda}\right)
\]

(5)

There are four possible conflict risks as shown in the previous FIGURE 2 and denoting each of them as CP_1, CP_2, CP_3, and CP_4. Given the uncertainty of merging behavior, at each time step the overall potential conflict risk (CR_j) associated with the jth subject vehicle in merging process can be written as equation (6) and (7):

\[
CR_j = \Pr(\text{Merge} \mid X) \times (CP_1 + CP_2) + \Pr(\text{NotMerge} \mid X) \times (CP_3 + CP_4)
\]

(6)

\[
CR_j = \Pr(\text{Merge} \mid X) \times \left[\exp\left(-\frac{MTTC_j}{\lambda}\right) + \exp\left(-\frac{MTTC_j}{\lambda}\right)\right] + \Pr(\text{NotMerge} \mid X) \times \left[\exp\left(-\frac{MTTC_j}{\lambda}\right) + \exp\left(-\frac{MTTC_j}{\lambda}\right)\right]
\]

(7)

To describe the conflict risk involving all N merging processes at a given segment during certain period \( T \), the following formula (8) can be used as an index to identify the overall level of conflict risk (LOCR).

\[
LOCR = \frac{1}{T \times N} \sum_{t=1}^{T} \sum_{j=1}^{N} CR_{jt}
\]

(8)

Where \( CR_{jt} \) is the potential conflict risk of merging associated with the jth subject vehicle at each time step t.

**CASE STUDY**

A field vehicle tracking dataset namely “I-101 Dataset” generated by the Next Generation Simulation (NGSIM)\(^1\) program are used to demonstrate the applicability of the proposed methodology for the study of traffic conflicts. The dataset is “specifically collected to improve the quality and performance of simulation tools, promote the use of simulation for research and applications, and achieve wider acceptance of validated simulation results.” The data were collected at a segment of southbound direction of U.S. highway 101 in Universal City neighborhood of Los Angeles, California. The schematic illustration of the location is shown in FIGURE 3.

\( ^1 \) NGSIM is a research project let by the US FHWA to provide resolution and high quality driver behavior data and algorithms. Detailed information is available at official website: [http://www.ngsim.fhwa.dot.gov](http://www.ngsim.fhwa.dot.gov).
The objective range of data collection was approximately 2100 feet in length. The auxiliary lane for on-ramp vehicle merging and vehicle diverging is about 698 ft. About 6,000 vehicle trajectories were collected based on video data with a 0.1-second time increment. This amount of detail trajectory data is unique in history of traffic studies and provides a better basis to objectively investigate the traffic conflicts using the parameters in the data. It was also separated into three 15-minute periods of data representing transitional and congested flow conditions in the morning, on June 15, 2005: (a) 07:50~08:05, (b) 08:05~08:20, and (c) 08:20~08:35. Vehicle trajectories associated with merging vehicles and their surroundings on auxiliary lane and adjacent through lane are retrieved for further analysis.

Statistical software package, R, is used for analyzing NGSIM vehicle trajectory data. Instead of modeling the merging decisions using a gap acceptance model, the merging behaviors along the auxiliary lane are investigated based on the observed data. Data of time period (a) and (c) are used as training data to identify the merging probability at each location along the merge lane. It is found that the merging probability can be fitted as a lognormal distribution, which is shown in FIGURE 4 (a). The probability model developed in this study with the estimated parameters is shown in Equation (9). To test the goodness of fit, $\chi^2$ test is used. The test statistic is 13.076, which is less than the critical value of 15.507 given the significance level of 0.05. Thus it indicated that it is reasonable to assume the merging probability along the auxiliary lane comes from the fitted lognormal distribution. To further verify the validation of the fitted model, empirical data of time period (b) is used as test data. Kolmogorov-Smirnov test is used to decide if the testing data can be also assumed to come from a population with the specified lognormal distribution. The null hypothesis that the testing data also follow the lognormal distribution is accepted because the p-value (=0.1513) of the test is higher than significance levels of 0.05. Therefore, the merging probability model (9) is used for following study.

$$Pr(Merge \mid X = Position) = f(X) = \frac{\exp\left[-\frac{1}{2\sigma^2}(\ln x - \mu)^2\right]}{x\sigma\sqrt{2\pi}} = \frac{\exp\left[-\frac{1}{2\times0.9173^2}(\ln x - 5.3785)^2\right]}{0.9173\times\sqrt{2\pi}\times x}$$ (9)
As mentioned in the last section, the exponential decay function is adopted to model the conflict probability. To do this, the parameter $\lambda$ has to be specified. As an example in this study, assuming MTTC of 4 seconds corresponds to a conflict probability of 0.5. The parameter $\lambda$ thus can be set to 5.77. If a shorter MTTC of 3 seconds is assumed then this would correspond to a conflict probability of 0.5, and $\lambda$ can be set to 4.32. FIGURE 5 shows an example of the exponential decay curve using the assumed parameters. The model using $\lambda=5.77$ can be written as equation (10). As MTTC increases, the conflict probability will decrease. FIGURE 5 shows that the same MTTC will have higher conflict probability if a larger parameter $\lambda$ is used. Arguably the value of the parameter $\lambda$ deserves more considerations to adjust the shape of curve for different traffic conditions.

$$CP_i = \Pr(\text{Conflict} \mid \text{MTTC}_i) = \text{Exp}\left(-\frac{\text{MTTC}}{5.77}\right)$$

MTTCS between the subject vehicle and vehicles around it are computed using formula (3) or (4). Assuming $\lambda=5.77$, then using equation (9) and (10) with equation (7), the conflict
probability associated with the merging vehicle at each time step can be estimated by equation (11):

\[ CR_i(t) = \frac{1}{\lambda} \ln \left[ \frac{\lambda}{\sqrt{2\pi}} \exp \left( -\frac{\lambda^2}{2} \right) \right] \]

Aggregating the computed conflict risks from equation (11), the overall level of conflict risks over time and space can be computed by equation (8). FIGURE 6 illustrates maps of the level of conflict risk (LOCR) over 1-minute time interval and 50-feet spatial interval aggregation using the NGSIM data. FIGURE 6 (a) shows the estimated risk using assumed parameter \( \lambda = 5.77 \). As a sensitivity comparison, the risk map using a relatively smaller \( \lambda = 4.32 \) is also presented in FIGURE 6 (b). The overall level of conflict risk for FIGURE 6 (b) is smaller because crash risk computation model (7) is an increasing function of the parameter \( \lambda \) given a fixed MTTC. Both maps suggest that the conflict risk associated with merging vehicle increases when traffic flow becomes more congested at the last 15 minutes. This may be due to shorter gaps available for merging increase under high traffic density and that it is more risky to merge into these gaps. The risk maps also show that the LOCR is lower at the end of the auxiliary lane. This is due to fewer vehicles merging at the end of the auxiliary lane and vehicles have more chances to find acceptable gaps when travelling farther on merge lane. Some of the larger LOCR occurring at the end of merge lane may be as a result of those forced merging behaviors.

FIGURE 6 Example of level of conflict risk associated with merging vehicles.
It should be noted that the value of the LOCR itself does not have a practical meaning. It only performs as a measure to describe potential conflict risk of different traffic conditions. Rather than predicting actual crashes, it can be used as an index for real-time traffic control to reduce conflicts associated with merging vehicles. For instance, on-ramp merging flow can be regulated (e.g., by ramp metering) when the LOCR is relatively higher than that of normal traffic conditions.

CONCLUSIONS
Merge sections are locations where traffic collisions frequently occur. In terms of short-term evaluation of safety performance of countermeasures available for merging collision reduction, crash-data-based safety evaluation approach is not always practical because the number of crashes may be relatively low and the safety engineers have to wait for years to collect such crash data. This study proposes an alternative methodology for estimating conflict risk associated with merging vehicles on freeway merge sections. Four types of conflicts are studied. They include conflict with preceding vehicle, conflict with following vehicle on merge lane, conflict with leading vehicle on target lane, and conflict with lagging vehicle on target lane. The structure of the proposed methodology consists of two major parts: estimating the merging probability and estimating conflict probability when subject vehicle interacts with its surrounding vehicles. Detailed vehicle trajectory data obtained from NGSIM dataset are used to find the underlying probability density function of merging decisions. A new surrogate safety measure MTTC recently proposed by Ozbay et al. (20) is used to capture the potential conflict probability through an exponential decay function. Combining these two parts together, a conflict risk (CR) index is computed to describe the potential risk associated with a merging vehicle at each time step. By aggregating the conflict risk of all the merging vehicles, the overall level of conflict risk (LOCR) is computed for the specific merge section. A case study using NGSIM data illustrates the application of the proposed methodology. The map of LOCR can be used to visually highlight the potential conflict risk associated with vehicles over time and space and to develop real-time traffic control measures to prevent potential accidents at merge sections.

Although the feasibility of the proposed method is demonstrated using real data, further research is needed to fully implement this methodology in the field. The method mainly describes the linear conflicts between consecutive vehicles, so it does take the sideswipe collisions into account. More analysis of the merging probability model should also be conducted through additional trajectory data. The determination of the model parameter in the exponential decay function also deserves more detailed study. Relationship between estimated conflict risk and actual crashes should also be explored.

REFERENCES


20. Ozbay, K., H. Yang, B. Bartin and S. Mudigonda. Derivation and validation of new simulation-based surrogate safety measure. Transportation Research Record: Journal of
the Transportation Research Board No.2083, Transportation Research Board of the

21. Van der Horst, R. Time-to-collision as a cue for decision making in braking. In A.G. Gale

22. Farber, B. Designing a Distance Warning System from the User Point of View. APSIS
report, Glonn-Haslach: Institute fur Arbeitspsychologie and Interdisziplinare