Transportation Research Procedia

Volume 15, 2016, Pages 794–805

ISEHP 2016. International Symposium on Enhancing Highway Performance

A Prediction Accuracy-Practicality Tradeoff Analysis of the State-of-the-art Safety Performance Assessment Methods

Jaehyun (Jason) So[1], Silja Hoffmann[1], Joyoung Lee[2], Fritz Busch[1] and Keechoo Choi[3]

[1]*Technical University of Munich, Munich, Germany*

[2]*New Jersey Institute of Technology, Newwark, NJ, U.S.A.*

[3]*Ajou University, Suwon, Korea*

jaehyun.so@tum.de, silja.hoffmann@tum.de, jo.y.lee@njit.edu, fritz.busch@tum.de and keechoo@ajou.ac.kr

Abstract

This study proposes advanced safety assessment methods in the perspectives of prediction performance and practicality. This study thus develops three different safety assessment approaches (simulated conflicts-incorporated, estimated conflicts-incorporated, and intersection operational attributes-based safety performance function) and utilizes two existing approaches (annual average daily traffic-based and simulated conflicts-based safety performance functions. These five safety assessment approaches are compared in terms of crash prediction performance at intersections and practicality representing the required efforts in implementing a method. The results showed that the simulated conflicts-incorporated safety performance function approach was best in terms of prediction performance while the annual average daily traffic-based safety performance function approach was best in the practicality aspect. The discussion on trade-off between prediction performance and practicality then followed based on the analysis on the prediction performance and practicality aspects. This study will be a reference to safety assessment practitioners when they need to assess safety on roadways and to select an appropriate safety assessment method with limited resources.

Keywords: Safety Performance Function, Annual Average Daily Traffic, microscopic traffic simulation model, traffic conflict, Surrogate Safety Assessment Model.

1 Introduction

Many helpful tools and guidelines have been developed for assessing the safety performance of roadways. The most distinctive footprint would be Highway Safety Manual (HSM), including the recently-released 2014 supplement (AASHTO, 2010). HSM provides various safety performance functions (SPFs) enabling to estimate the frequency and severity of crashes for a variety of roadway types (e.g., freeway, ramp, intersection, multi- and two-lane highways, and urban arterial). The Federal Highway Administration (FHWA) in the United States also developed a procedure for identifying high-risk locations (hereafter 'hot-spots'), and suggested each state to develop

 Selection and peer-review under responsibility of the Scientific Programme Committee of ISEHP 2016

doi:10.1016/j.trpro.2016.06.066

state-specific SPFs based on crash and traffic volume data collected from the subject state because each jurisdiction may have different traffic operation characteristics (ITS_Corporation, 2008). Following this FHWA recommendation, many states in the U.S. including Minnesota, Colorado, California, Texas, New York, and Virginia have developed their own state-specific SPFs (Garber & Rivera, 2010). While the SPF-based method can directly connect to the crash-based results, SPFs in HSM are still challenging to precisely reflect the microscopic operational characteristics of roadway, such as detailed geometries and traffic control algorithm, particularly at signalized intersections, which hinders detailed safety analysis. For example, under the current SPF-based approach, two signalized intersections with similar Annual average daily traffics (AADTs) on both major and minor streets but different lane configurations and signal timing plans would have similar safety assessment results.

A microscopic simulation-based surrogate safety assessment model (SSAM) has gained great attention due to its exclusive capabilities of handling the individual driver behaviors and the detailed operational characteristics of intersection, which is not achieved by the existing SPF-based approach. That is, the SSAM-based approach can reflect the impact of various intersection control parameters such as signal timings, lane configurations, right of way, and yield/stop rule. On the other hand, the SSAM-based approach generally requires tons of simulation modeling efforts.

In summary, these two distinctive safety assessment methods, SPF-based method and SSAM-based method, have been developed and evolved in order to enhance the safety assessment in terms of the safety measure prediction performance and the practicality of method implementation. Based on this stream in the traffic safety research, this study proposes an incorporated statistical modeling approach to take the advantages of both SPF- and SSAM-based methods by connecting the simulated conflicts to the crash-based safety assessment results, in order to maximize the crash prediction performance. The simulated conflicts are thus incorporated into the SPF form that originally consists of AADTs on major and minor links. Also, to utilize the traffic conflicts-based safety assessment method and enhance its practicality, a statistical modeling approach to estimate traffic conflicts, replacing microsimulation and SSAM implementations, is attempted. The relationship between conflicts and microscopic intersection operational characteristics is thus modeled, in order to estimate traffic conflicts without the simulation modeling and implementation efforts, which enhances practicality in assessing safety. As such, this study develops several enhanced safety assessment methods in pursuing the two different purposes, prediction performance and practicality, based on the conventional safety assessment approaches (i.e., SPF- and SSAM-based methods). Furthermore, this study investigates the performance of both the conventional and the proposed safety assessment approaches in terms of prediction performance and practicality, and finally analyzes the trade-off between the two measures among the state-of-the-art safety assessment methods.

2 Literature Review

Traffic safety has been a major issue among traffic engineers, and significant research efforts on statistical model-based safety assessment have been made. $SafetyAnalyst^{TM}$, a SPF-based safety assessment software, provides a set of traffic safety management tools such as a network screening tool, a priority ranking tool, and a countermeasure evaluation tool, in order to support state and local highway agencies' decision making process in selecting the hot-spot locations that need to be treated in priority (FHWA, 2010). Although the software provides extensive safety analysis capabilities with several SPFs for various road facility types, these SPFs are based on the Minnesota data, which would be risky for other jurisdictions to use. Therefore, many other states in the United States including Colorado, California, Texas, New York, and Virginia have developed their own state-specific SPFs (Garber & Rivera, 2010). The Idaho Transportation Department is also developing SPFs for the state of Idaho, but the results are not available yet. Beyond these efforts from public transportation agencies, several studies have been conducted to develop and improve SPFs or other crash prediction models as follows: a road design variables-incorporated SPF (Montella & Imbriani, 2015), developing SPF for bicycles (Nordback et al., 2014), mountainous freeway (Ahmed et al., 2011), urban road network (Lord & Persaud, 2004), rural motor way (Montella et al., 2008), two-lane rural highways (Cafiso et al., 2010), and unsignalized superstreet (Ott et al., 2012).

Due to limitations of statistical model-based crash prediction methods pointed in the Introduction section, another safety assessment stream using traffic conflicts has been recently highlighted. This is based on the hypothesis that a traffic conflict, which is a vehicle interaction that would lead to a crash if not one of the participants conducts a change in its behavior to avoid the crash, represents a high probability of a traffic crash. This traffic conflict-based safety assessment approach has been accelerated by an automated surrogate safety measures computation tool, Surrogate Safety Assessment Model (SSAM) (Gettman & Head, 2003; Gettman et al., 2008). SSAM automates the process of analyzing vehicle trajectories from microscopic traffic simulation models; computes surrogate safety measures such as time-to-collision (TTC) and post-encroachment time (PET) using the vehicle trajectories; and identifies traffic conflicts that computed TTC and PET within a pair of vehicles are lower than 1.5 and 5.0 seconds, respectively. This microsimulation and SSAM-based safety assessment approach has been used to compare traffic alternatives in many safety studies as follows: active traffic management (ATM) strategies

(Nezamuddin et al., 2010), Cooperative Vehicle Intersection Control (CVIC) (Lee et al., 2013), intersection design (Kirk & Stamatiadis, 2012), roundabouts (Al-Ghandour et al., 2011), and the safety impact of GPS accuracy and communication delays (J. So et al., 2014; J. J. So et al., 2014).

Beyond these two different safety assessment methods (i.e., statistical model-based method and simulated conflicts-based method), recent studies investigated the relationship between traffic conflicts and crashes or the viability of safety assessment through conflict analysis. Shahdah et al. (2014) developed an integrated crash-conflict model in an alternative way of estimating crash modification factors (CMFs). So et al. (2015) compared two major safety assessment paradigms, namely the conflict-based and statistical modeling (Empirical-Bayes SPF) methods, in assessing crash risks at signalized intersections and arterial segments. Cunto and Sacomanno (2008) compared two different sets of vehicle trajectories obtained from the field and the microsimulation in computing the deceleration rate to avoid crashes (DRAC) and the crash potential index (CPI). Caliendo and Guida (2012) tested various forms of surrogate safety measures-based crash prediction models and concluded that the traffic conflict-based model performed best.

Based on the literature review, there were significant research efforts to assess road safety performance by taking advantage of not only statistical models but also micsosimulation. Also, a few studies attempted to use surrogate safety measures to predict crashes, ultimately assess the road performance in safety. However, there is still a gap to be improved in assessing the road safety performance in terms of both prediction performance and the practicality of method. Previous studies only focused on specific crash types such as rear-end crashes; investigated the performance of sole conflicts in accounting for crashes; experimented with a relatively small number of intersections/areas; proposed complicated statistical models or multiple software implementation approaches which may require significant computation time, even though safety assessment generally needs to be conducted with a large number of road facilities and various crash/conflict types in a practical manner.

In filling this gap, this study proposes an enhanced crash prediction model by incorporating traffic conflicts into the existing SPF form in ways of simulation implementation and statistical modeling, in order to prove a better prediction performance and practicality, respectively. This study also examines the proposed safety assessment methods in terms of the prediction performance and the practicality, and finally analyzes the trade-off between the two performance measures among the proposed safety assessment methods, in order for this trade-off analysis results to be used as a reference when traffic safety engineers need to select an effective and efficient safety assessment method under limited resources.

3 Methodology

3.1 Safety Performance Assessment Approaches

A total five highway safety assessment approaches, including conventional methods and enhanced methods developed in this study, were tested in terms of prediction performance and practicality. The safety assessment approaches 1 and 2 were implemented using existing SPF-based method and SSAM-based microsimulation approach, respectively, while a simulated conflicts-incorporated SPF was developed in the third approach; a model-based conflicts-incorporated SPF was developed in the fourth approach; and an intersection operational attributes-based crash estimation model was calibrated and implemented in the fifth approach. Each safety assessment approach was tested in terms of predicting crashes (i.e., prediction performance) and required efforts to implement the method (i.e., practicality). The safety assessment approaches used in this study are described as follows.

Approach 1: AADT-based safety performance function

The first approach represents existing SPF-based safety assessment methods. The HSM suggests that each state (or city) should either develop their own SPF, or calibrate SPF parameters based on local crash and AADT data. Currently a study to customize SPFs for Idaho, United States (U.S.) is being conducted, but the results are not available yet. This study thus calibrated SPF parameters using crash and AADT data collected in a City of Boise, Idaho, U.S. and a suggested SPF form (Eq. 1) from the $SafetyAnalyst^{TM}$ software. Note that the SPF parameter calibration was conducted based on HSM's SPF development guidelines (AASHTO, 2010), using the negative binomial (NB) regression modeling functionality of IBM SPSS statistics software version 22.0 (IBM, 2013).

$$\mathrm{CF} = e^{\alpha} \cdot AADT_{major}{}^{\mathrm{b1}} \cdot AADT_{minor}{}^{\mathrm{b2}} \quad \text{Eq. (1)}$$

Approach 2: Microsimulation-based safety assessment (using traffic conflicts)

The second approach uses traffic conflicts estimated using a microscopic traffic simulation model and SSAM. A general method of estimating traffic conflicts is to use vehicle trajectories consisting of vehicle positions (x/y/z), speed, and acceleration/deceleration, which are some of the outputs from microscopic traffic simulation models. Note that VISSIM 7.0 was selected because of its detailed representation of microscopic vehicle behavior, and because of its SSAM compatibility. VISSIM generates a binary-coded vehicle trajectory data set (.trj), which can be used as an input to SSAM. SSAM then uses this data set to compute surrogate safety measures such as time-to-collision, post-encroachment time, and estimated traffic conflicts.

Twelve replications were made with different random number seeds, to capture variability in the simulation runs. The simulation period for collecting vehicle trajectories was set at 3,600 seconds (1 hour). Two hours of warm-up time were used to fill the network with vehicles. The number of simulation runs was determined based on a computed sample size. Twelve replications were statistically sufficient to cover the variability of this simulation, at the 95% confidence level (Robertson, 1994).

Regarding threshold values in SSAM, values of 1.5 and 5.0 seconds were used for TTC and PET respectively, as thresholds for identifying traffic conflicts (Caliendo & Guida, 2012; Gettman et al., 2008; Wu & Jovanis, 2012). Note that 'TTC = 0' cases were excluded from this analysis. The conflicts in SSAM were classified into three different conflict types: rear-end, lane change, and crossing based on conflict angle between vehicles. Specifically, the conflict types are classified as follows: 1) rear-end conflict if $|conflict\ angle| < 30°$, 2) crossing conflict if $|conflict\ angle| > 85°$, and 3) all others are lane change conflicts. In addition, all traffic conflicts were classified by intersections (i.e., at- or inside of 250 ft from the center of an intersection or by the middle of two intersections) based on the geo coordinates (x and y) of each conflict. For example, the estimated conflicts between two intersections were classified into the intersection closely located respectively, if the distance between the two intersections are less than 500 ft (doubled of 250 ft). The simulated conflicts were finally used to predict crashes at intersections using the following SPF form.

$$\mathrm{CF} = e^{\alpha} \cdot Conflicts^{c} \qquad \text{Eq. (2)}$$

Approach 3: Simulated conflicts-incorporated safety performance function

The third approach develops an enhanced crash prediction model by utilizing existing AADT-based SPF form and simulated conflicts. The existing SPF-based method is developed based on the field-collected crashes while it is still challenging due to limited crash data and lack of reflecting microscopic intersection operational characteristics (e.g., traffic signal controls, lane configurations, and driver aggressiveness). On the other hand, the SSAM-based method is based on the simulated vehicle trajectories reflecting the intersection operational and geometric characteristics and driving behavior factors (e.g., aggressiveness of car-following and lane-change behaviors). The SSAM-based method thus can serve as a pragmatic supplement to the existing SPF-based method. Therefore, this approach was motivated to exploit the advantages of both safety assessment methods (i.e., SPF-based method and SSAM-based method). To integrate AADT effects and traffic conflict effects, six types of SPF forms were initially considered as follows:

Form 1: $$\mathrm{CF} = e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \qquad \text{Eq. (3)}$$
Form 2: $$\mathrm{CF} = e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \cdot {Conflicts_{Total}}^{c1} \qquad \text{Eq. (4)}$$
Form 3: $$\mathrm{CF} = e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \cdot {Conflicts_{RE}}^{c2} \cdot {Conflicts_{LC}}^{c3} \cdot {Conflicts_{CR}}^{c4} \qquad \text{Eq. (5)}$$
Form 4: $$\mathrm{CF} = e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \cdot {Conflicts_{RE}}^{c2} \qquad \text{Eq. (6)}$$
Form 5: $$\mathrm{CF} = e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \cdot {Conflicts_{LC}}^{c3} \qquad \text{Eq. (7)}$$
Form 6: $$\mathrm{CF} = e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \cdot {Conflicts_{CR}}^{c4} \qquad \text{Eq. (8)}$$

where (applied for Equations 1 to 8),
CF = crash frequency (total number of crashes)
$AADT_{major}$ = AADT on major approaches
$AADT_{minor}$ = AADT on minor approaches
$Conflicts_{Total}$ = total number of (estimated) traffic conflicts
$Conflicts_{RE}$ = number of (estimated) rear-end traffic conflicts
$Conflicts_{LC}$ = number of (estimated) lane-change traffic conflicts
$Conflicts_{CR}$ = number of (estimated) crossing traffic conflicts
$a, b1, b2, c1, c2, c3, c4$ = calibration parameters

Each enhanced SPF form was based on simulated conflicts, AADTs, and crashes, and a selected model showing best prediction performance was used as a representative model of this approach and compared with the other approaches.

Approach 4: Estimated conflicts-incorporated safety performance function

This approach is to provide more practicality in estimating traffic conflict, thus developed a conflict estimation model based on the assumption that traffic conflicts are the function of microscopic intersection operational attributes such as geometry, signal timings and traffic composition, and resulted driving behaviors. In other words, this approach is to estimate traffic conflicts without simulation implementation which requires tons of simulation coding, computation, and evaluation works that are often time consuming and cost-ineffective. To this end, a statistical modeling approach was attempted using collected microscopic intersection operational parameters. The collected parameters were used as independent variables to estimate the number of traffic conflicts, and the simulated traffic conflicts obtained from actual simulation runs were used as a dependent variable to calibrate the parameters of the independent variables. The independent variables collected for this approach are indicated in the $Data\ Collection$ section. The estimated traffic conflicts replaced the $conflicts$ terminology in the proposed-enhanced SPF forms of the approach 3, thus a goodness-of-fit of these models was measured.

Approach 5: Intersection operational attributes-based safety performance function

This approach is to directly estimate the number of crashes based on AADTs and the other microscopic intersection operational attributes that can be collected in the field. This is attributed by the possibility of directly estimating the number of crashes based on the basic traffic and geometry information such as signal parameters, lanes, approaches, etc.,. While this approach is expected to be time-efficient because it does not require the time for building and running a simulation model, it is also investigated in terms of prediction performance.

3.2 Study Area

The downtown area in Boise, Idaho, United States was chosen as a test-bed in this study. This network includes a sizable number of intersections (i.e., 40 4-leg signalized intersections), which is appropriate for a statistical analysis, and the simulation network is already available among the VISSIM demo networks. The selected Boise VISSIM simulation model was calibrated and validated with traffic data (volume and speed) from 2004, and the parameters of the VISSIM's driving behavior models (i.e., Wiedemann's car-following model and lane change model) were adjusted to reflect actual driving behavior in reality. In other words, the volume and speed outputs resulted from simulation runs having different driving behavior parameters sets were compared with the field-collected volume and speed data, and the parameter set that fits best to match the field-collected data was finally selected and applied. Figure 1 shows an aerial view of this network having the 40 4-leg signalized intersections selected for this study, including corridor names, intersections, and VISSIM's links and connectors.

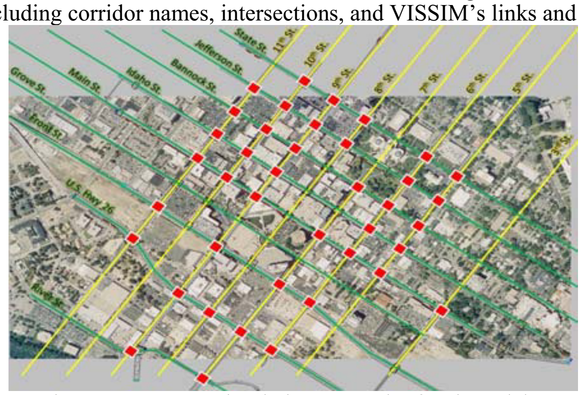

Figure 1: VISSIM simulation network of Boise, Idaho

3.3 Data Collection

Crash data was retrieved from WebCARS, the crash analysis reporting system of the Idaho Transportation Department, Office of Highway Safety. This system maintains crash data from 1997 to the present, and the sources of the crash data are the crash reports made by law enforcement agencies in the state. Three years of crash data (2004 through 2006) were collected and aggregated because crashes are rare events and too few crashes are observed within one year. Aggregation of crash data was essential in order to have an adequate number of crashes for a statistical analysis conducted in this study.

The following data reduction was conducted before the data analysis in order to obtain only appropriate crash data corresponding to the study purpose: both property-damage only crashes and injury/fatal crashes were included; only the rear-end, angle, and crossing vehicle crash types that are closely related to vehicle interactions were considered, while the other types (e.g., crashes with parked cars, bicycles, and pedestrians and driver inattentions) that relate to non-vehicle objects and reflect human errors were excluded; and only crashes occurring at- or inside of 250ft from the center of an intersection were included, while crashes occurring at parking lots and pedestrian/bicycle roads were excluded. In addition, AADTs on major and minor roads were also collected during the period. Data was retrieved from the Ada County Highway District's traffic counts database (ACHD, 2015) (accessed on April 10, 2015). Although this AADT data collection period is not the same with the crash data collection period due to nonavailability of data, it should be noted that there was no significant changes in geometries and traffic operations during the two periods (i.e., data collections for crashes and AADTs). Descriptive statistics of crash and AADT data are as shown in Table 1. Note that the crash and AADT data were collected for 40 four-leg signalized intersections in Boise, Idaho.

Table 1: Descriptive statistics of AADT and crashes

Statistics		Total	Average	Max.	Min.	STDEV
Intersections		40	-	-	-	-
Crashes	Total	139	3.48	14	0	3.96
	Fatalities	0	-	-	-	-
	A-Injury	1	0.03	1	0.00	0.16
	B-Injury	9	0.23	2	0	0.48
	C-Injury	23	0.58	4	0	0.93
	Property Damage	106	2.65	14	0	3.17
AADT	Major	-	11747	40188	1954	10741
	Minor	-	7099	27842	1954	5888

In addition, intersection operational factors including AADTs on major/minor links, geometric characteristics, signal parameters, and resulted intersection performance measures were collected from the VISSIM network since the simulation network was built based on the field-collected data. Table 2 shows the collected parameters and its descriptions.

Table 2: Descriptive statistics of intersection operational attributes

Categories	Variables	Description	Descriptive statistics				
			Total	Average	Max.	Min.	STDEV
Geometric characteristics	N_{legs}	Number of operational ways	104	2.6	4	2	0.7
	N_{lanes}	Number of lanes	239	6	10	3	1.7
	Pct_{TH}	Percentage of exclusive through lanes (%)	-	40.8%	77.8%	0.0%	26.1%
	Pct_{LT}	Percentage of exclusive left-turn lanes (%)	-	2.1%	20.0%	0.0%	5.1%
	Pct_{RT}	Percentage of exclusive right-turn lanes (%)	-	3.0%	20.0%	0.0%	6.3%
	Pct_{THRT}	Percentage of shared left-turn lanes (%)	-	24.1%	50.0%	0.0%	13.4%
	Pct_{THRT}	Percentage of shared right-turn lanes (%)	-	24.3%	66.7%	0.0%	15.3%
	Srd_{THLT}	Presence of shared left-turn lanes (yes=1, no=0)	-	"Yes" for 90% and "No" for 10%			
	Srd_{THRT}	Presence of shared right-turn lanes (yes=1, no=0)	-	"Yes" for 90% and "No" for 10%			

	Srd_{ALL}	Presence of shared left and right-turn lanes (yes=1, no=0)	-	"Yes" for 10% and "No" for 90%			
Signal parameters	Pct_{Gmaj}	Percentage of green phase on major road (%)	-	56.6%	72.5%	38.3%	9.2%
	Pct_{Gmin}	Percentage of green phase on minor road (%)	-	43.4%	61.7%	27.5%	9.2%
	L_{CL}	Cycle length (seconds)	2,640	66	120	60	18.2
Intersection performance measures	Nd_{QL}	Queue length (meters)	728.68	18.2	83.5	3.1	17.5
	Nd_{QLmax}	Maximum queue length (meters)	6,207.3	155.2	356.1	59.9	77.0
	Nd_{VD}	Total vehicle delays (seconds)	374.9	9.4	20.4	1.4	4.2
	Nd_{VSD}	Total vehicle stop delays (seconds)	204.9	5.1	16.0	0.6	3.1
	Nd_{Stops}	Total number of stops	127.0	3.2	7.7	0.3	1.6

3.4 Goodness-of-fit Measures

A goodness-of-fit test showing how well the predicted number of crashes fits actual crash frequencies, four measures are thus used: 1) log-likelihood ratio (LL), 2) scaled deviance (SD), 3) Pearson chi-squared (PC), and 4) R-squared measures (R^2) (Owen, 2010). Note that a model fits better to the observed crash frequencies as a log likelihood ratio is higher; a scaled deviance is smaller; a Pearson chi-squared is smaller; and a R-squared is higher.

4 RESULTS

4.1 Modeling Results

4.1.1 AADT-based safety performance function – Approach 1

A basic form of SPF was applied and calibrated based on Boise's crash and AADT data as follows (goodness-of-fit: -89.15 of LL, 45.08 of SD, 42.32 PC, and 0.42 of R^2).

$$\mathrm{CF} = e^{-3.30} \cdot AADT_{major}{}^{0.32} \cdot AADT_{minor}{}^{0.24} \quad \text{Eq. (9)}$$

4.1.2 Microsimulation-based safety assessment (using traffic conflicts) – Approach 2

Table 3 shows the descriptive statistics of simulated traffic conflicts for each conflict type (rear-end, lane-change, crossing, and total) estimated by SSAM software against the descriptive statistics of actual crash frequencies.

Table 3. Comparison of crash frequencies and simulated conflicts

Statistics		Crash frequency	Simulated conflicts: Total	Rear-end	Lane-change	Crossing
Number of intersections						40
Descriptive Statistics	Total	139	2089	1455	412	222
	Average	3.5	52.2	36.4	10.3	5.6
	Max.	14	211	130	52	37
	Min.	0	0	0	0	0
	STDEV	4.0	44.2	30.9	13.1	7.7
Pearson Correlation Analysis	Coefficient (r)	-	0.450**	0.531**	0.177	0.154
	t statistic	-	0.004	0.001	0.275	0.343

**Correlation is statistically significant at the 0.05 level (2-tailed).

The rear-end conflicts appeared to have the highest correlation with actual crash frequencies with a correlation coefficient of 0.531, and total conflicts followed with a correlation strength of 0.450. Correlation coefficients for both rear-end and total conflicts were statistically significant at the 95% of confidence level. Note that the correlation coefficient is considered significant if a t-statistics value is less than 0.05. On the other hand, lane-change and crossing conflicts had relatively weak correlation strength with coefficients of 0.177 and 0.154. Therefore, rear-end conflict was expected to be the most effective surrogate safety measure, and a safety performance function was calibrated using the rear-end conflicts as follows (goodness-of-fit: -86.59 of LL, 40.79 of SD, 32.51 PC, and 0.49 of R^2).

$$\text{CF} = e^{-1.62} \cdot {Conflicts_{RE}}^{0.38} \qquad \text{Eq. (10)}$$

4.1.3 Simulated conflicts-incorporated safety performance function – Approach 3

Based on the correlation analysis results between simulated conflicts and actual crash frequencies, only the SPFs formed with rear-end conflicts and total conflicts were used to develop enhanced SPF among the other SPF forms having the other conflict types. Parameters for the selected four SPF forms (form 1 to 4) were then calibrated using actual crash frequencies, AADTs, and estimated traffic conflicts by types. Table 4 shows the model fitting results including calibrated parameters and goodness-of-fit values for each calibrated SPF form.

Table 4. Calibrated parameters and goodness-of-fit measures

Measures		Form 1	Form 2	Form 3	Form 4
Calibrated parameters	A	-3.303	-3.814	-3.553	-3.814
	b1	0.320	0.231	0.210	0.231
	b2	0.236	0.241	0.244	0.241
	c1	-	0.369	-	-
	c2	-	-	0.284	0.369
	c3	-	-	0.041	-
	c4	-	-	0.104	-
Goodness-of-fit measures	Log likelihood	-88.45	-84.24	-83.33	-83.15
	Scaled deviance	44.89	36.48	34.66	34.29
	Pearson chi-squared	40.91	23.41	22.35	21.81
	R-squared	0.42	0.62	0.62	0.64

Significantly, the new SPF forms incorporated with simulated conflicts had a better goodness-of-fit based on the four goodness-of-fit measures (i.e., log likelihood, scaled deviance, Pearson chi-squared, and R-squared) than the existing SPF. SPF form 4 consisting of AADTs on major/minor roads and rear-end conflicts performed best among the candidate models. The formula of the best-performing SPF is thus as follows:

$$\begin{aligned}\text{CF} &= e^{a} \cdot {AADT_{major}}^{b1} \cdot {AADT_{minor}}^{b2} \cdot {Conflicts_{RE}}^{c2} \\ &= e^{(-3.814)} \cdot {AADT_{major}}^{(0.231)} \cdot {AADT_{minor}}^{(0.241)} \cdot {Conflicts_{RE}}^{(0.369)} \qquad \text{Eq. (11)}\end{aligned}$$

4.1.4 Intersection operational attributes-based conflict estimation model – Approach 4

This approach was attributed by the idea that traffic conflicts can be statistically modeled without simulation modeling and runs, which could enhance a practicality in estimating the number of conflicts by saving time in building a simulation network, calibrating, validating, and running. To this end, the variables (i.e., AADTs, geometric characteristics, signal parameters, intersection performance measures) were examined its collinearity using a variance inflation factor (VIF), and Pct_{THLR}, Pct_{THRT}, Pct_{THLTRT}, Pct_{Gmaj}, Nd_{QLmax}, Nd_{VSD}, and Nd_{Stops} were thus excluded in the conflict modeling. Finally, the following 14 variables, $AADT_{major}$, $AADT_{minor}$, N_{legs}, N_{lanes}, Pct_{TH}, Pct_{LT}, Pct_{RT}, Srd_{THLT}, Srd_{THRT}, Srd_{ALL}, Pct_{Gmin}, L_{CL}, Nd_{QL}, and Nd_{VD}, were used to account for traffic conflicts. Note that rear-end conflicts were used as a dependent variable since it had the highest correlation strength with actual crash frequencies.

Based on the linear model fitting functionality of IBM SPSS software, the rear-end conflict estimation model were developed as follows.

$$\text{Rear-end conflicts} = (0.048)\cdot AADT_{major} + (0.093)\cdot AADT_{minor} + (0.513)\cdot N_{legs} + (-0.136)\cdot N_{lanes} + (0.409)\cdot Pct_{TH} + (-0.113)\cdot Pct_{LT} + (-0.298)\cdot Pct_{RT} + (-0.199)\cdot Srd_{THLT} + (-0.583)\cdot Srd_{THRT} + (0.091)\cdot Srd_{ALL} + (-0.199)\cdot Pct_{Gmin} + (-0.229)\cdot L_{CL} + (-0.118)\cdot Nd_{QL} + (0.015)\cdot Nd_{VD} \quad \text{Eq. (12)}$$

A goodness-of-fit test between simulated and model-estimated conflicts was conducted to ensure the performance of the rear-end conflict estimation model, and R^2 was 0.77 as shown in Figure 3.

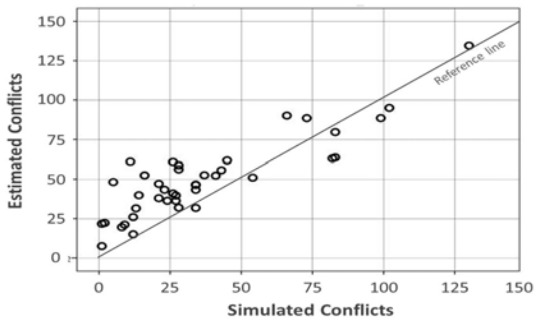

Figure 2: Scatter plot of goodness-of-fit test results

The estimated traffic conflicts based the developed conflict estimation model were used to predict crash frequencies using a NB regression form as follow (goodness-of-fit: -85.98 of LL, 39.02 of SD, 29.51 PC, and 0.55 of R^2):

$$\text{CF} = e^{a}\cdot {AADT_{major}}^{b1}\cdot {AADT_{minor}}^{b2}\cdot {ModelConflicts_{RE}}^{c2}$$
$$= e^{(-4.311)}\cdot {AADT_{major}}^{(0.257)}\cdot {AADT_{minor}}^{(0.246)}\cdot {ModelConflicts_{RE}}^{(0.418)} \quad \text{Eq. (13)}$$

4.1.5 Intersection operational attributes-based crash estimation model – Approach 5

One can argue to use the intersection operational attributes for predicting crashes by integrating them with the AADT-based SPF form. This method does not require neither simulation implementation nor conflict estimation, and directly use the microscopic operational attributes to predict crashes. To this end, a linear modeling approach was applied to calibrate the parameters of the operational attributes, and the following equation is the resulted model (goodness-of-fit: -85.06 of LL, 38.29 of SD, 25.26 PC, and 0.60 of R^2):.

$$\text{CF} = e^{-1.265}\cdot {AADT_{major}}^{(0.126)}\cdot {AADT_{minor}}^{(0.129)}\cdot {N_{legs}}^{(0.158)}\cdot {N_{lanes}}^{(0.457)}\cdot {Pct_{TH}}^{(0.111)}\cdot {Pct_{LT}}^{(-0.377)}\cdot {Pct_{RT}}^{(-0.217)}\cdot {Srd_{THLT}}^{(0.188)}\cdot {Srd_{THRT}}^{(0.445)}\cdot {Srd_{ALL}}^{(-0.150)}\cdot {Pct_{Gmin}}^{(-0.168)}\cdot {L_{CL}}^{(0.112)}\cdot {Nd_{QL}}^{(-0.169)}\cdot {Nd_{VD}}^{(-0.173)} \quad \text{Eq. (14)}$$

4.2 Prediction Performance

This study compared state-of-the-art safety assessment methods including existing (approaches 1 and 2) and enhanced methods (approaches 3 to 5) in terms of prediction performance. It should be note that the five safety assessment approaches are as follows:

- Approach 1: AADT-based safety performance function
- Approach 2: Microsimulation-based safety assessment (using traffic conflicts)
- Approach 3: Simulated conflicts-incorporated safety performance function
- Approach 4: Estimated conflicts-incorporated safety performance function
- Approach 5: Intersection operational attributes-based safety performance function

Approach 3 was best in terms of prediction performance (i.e., goodness-of-fit measures), and approaches 5, 4, 2, and 1 followed in order. The approach 3 incorporated simulated conflicts, which were expected to reflect intersection's microscopic operational characteristics by simulating real traffic volume under mimicked geometry and traffic controls, into existing AADT-based SPF form. This combination of AADTs and the simulated conflicts appeared effective to predict crashes at each intersections. This corresponds to previous surrogate safety studies indicated that conflicts can supplement safety assessment on roadways (F. J. C. Cunto, 2008; El-Basyouny & Sayed, 2013; So et al., 2015; Sobhani et al., 2013). The approach 5, which utilized all collectable intersection operational attributes to calibrate SPF, was next to the approach 3, indicating that the approach 3 was also effective to assess safety. The approach 4, which incorporated estimated conflicts into existing AADT-based SPF form, showed lower goodness-of-fit than the approaches 3 and 5 because insufficient goodness-of-fit in estimating conflicts led lower goodness-of-fit in predicting crashes by calibrating SPF. The approaches 1 and 2, as existing safety assessment methods, were insufficient to predict crashes due to a lower goodness-of-fit.

Table 5: Goodness-of-fit measures

Goodness-of-fit measures	Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
Log likelihood (LL)	-89.15	-86.59	-83.15	-85.98	-85.06
Scaled deviance (SD)	45.08	40.79	34.29	39.02	38.29
Pearson chi-squared (PC)	42.32	32.51	21.81	29.51	25.26
R-squared (R^2)	0.42	0.49	0.64	0.55	0.60

4.3 Practicality Aspect

The five safety assessment approaches were compared also in terms of its practicality representing efforts in implementing safety assessment. As indicated in Table 6, the approach 3 required significant efforts for data collection, statistical analysis, simulation coding/runs, and SSAM implementation, among the employed safety assessment approaches in this study. This is because the approach 3 requires not only to utilize existing SPF but also to produce simulated conflicts, in order to implement the simulated conflicts-incorporated SPF approach. On the other hand, existing AADT-based SPF (approach 1) was the readiest method because this does not require simulation runs and additional data collection for signal controls and driving behaviors. For the other approaches (approaches 2, 4, and 5), data collection efforts were essential, but the implementation efforts were different by the simulation-based or the statistical model-based. In this view, the approach 3 required the most significant implementation efforts, and the approach 5 was best in terms of the practicality.

Table 6: Required tasks for safety assessment

	Data collection (parameters)				Statistical analysis	Simulation coding/runs	SSAM Implement.
	Volume	Geometry	Signal	Driving			
Approach 1	○	×	×	×	○	×	×
Approach 2	○	○	○	○	×	○	○
Approach 3	○	○	○	○	○	○	○
Approach 4	○	○	○	○	○	×	×
Approach 5	○	○	○	○	○	×	×

○: necessary, ×: unnecessary

4.4 Trade-off between Prediction Performance and Practicality

With the analysis on prediction performance and practicality aspects in mind, the approach 3 was best in terms of prediction performance while it requires significant efforts in implementing the method due to the efforts in statistical modeling and simulation implementation. On the other hand, the approach 1 was straightforward to implement compared to the other approaches, but the crash prediction performance was not acceptable. The approach 2 utilized microscopic traffic simulation model through data collection, simulation coding/runs, and SSAM implementation, but using solely simulated conflicts was insufficient for safety assessment. Both approach 4 and 5 needed to conduct statistical modeling while they do not utilize simulations. Especially, the approach 5 provided fair prediction performance, which was similar to the prediction performance approach 3, while it does not require the efforts in simulation modeling.

5 Conclusions

This study developed enhanced safety assessment methods for vehicle-to-vehicle crash/conflict situations, and investigated the performances in the aspects of prediction performance and practicality. As base scenarios representing existing safety assessment methods, a volume-based crash estimation (approach 1) and a simulated conflicts-based surrogate safety assessment (approach 2) were employed. Beyond these existing safety assessment methods, three new safety assessment methods were developed and suggested to enhance either prediction performance or practicality compared to the existing safety assessment approaches: an integrated approach of simulated conflicts and volume parameters (approach 3), an estimated conflicts-incorporated SPF approach (approach 4) and an intersection operational attributes-based SPF approach (approach 5),..

Crashes were predicted at each intersection using the five approaches, and the predicted crashes were then compared with actual crash frequencies collected at 40 signalized intersections, in order to examine the prediction performance of each safety assessment approach. The implementation efforts required for conducting each approach were also reviewed by the authors, and the required efforts were examined and categorized into four aspects such as data collection, statistical analysis, simulation coding/runs, and SSAM implementation, in the view of practicality. Finally, trade-off between prediction performance and practicality of the five safety assessment approaches was discussed based on the aspects of prediction performance and practicality.

The approach 3 (integrated approach of simulated conflicts and volume parameters) and the approach 1 (AADT-based SPF) were best in terms of prediction performance and practicality, respectively. However, this study did not select one best safety assessment approach and rather investigated the advantages and disadvantages of each method in the aspects of prediction performance and practicality, to provide a reference for traffic safety engineers/researchers to select a best safety assessment method under specific circumstances. This is because selecting a safety assessment method depends on many factors including required level of detail/accuracy, time scope, knowledge of practitioner, data availability, and software availability. Even though one approach is best to predict crashes at intersections (approach 3 in this study), this approach may not be widely used if this requires significant efforts in the implementation step. Instead of providing one best safety assessment approach, this study will answer the question of practitioners that which safety assessment approach will be appropriate by considering given resources (e.g., time, labor, hardware, and software). In other words, the investigations of state-of-the-art safety assessment approaches in the aspects of prediction performance and practicality will be a reference when practitioners need to assess road safety, especially for vehicle-to-vehicle crashes at signalized intersections, and to select an appropriate method with limited resources.

Following recommendations were suggested in the perspective of enhancing the reliability of safety assessment. This study used a single network calibrated and validated with one driving behavior parameter set. Since the driving behavior (i.e., driver aggressiveness) was expected to impact on safety, there is a need to apply the proposed approaches for different simulation networks reflecting different driving behaviors. Also, experimenting with different types of signalized intersections and highway sections (without signal interruptions) will enhance the reliability of the methods used in this study while this study used 4-leg signalized intersections. Last, conducting a rank test with the subject intersections using the safety assessment approaches used in this study and identifying hot-spots based on the rank test results would be of further interest to safety practitioners.

Acknowledgement

The authors thank Dr. David Hale, David Petrucci, Dr. Joyoung Lee, Dr. Mandar Khanal, Dr. Peng Su for their helpful comments and sincere helps on this research, especially in developing a simulated conflicts-incorporated safety performance function. This research was in part supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT & Future Planning (NRF-2010-0029446).

References

AASHTO. (2010). Highway Safety Manual: American Association of State and Highway Transportation Officials.

ACHD. (2015). Ada County Highway District's traffic counts database, from http://www.achdidaho.org/Departments/Traffic/TrafficCounts.aspx

Ahmed, M., Huang, H., Abdel-Aty, M., & Guevara, B. (2011). Exploring a Bayesian hierarchical approach for developing safety performance functions for a mountainous freeway. *Accident Analysis & Prevention, 43*(4), 1581-1589.

Al-Ghandour, M. N., Schroeder, B. J., Williams, B. M., & Rasdorf, W. J. (2011). Conflict Models for Single-Lane Roundabout Slip Lanes from Microsimulation. *Transportation Research Record: Journal of the Transportation Research Board, 2236*(1), 92-101.

Cafiso, S., Di Graziano, A., Di Silvestro, G., La Cava, G., & Persaud, B. (2010). Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables. *Accident Analysis & Prevention, 42*(4), 1072-1079.
Caliendo, C., & Guida, M. (2012). Microsimulation Approach for Predicting Crashes at Unsignalized Intersections Using Traffic Conflicts. *ASCE Journal of Transportation Engineering, 138*(12), pp. 1453-1467.
Cunto, F., & Saccomanno, F. F. (2008). Calibration and Validation of Simulated Vehicle Safety Performance at Signalized Intersections. *Accident Analysis & Prevention, ELSEVIER 40*(3), pp 1171-1179.
Cunto, F. J. C. (2008). *Assessing safety performance of transportation systems using microscopic simulation.* University of Waterloo.
El-Basyouny, K., & Sayed, T. (2013). Safety performance functions using traffic conflicts. *Safety Science, 51*(1), 160-164.
FHWA. (2010). SafetyAnalyst: Software Tools for Safety Management of Specific Highway Sites, from http://www.safetyanalyst.org/docs.htm
Garber, N. J., & Rivera, G. (2010). Safety performance functions for intersections on highways maintained by the Virginia Department of Transportation.
Gettman, D., & Head, L. (2003). *Surrogate Safety Measures From Traffic Simulation Models, Final Report.* Federal Highway Administration (FHWA).
Gettman, D., Pu, L., Sayed, T., & Shelby, S. (2008). Surrogate Safety Assessment Model and Validation: Final Report (U. S. D. o. Transportation, Trans.): Federal Highway Administration (FHWA).
IBM. (2013). IBM SPSS Statistics, from http://www-01.ibm.com/software/analytics/spss/products/statistics/
ITS_Corporation. (2008). SafetyAnalyst User's Manual. *Turner-Fairbank Highway Research Center, McLean, VA.*
Kirk, A., & Stamatiadis, N. (2012). Development of Intersection Safety Exposure Estimates Through Conflict Models. *TRB 91st Annual Meeting Compendium of Papers DVD* 14.
Lee, J., Park, B., Malakorn, K., & So, J. (2013). Sustainability Assessments of Cooperative Vehicle Intersection Control at an Urban Corridor. *Transportation Research Part C, 32*, 193-206.
Lord, D., & Persaud, B. N. (2004). Estimating the safety performance of urban road transportation networks. *Accident Analysis & Prevention, 36*(4), 609-620.
Montella, A., Colantuoni, L., & Lamberti, R. (2008). Crash prediction models for rural motorways. *Transportation Research Record: Journal of the Transportation Research Board*(2083), 180-189.
Montella, A., & Imbriani, L. L. (2015). Safety performance functions incorporating design consistency variables. *Accident Analysis & Prevention, 74*, 133-144.
Nezamuddin, N., Jiang, N., Ma, J., Zhang, T., & Waller, S. T. (2010). Active Traffic Management Strategies: Implications for Freeway Operations and Traffic Safety. *90th TRB Annual Meeting Conference, Washington D.C.*
Nordback, K., Marshall, W. E., & Janson, B. N. (2014). Bicyclist safety performance functions for a US city. *Accident Analysis & Prevention, 65*, 114-122.
Ott, S. E., Haley, R. L., Hummer, J. E., Foyle, R. S., & Cunningham, C. M. (2012). Safety effects of unsignalized superstreets in North Carolina. *Accident Analysis & Prevention, 45*, 572-579.
Owen, A. (2010). Outline of GLMs, from http://statweb.stanford.edu/~owen/courses/306a/glm.pdf
Robertson, H. D. (1994). ITE Manual of Transportation Engineering Studies. *Prentice Hall, Englewood Cliffs, N.J.*
Shahdah, U., Saccomanno, F., & Persaud, B. (2014). Integrated traffic conflict model for estimating crash modification factors. *Accident Analysis & Prevention, 71*, 228-235.
So, J., Lim, I.-k., & Kweon, Y.-J. (2015). Exploring Traffic Conflict-Based Surrogate Approach for Safety Assessment of Highway Facilities. *in press at Transportation Research Record, Washington D.C., United States.*
So, J., Park, B., Wolfe, S. M., & Dedes, G. (2014). Development and validation of a vehicle dynamics integrated traffic simulation environment assessing surrogate safety. *Journal of computing in civil engineering.*
So, J. J., Park, B. B., & Yun, I. (2014). Classification modeling approach for vehicle dynamics model - integrated traffic simulation assessing surrogate safety. *Journal of advanced transportation.*
Sobhani, A., Young, W., & Sarvi, M. (2013). A simulation based approach to assess the safety performance of road locations. *Transportation Research Part C: Emerging Technologies, 32*, 144-158.
Wu, K.-F., & Jovanis, P. P. (2012). Crashes and crash-surrogate events: Exploratory modeling with naturalistic driving data. *Accident Analysis & Prevention, 45*, 507-516.