

COMPARING SIMULATED ROAD SAFETY PERFORMANCE TO OBSERVED CRASH FREQUENCY AT SIGNALIZED INTERSECTIONS

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Submitted to the 3rd International Conference on Road Safety and Simulation, September 14-16, 2011, Indianapolis, USA

ABSTRACT

Microscopic traffic simulation has been developed and applied over the past two decades with the main focus towards the design and operations of transportation systems. Recently, due to advancements in data collection techniques and microscopic algorithms, the potential of microscopic simulation as a tool for safety assessments has been under considerable debate. This type of approach may allow better knowledge regarding the chain of events preceding crash occurrences; therefore, leading to a more comprehensive methodology for safety studies when compared to traditional observational studies. This paper presented a validation effort between observed rear-end collisions and simulated traffic conflicts, as reflected by three Safety Performance Measures (SPM) namely: Time to Collision (TTC), Deceleration Rate to Avoid the Crash (DRAC) and Crash Potential Index (CPI). Three years of accident data (2007-2009) for two-hour peak (7:00AM - 9:00AM) and off-peak (9:00AM - 11:00AM) were compared to the estimated number of traffic conflicts as obtained by a microscopic simulation experiment. The results suggested that simulated SPM did not reflect the apparent decrease in observed rear-end crashes for peak and off-peak periods. This might be due to the inherently rare random characteristic of traffic accidents and the somewhat simplified microscopic environment provided by current algorithms. On the other hand, all tested SPM were capable of capturing differences in the number of accidents among the three different study sites.

Keywords: surrogate safety measures, road safety, microscopic simulation, time to collision.

INTRODUCTION

The use of microscopic traffic simulation over the last two decades has essentially focused on the analysis of the efficiency of transportation infrastructure, such as signalized intersections, arterial networks and freeway corridors. The potential of microscopic simulation in traffic safety and traffic conflict analysis was initially recognized by Darzentas et al (1980) and has gained interest mostly due to recent developments in human driver behavior modeling and advancements in real-time vehicle data acquisition.

In theory, microscopic traffic models have the potential to account for important factors that heavily influence crash occurrences, including different behavioral aspects of drivers and individual pair-wise vehicular interactions in real-time. This would provide a platform for the development of safety studies that apply a more microscopic “mechanistic” approach to improve the knowledge of crash occurrence. However, some methodological aspects of this approach need to be fully investigated including:

- Traditional microscopic car-following, gap acceptance, and lane changing algorithms have not been developed specifically to account for the full range of factors explaining the potential for crashes. Models should allow errors to occur as the result of “less-than-perfect” perception, decision-making, and action, thereby causing different levels of risk in the interactions between road-users and the environment (Archer, 2000; Archer, 2005; Xin et al., 2008).
- An objective link between simulated safety performance and observed high risk traffic events can enhance the scope of microscopic modeling as a tool for safety assessments of transportation systems.

Safety performance measures (SPMs), also known as proximal safety indicators or surrogate safety measures, have been calculated from microscopic simulation packages to reflect high risk events involving at least one vehicle in relation to a projected point of collision. The most commonly documented SPMs are TTC-time to collision (Hayward, 1972), DRAC-deceleration rate to avoid the crash (Cooper and Ferguson, 1976), PET-post encroachment time (Cooper, 1983), CPI-crash potential index (Cunto and Saccomanno, 2008) and others. The usefulness of microscopic simulation for assessing safety depends on the ability of these measures to capture complex behavioural relationships that could lead to crashes and to establish a link between simulated safety measures and observed crash risk.

The main objective of this paper is to present a SPM relative validation effort by comparing observed rear-end crashes and simulated TTC, DRAC and CPI for three urban arterial signalized intersections in the city of Fortaleza, Brazil. The underlying premise is that if simulated SPM reflects high risk behaviour in the traffic stream, then crashes tend to occur more frequently when those indicators are consistently higher. Conversely, it is expected that in non-crash situations these measures would be closer to the average for the prevailing traffic conditions and location.

SIMULATED SAFETY PERFORMANCE MEASURES

Simulated safety performance is usually expressed in terms of proximal safety indicators defined to reflect high risk events in relation to a projected point of collision. These measures are usually based on pair-wise vehicular speed and spacing attributes. The main assumption underlying the use of safety performance measures is that if one is able to detect high risk situations that occur considerably more frequently than crashes, then statistically reliable results will be possible without the need of historical crash data.

The use of safety performance measures also constitutes in essence a proactive approach to road safety studies since it is able to detect safety problems before they result in crash (Barceló et al., 2003; Dazentas et al., 1980; Perkins and Harris, 1968). Three basic categories of SPM have been identified in the literature as follows (Cunto, 2008): time based measures, required braking power measures and safety indices.

Time based measures are estimated according to a projected time of a potential collision assuming vehicles maintaining their current speeds and trajectories. The most common time based measures found in the literature are time to collision (TTC), time to accident (TTA), post-encroachment time (PET), encroachment time (ET), and gap time (GT) (Hayward, 1972; FHWA, 2003). A problem that limits the application of this safety measure is that several combinations of speed and distance can produce the same measure; therefore, inferences about crash severity become more cumbersome.

The differential speeds of vehicles at the moment of impact plays a major role in crash severity due to the kinetic energy of the system immediately before the collision. Safety measures based on the required rate of speed reduction or braking power of vehicles have a theoretical formulation to provide good estimates of potential conflicts, as well as to produce an objective platform for safety studies on which severity is a major factor. Two safety performance measures based on vehicles require braking power while in conflicts are: deceleration rate to avoid the crash (DRAC) and proportion of stopping distance (PSD) (Brian et al., 1978; Archer, 2005; Cooper and Ferguson, 1976; Darzentas et al., 1980; Gettman and Head, 2003).

Recent developments in real-time data acquisition techniques and increasing use of microscopic simulation in safety studies have fostered the development of safety indices that incorporate a temporal dimension to traditional SPMs. The fundamental assumption underlying the use of safety indices is that the conflict severity and the correspondent time exposed to such conflict can provide a better measure of safety than a single measurement, such as the lowest TTC, the highest DRAC, etc. Among the safety indices are time exposed time to collision (TET), time integrated time to collision (TIT), the unsafety density parameter (UD) and the crash potential index (CPI) (Barceló et al., 2003; Minderhoud and Bovy, 2001; Cunto, 2008).

This paper investigates one indicator of each category of SPM by estimating the number of rear-end conflicts obtained from measures of the TTC, DRAC and CPI simulated for three isolated signalized intersections for short increments of time (0.1s). TTC can be estimated using an expression of the form

$$TTC_{i,t} = \frac{(X_{i-1,t} - X_{i,t}) - L_{i-1,t}}{V_{i,t} - V_{i-1,t}} ; \quad V_{i,t} > V_{i-1,t} \quad (1)$$

where

t = time interval

X = position of the vehicles (i = following vehicle, $i-1$ = lead vehicle)

L = vehicle length

V = velocity

The deceleration rate to avoid the crash or DRAC can be defined using time-space relationships applied to a given vehicle pair as the deceleration required by the following vehicle to come to a timely stop or attain a matching lead vehicle speed in order to avoid a rear-end crash. This can be expressed as

$$DRAC_{i,t+1} = \frac{(V_{i,t} - V_{i-1,t})^2}{(X_{i-1,t} - X_{i,t}) - L_{i-1,t}} \quad (2)$$

The CPI index can be obtained using an expression of the form (Cunto, 2008):

$$CPI_i = \frac{\sum_{t=t_i}^{t_f} P(MADR^{(a_1, a_2, \dots, a_n)} \leq DRAC_{i,t}) \cdot \Delta t \cdot b}{T_i} \quad (3)$$

where,

CPI_i = crash potential index for vehicle i

t_i = initial time interval for vehicle i

t_f = final time interval for vehicle i

$DRAC_{i,t}$ = deceleration rate to avoid the crash (m/s^2) for vehicle i in time t

$MADR_i$ = maximum available deceleration rate (m/s^2) for vehicle i given conditions (a_1, \dots, a_n)

Δt = observation time interval (sec)

T_i = total simulated time for vehicle i (sec)

The parameter b in the above equation denotes a binary state variable, 1 if $DRAC_{i,t} > 0$ and 0 otherwise. Thresholds for the definition of a rear-end traffic conflict have been assumed according to studies elsewhere (Van der Horst, 1990; Hydén, 1996 and Cunto, 2008). For TTC and DRAC, a traffic conflict has been assigned for vehicle interactions resulting on TTC values lower than 1.5s and DRAC values exceeding $3.35m/s^2$.

Defining conflicts using CPI requires assumption on the maximum available deceleration rate (MADR) for each vehicle and estimates (simulation environment) of DRAC over time. For every vehicle in the simulation an individual MADR value was assigned from a truncated normal distribution for cars and trucks separately (Table 1). The values on Table 1 were obtained from field tests for different vehicles with initial speeds from 80 to 100km/h coming to a full stop

(Nielsen, J., 2007; MOVIT, 2007). DRAC values, on the other hand, were obtained from rear-end vehicle interactions as represented by a combination of geometric and traffic attributes and their relationships according to microscopic car-following, gap-acceptance and lane change algorithms. In this case a traffic conflict is detected when a given vehicle required braking effort is greater than its assigned maximum braking capability, i.e., $DRAC > MADR$.

Table 1 Assumed truncated normal distribution parameters for MADR

MADR distribution parameters	Car	Trucks and Buses
Average (m/sec^2)	8.45	5.01
Standard Deviation (m/sec^2)	1.40	1.40
Upper Limit (m/sec^2)	13.45	7.98
Lower Limit (m/sec^2)	3.45	2.05
Max. Conflict Distance (m)	100	100

SIMULATED SPM AND CRASHES COMPARISON FRAMEWORK

The framework for the tests to explore the relative validation between observed crashes and simulated safety performance is illustrated in Figure 1. This framework consists of seven steps: 1) Defining sites (intersections) and respective area of interest to be investigated, 2) Obtaining crash data for study areas, 3) Geometric and traffic attributes data collection, 4) Microscopic network coding, 5) Calibration and validation of microscopic algorithms, 6) Estimating safety performance measures for selected sites, and 7) Spatial and Temporal SPM/Crash comparison.

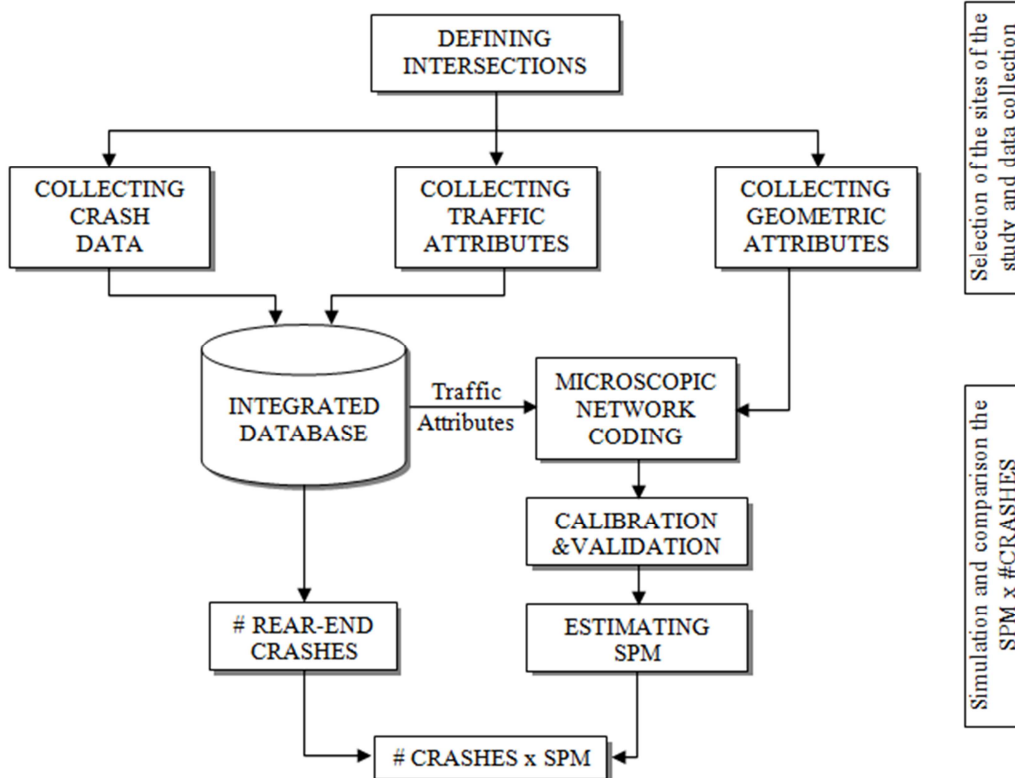


Figure 1 Framework of the steps on the relative validation process of the SPM.

Defining Intersections and Areas of Interest

The validation exercise discussed here is based on the analysis of three intersections selected based on the following criteria: type of traffic control, parking conditions and influence of other intersections. The selected intersections are signalized with actuated signal controllers to facilitate the data collection process since traffic flow, average delay and other information are easily obtained from loop detectors and the SCOOT (Split Cycle Offset Optimization Technique) system.

The influence of parking conditions on rear-end crashes was considered to be a potential source of bias since current microscopic algorithms do not consider explicitly these maneuvers in their formulation. Consequently attempts were made to select only intersections with no parking spaces and driveways within the area of interest on every approach.

The third selection criterion was related to traffic arrival and spatial dependence of intersections. In this case intersections with a considerable distance from other signalized intersections (>200meters) were selected to avoid vehicle platooning from upstream intersection and the introduction of a spatial crash dependency (bias) between entities. These factors would produce an extra level of effort to be adequately considered by current microscopic traffic algorithms.

Figure 2 illustrates the selected intersections, namely: Intersection #168 (Dedé Brasil Avenue and dos Expedicionários Avenue), Intersection #243 (Murilo Borges Avenue and Rogaciano Leite Avenue) and Intersection #250 (Murilo Borges Avenue and Raul Barbosa Avenue). All study areas are four-legged signalized arterial intersections with central medians and two to three lanes per approach.

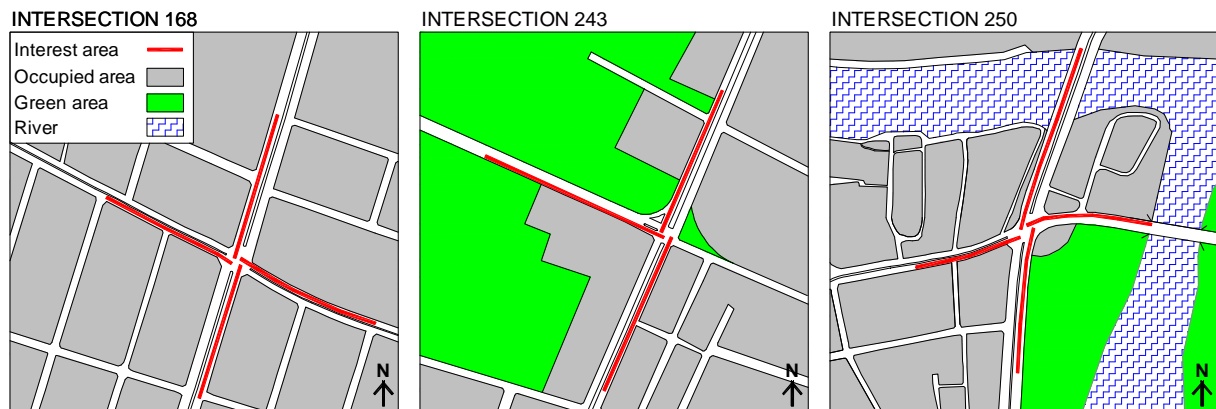


Figure 2 Selected Intersections and Area of Interest.

Areas of interested have been defined for every intersection to encompass the average queue length measured from the stop line for every approach during peak (7:00AM-9:00AM) and off-peak (9:00AM-11:00AM) periods. The average queue length obtained from SCOOT/ASTRID historical database ranged from: 140 to 150 meters on Intersection #168; 90 to 160 meters on Intersection #243; and 80 to 200 meters on Intersection #250.

Crash Data for Areas of Interest

In this study, three years of accident data (2007-2009) were collected from the municipal accident information system (SIAT-FOR) to be compared to the simulated SPM. A series of filters were then applied to select rear-end crashes only, time of the analysis, vehicle type and spatial configuration of the observed collisions.

In order to minimize random fluctuations due to different driving behavior observed on weekends, accidents recorded on Saturdays and Sundays have been removed from the dataset. An important aspect observed in many Brazilian cities is the considerable use of motorcycle for commercial purposes. This introduces a significant number of collisions involving those users that may not be adequately represented in microscopic traffic algorithms; therefore this type of crash was also removed from the dataset.

Finally, to consider target accidents within the areas of interests, two types of accident location have been investigated, as follows: 1) Accidents within intersection area and 2) Accidents within the area encompassed by the average queue length (segments). To identify the actual location of accidents observed on segments two types of information have been applied: the building number as recorded by the police and reference points provided by the SIAT system. Table 2 presents a summary of the recorded and “valid” crashes for the three years of the analysis.

Table 2 Total of recorded and “valid” crashes (2007-2009)

	# TOTAL OF CRASHES	# REAR END CRASHES
INT 168 _{Peak}	79	34
INT 168 _{Off-peak}	48	12
INT 243 _{Peak}	25	10
INT 243 _{Off-peak}	9	4
INT 250 _{Peak}	72	37
INT 250 _{Off-peak}	40	19

Geometric and Traffic Attributes

The geometric attributes for network coding were collected using the software Google Earth® and complemented by field measurements to confirm geometric aspects such as the number and lane width, central median width and intersection angles. The basic traffic input data obtained from the adaptive traffic control system (ATCS) SCOOT/ASTRID database include average traffic flow aggregated over 15 minutes per approach, cycle length and average delay. Table 3 presents a sample of the traffic attributes as obtained from the ATCS for intersection #168.

Table 3 Sample of traffic attributes for intersection #168

Intersection approach	Day Date (dd-mmm-yyyy)	Start Time (hh:mm)	End Time (hh:mm)	Average Flow (veh/h)	Average Delay (veh)	Average Vehicle Delay (s)
00168:a	FR 6-Mar-2009	07:00	07:15	688	21.9	114.5
00168:a	MO 9-Mar-2009	07:00	07:15	735	21.9	107.2
00168:a	TU 10-Mar-2009	07:00	07:15	762	20.5	96.8
00168:a	WE 11-Mar-2009	07:00	07:15	785	20.9	95.8

The dataset used for estimating traffic attributes was obtained from a sample of 80 typical days from the year of 2009. Similar to the collision dataset, the traffic sample was filtered and compiled for the months, days and hours of the study period. Additionally the dataset was statistically treated to identify outliers and missing observations using box plot tools as proposed by Oliveira (2004). Using ATCS CCTV cameras, four hours of traffic survey (7:00AM - 11:00AM) were performed for each intersection to estimate the percentage of heavy vehicles (trucks and buses), as well as traffic directional split. Table 4 presents a summary of the operational attributes used for the selected intersections on the simulation experiment.

Table 4 Summary of the Traffic Attributes Input

	Flow Peak (veh/h)	Flow Off-peak (veh/h)	Movement (%)			Trucks and Buses (%)	Cicle Time Peak (s)	Cicle Time Off-peak (s)
			Left	Front	Righth			
00168:a	811	833	21	72	7	6	176	160
00168:b	793	855	-	82	18	14	176	160
00168:c	1309	1060	20	75	5	8	176	160
00168:d	733	759	-	86	14	16	176	160
00243:a	1095	1202	27	30	43	2	160	144
00243:c	874	637	34	64	2	6	160	144
00243:d	705	613	34	59	6	4	160	144
00250:a	1610	1670	-	86	14	6	176	144
00250:b	910	905	35	53	12	4	176	144
00250:c	1017	954	-	78	22	10	176	144
00250:d	768	728	36	64	1	6	176	144

Platform for Estimating Safety Performance Measures

The simulation platform for estimating safety performance measures used in this research (VISSIM 5.30-03) is based on psychophysical driving algorithms. In particular, VISSIM’s car-following model considers four types of regimes where drivers adjust their desired spacing and speeds through changes in their acceleration/deceleration rates. It has been recognized that despite its limitations to reflect real crashes, these algorithms are able to generate a large variety of driving interactions reflecting a considerable heterogeneity in the traffic stream (FHWA, 2003; Archer, 2005; Cunto, 2008).

Geometry and traffic attributes were coded in VISSIM for every intersection during the two hours peak and off-peak periods. The average traffic flow for every approach was considered at 15 minutes intervals (8 intervals for each period) to account for traffic variability using the information described in the previous section.

Cunto and Saccomanno (2008) present a study for calibrating and validating VISSIM car-following, gap-acceptance, and lane-change parameters based on observed CPI as obtained from vehicle tracking data. The results of this calibration/validation exercise yielded “best estimate values” for those inputs that were found to be statistically significant in explaining safety

performance measures as obtained from the simulation. These values were assumed for this research and are found summarized in Table 5. VISSIM default values were used for those inputs not found to be statistically significant for simulating safety performance.

Table 5 Calibrated VISSIM input parameters (Cunto, 2008)

Input parameter	Calibrated	Description
Desired deceleration	-2.6	Maximum deceleration (m/s ²) drivers are willing to apply in ‘normal’ (not emergency) situation
CC0	3,0	Standstill distance (m); defines the desired distance between stopped cars
CC1	1,5	Headway time (s); defined as the minimum time a driver wants to keep from the lead vehicle; the higher the value, the more cautious the driver; CC0 and CC1 are combined to express the safety distance

A total of six simulation scenarios, two for each intersection has been considered. For each intersection scenario 10 simulation runs were performed using different number seeds to estimate the variability among TTC, DRAC and CPI measures. Individual vehicle information to estimate SPMs, such as vehicle coordinates, vehicle type, speed, length, acceleration/deceleration rate, headway, leading vehicle, preceding vehicle and others, have been recorded for every 0.1second time interval. These individual vehicle variables were compiled and processed using a visual basic application to obtain estimates of TTC, DRAC and CPI for every 0.1 seconds and recording traffic conflicts as described earlier in the manuscript.

SIMULATION RESULTS

For this validation exercise, the average number of rear-end conflicts resulting from 10 simulation runs using different number seeds for each scenario (2 hours peak and off-peak period) was compared to rear-end crashes recorded for the same two hours intervals during three years (2007-2009) for each intersection. The average number of conflicts was normalized to provide an estimate of the total number of conflicts for the same time period of the crash data (739 days). Table 6 presents the number of observed crashes and respective average number of conflicts and conflict/flow ratio for each SPM, followed by the average traffic flow and the flow of simulation.

Table 6 Number of crashes, average flow and average simulation results

Scenario	# Crashes	Average flow (veh/h)	#Simulated vehicles	# Conflicts (three years)			# Conflicts/vehicle (x10 ³) (coefficient of variation)		
				TTC	DRAC	CPI	TTC	DRAC	CPI
<i>INT#168_{Peak}</i>	34	3647	7300	147652	26826	2882	27.4 (0.06)	5.0 (0.15)	0.5 (0.53)
<i>INT#168_{Off-peak}</i>	12	3507	7026	139523	24239	3178	26.9 (0.06)	4.7 (0.16)	0.6 (0.44)
<i>INT#243_{Peak}</i>	10	2673	5117	67766	14780	739	17.9 (0.11)	3.9 (0.13)	0.2 (1.08)
<i>INT#243_{Off-peak}</i>	4	2452	4645	67619	16406	1109	19.7 (0.09)	4.8 (0.13)	0.3 (0.73)
<i>INT#250_{Peak}</i>	37	4308	8412	178173	47518	6725	28.7 (0.07)	7.6 (0.08)	1.1 (0.38)
<i>INT#250_{Off-peak}</i>	19	4258	8138	151865	41680	6429	25.3 (0.05)	6.9 (0.08)	1.1 (0.33)

In the analysis for peak and off-peak periods it has been noted that the apparent decrease observed in accident data was not directly reflected on the number of conflicts regardless of the SPM tested. Simulated conflicts appear to be consistent with small changes presented in traffic flows between peak and off-peak scenarios (50 to 221veh/h) although these indicators did not adequately reproduced the downward trend in collisions as stated before. Part of this inconsistency can be accredited to the rare random nature of accidents as well as to the somewhat simplified simulation environment.

When comparing the three SPM it can be noted that TTC and DRAC thresholds (1.5s and 3.35m/s², respectively) yielded considerably more vehicles in conflicts when compared to CPI. Furthermore, the results have indicated that CPI based conflicts presented the highest variability among the indicators. This variability can be attributed to the fact that this indicator has two stochastic components, the first being associated with the process of generation of vehicles in the simulation (random seed generation) and second associated with the distribution for MADR shown in Table 1.

A paired t-test showed no statistical difference for any of the indicators between peak and off-peak periods. In this case, another possible analysis can be done by estimating the conflict/flow ratio to the combined peak and off-peak periods (Table 7).

Table 7 Number of crashes and average simulation results – combined scenarios

	# Crashes	#Simulated vehicles	# Conflicts/vehicle (x10 ³)		
			TTC	DRAC	CPI
INT#168	46	14327	27.1	4.8	0.6
INT#243	14	9763	18.8	4.3	0.3
INT#250	56	16550	27.0	7.3	1.1

The comparative analysis between intersections suggests a fairly reasonable consistency between the estimated numbers of conflicts and observed number of crashes. In general, higher levels of observed crashes have implied on higher number of traffic conflicts for all the three tested SPM. Similar trend has been observed with respect to average flow, crashes and SPM, thus reinforcing the generally accepted notion that accidents and traffic conflicts tend to increase with exposure.

The results from Table 7 also suggest that Intersection #243 presented the lowest number of conflicts per vehicle regardless the safety indicator when comparing to the other intersections. This can be explained by two factors, namely: 1) The existence of only three approaches at Intersection #243 resulting in less rear-end interactions at the study area; and 2) There is a protected right-turn movement (island) on the southbound therefore resulting on a lower number of rear-end interaction on that approach.

CONCLUDING REMARKS

This paper presented a validation effort between observed rear-end collisions and simulated traffic conflicts as reflected by three Safety Performance Measures (SPM), namely: Time to Collision (TTC), Deceleration Rate to Avoid the Crash (DRAC) and Crash Potential Index (CPI). Three isolated signalized arterial four-legged intersections from Fortaleza city, Brazil

were selected for this study. Three years of accident data (2007-2009) for the morning peak (7:00AM - 9:00AM) and off-peak (9:00AM - 11:00AM) periods were compared to estimate the number of traffic conflicts as obtained by a microscopic simulation experiment.

The results suggest that simulated SPM did not reflect the apparent decrease in observed rear-end crashes for peak and off-peak periods. This might be due to the inherently rare random nature of traffic accidents which causes considerable overdispersion in traffic counts and the somewhat simplified microscopic environment provided by current algorithms. On the other hand, the all tested SPM were capable of capturing differences in the number of accidents among the three different sites.

Another important factor in the analysis was the behavior of the CPI index which had lowest number of conflicts between the three indicators. This result can be credited with the fact that the calculation of this indicator is influenced by two distinct random components. Additionally, CPI was found to present the highest variability among the tested measures, thus, it is expected that when using CPI one may need to increase the number of simulations on the experiment to obtain meaningful results.

The overall results indicate a potential for application of microscopic simulation tool for analyzing the performance of road safety. It is recommended however to expand the number of intersections and the period of analysis as well as to consider other components such as the presence of parking lots and a wider range of vehicle types. Another important aspect to be considered is the use of safety performance models to provide better estimates of the expected number of crashes to every intersection thus reducing the natural overdispersion found on historical crash data.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Brazilian Council for Scientific and Technological Development (CNPq) for funding this research and Mr. David Duong for providing valuable comments and suggestions to this manuscript.

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