



EVALUATION OF SAFETY PERFORMANCE IN URBAN NETWORKS: A CASE STUDY OF FORTALEZA CITY/BRAZIL

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ABSTRACT

Road safety performance is usually not objectively considered in traditional transportation planning process due to a myriad of problems regarding the methodologies to estimate the number of accidents on urban transportation networks. Conventionally, efforts regarding the assessment of road safety performance have been accomplished with the use of safety performance functions (SPF). This type of statistical modeling approach has been very useful when focused on isolated road entities such as intersections and road segments, mostly because it can reasonably deal with some of the stochastic problems related to the rare and random nature of crashes. Advances in data collection and spatial manipulation as well as modeling techniques have been fostering studies to support the use of SPF for safety assessment of urban networks. This paper investigates the use of SPF as a tool to evaluate different transportation planning scenarios for urban road networks. Initially, a geographic crash database, geometric and operational attributes of the network database were consolidated on a Geographic Information System (GIS) platform and then used for developed SPF for links (road segments) and nodes (intersections) of the urban road network of Fortaleza city, Brazil. Calibrated functions were implemented on a sample network modeled using macroscopic model TransCAD. A residual analysis was performed using observed and estimated crash frequency. Finally, tree hypothetical scenarios were applied to the network in order to explore the sensitivity of the safety performance obtained from this modeling exercise. The results shows that possible to plan for the implementation of additional measures to minimize the increase in crashes for the critically affected in road network, links and nodes within SPF. Some important pitfalls and limitations in the application of SPF on computerized transportation networks were highlighted in the research. The most important is the dependence of estimation of accidents with AADT of the estimation process. Although additional work needs to be done regarding the integration of traffic safety models into the urban transportation planning process, the product of this research should help other researchers pursue interesting and useful areas of research that would help, at the planning stage, to reduce the number and the severity of collisions on urban roads



1. INTRODUCTION

The traditional transportation planning process comprises procedures to estimate transport demand and its interaction with network supply enabling forecast of possible transportation scenarios. It is recognized that this process presents a reasonably well defined methodology for estimating performance measures mostly related to the level of service of traffic flow. Unfortunately, road safety performance is usually not objectively considered in this framework due to a myriad of problems regarding the methodologies to estimate the number of accidents, in a proactive approach, on urban transportation networks (Tarko, 2006; Lord and Persaud, 2004; Lord, 2000).

In Brazil, programs aimed at reducing the frequency and severity of accidents in urban areas have traditionally been reactive, i.e., focused on roadway operation. Ideally, the expected number of accidents should be estimated during the planning process, thus potentially dangerous elements can be identified and accordingly addressed, preventing or reducing the chances of road crashes. (Sayed et al., 2004).

The evaluation of road safety performance in the planning process can be divided according to the level of aggregation of variables involved. The aggregate modeling in areas such as traffic analysis zones (TAZ) would allow the estimation of crashes on the aggregated level. However, factors that contribute directly to the crashes may be related to a more disaggregated level. Conventionally, efforts regarding the assessment of road safety performance have been accomplished with the use of safety performance functions (SPF). This type of statistical modeling approach has been very useful when focused on isolated road entities such as intersections and road segments, mostly because it can reasonably deal with some of the stochastic problems related to the rare and random nature of crashes (AASHTO, 2010; Hauer, 2002; Lord, 2000).

Micro level SPF represents a reasonable option as they include road and traffic characteristics of individual links and nodes. According Song et al. (2015), micro-level crash analysis could lead to better insight about factors that closely contribute to crashes, such as geometric design of segments and intersections, and provide more direct measures and implications than macro-level zonal CPMs could for improving traffic safety. This approach also allow to comprehensively conduct network screening, crash hotspot identification, as well as system wide countermeasure prioritization. Advances in data collection and spatial manipulation as well as modeling techniques have been fostering studies to support the use of SPF for safety assessment of urban networks.

This paper investigates the use of SPF as a tool to evaluate different transportation planning scenarios for urban road networks in Brazil. To achieve this objective, the consolidation of a geographic database was required to in the following section develop SPF, which describes the relationship between the number of crashes and the most important independent variables such as traffic flow, lane configuration for different types of intersections and road segments.

2. SAFETY PERFORMANCE MODELLING AND TRANSPORTATION PLANNING

Considerable efforts have recently been made to incorporate safety considerations into transportation planning practice (Washington et al., 2006; Herbel et al., 2009). The state-of-the-art crash prediction techniques are limited to road entities of a single type, which is clearly reflected in Parts C & D of the Highway Safety Manual (HSM). This important manual provides a collection of SPF that are largely focused on estimating the expected crash frequency of individual sites (AASHTO, 2010).

Although safety consideration can be incorporated into planning in many ways, safety prediction must be present in all alternatives of a planning process. Recently, an increasing research effort is being focused on a more aggregated level of crash analysis such as traffic accident zones (TAZ). This approach seems to be more suitable for long-term planning to evaluate the safety impacts of land use



and socioeconomic factors (Tarko, et al., 1996; Hadayeghi, et al., 2003; de Geuvara, et al. 2004). Although some of these models include transportation characteristics (network density, AADT, etc.) the aggregate representation of the transportation infrastructure does not easily allow modeling infrastructure-specific solutions.

From another perspective, Song et al. (2015) shows the safety problem is anyhow a microscopic problem and the direct contributing factors of any road crash could be related to micro-level factors for a specific road segment or intersection, or the driver-vehicle units involved. Therefore, micro level SPF represents a reasonable option as they include road and traffic characteristics of individual links and nodes. In contrast to macro level SPF, a solution to estimate zonal safety situation is summing up crash predictions of all the road entities (i.e. road segments and intersections) located within the zones of interest.

2.1. SAFETY PERFORMANCE FUNCTIONS

Safety performance functions are statistical models that use data to express the safety of a given reference population (road segments, intersections, grade crossings, etc.) as a function their traits (traffic, geometry, operation).

The parameters of SPF cannot be estimated by the traditional ordinary least squares or weighted least squares regression methods. This is because the assumptions for these methods are violated by the discrete, non-negative nature of accident count data and the reality that the variance in the number of accidents increases as the traffic flow increases. Thus, it is now common to estimate the coefficients of SPF by using maximum likelihood methods to calibrate what are referred to as generalized linear models (GLM) (Lord and Persaud, 2000).

Due to its flexibility in specifying the probability distribution for the random component GLM are especially useful in the context of traffic safety, for which the distribution of accident counts in a population often follows the Poisson or negative binomial distributions. Following a review of various model forms used in the literature and applying selected model forms to the data, the following model form was used:

$$\ln(E\{k\}) = \ln(\beta_0) + \beta_1 \ln(AADT) + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_p X_p \quad (1)$$

where $\ln(E\{k\})$, natural log of accidents frequency per unit of time; AADT, average annual daily traffic; X_j , explanatory variables ($j=2, \dots, p$); β_j , model parameters ($j = 0, \dots, p$). The model form in Eq. (1) is consistent with the non-linear relationship between collisions and traffic intensity (measured in this case by AADT) which has been suggested by other researchers (Hadayeghi, 2010).

The parameters are usually estimated by maximizing likelihood. As explained by Hauer (2015), this approach estimate is not the most probable value of the parameter; it is that value of the parameter which makes the observed values most probable. It is in this sense that the parameter value is best supported by the data. To go to the next step and say which parameter value is most probable one would have to have some prior information about the probability of parameters and a foot in the Bayesian camp of statisticians,

The weakness of the likelihood is in the need to make specific, detailed, and explicit assumptions about the probability distribution that generated the accident counts. In traffic safety studies, the standard Poisson regression model has traditionally been the starting point for analysing crash data. Assuming a Poisson distribution for accident data with problems of over-dispersion, would result in an underestimation of the standard error of the regression coefficients, which can lead to a biased selection of covariates. A common approach to address the over-dispersion problem is to consider random effect or mixed Poisson models such as, the popular negative binomial (NB) model also known as the Poisson-Gamma model (Badran and Miranda, 2015).



The NB distribution is based on four assumptions: (i) that, as before, the accident counts on every unit are Poisson distributed, (ii) that the μ 's of the units in each population (real or imagined) are different, i.e., that $V\{\mu\} > 0$, (iii) that the diversity of the μ 's in each population can be well approximated by a Gamma distribution and (iv) that the "shape" parameter of the gamma distributions for all populations behaves in a specific manner. This distribution is consistent with the image of populations of units with diverse μ 's. Each crash count in the data is an observation from a probability distribution, the μ of which is one of the μ 's from that population.

According Hauer (2015), when in SPF modeling the focus is on applications attention shifts from parameters to estimates and predictions of $E\{\mu\}$ and of $V\{\mu\}$. This change of focus opens the door to the use of other objective functions. Now it is not the parameter value and the testability of statistical hypotheses about it that are of interest; now one wants the model to produce good estimates and predictions of $E\{\mu\}$ and $V\{\mu\}$ for use in practice. Thus, when the purpose of SPF development is to support practical road safety management, quality of fit rather than maximization of likelihood may be the preferred alternative objective functions, they proved be simple and attractive

The fit of a model is judged by its residuals (the differences between the number of recorded accidents and the number fitted by the model equation). A model is thought to fit well if the residuals are around zero (Hauer, 2015). There are many ways in which this tightness of packing is measured. Commonly used are single-number measures of goodness-of-fit. Among these stand out the Pearson product moment coefficient between observed and predicted crash frequencies. Pearson's product moment correlation coefficient, usually denoted by r , is one example of a correlation coefficient. It is a measure of the linear association between two variables that have been measured on interval or ratio scales. Another important tool for checking model adjustment is the cumulative residual plot (Cureplot).

The cumulative residual method is tied to the examination of residuals after regression constants were estimated. Its purpose is examine whether the chosen functional form indeed fits the explanatory variable along the entire range of its values represented in the data and ascertain whether a candidate explanatory variable, one not yet used, should be introduced into the model equation. The central idea is that even when the usual plot of residuals does not show any systematic drift, by examining the cumulative residuals, potentially important patterns may emerge (Hauer and Bamfo, 1997). The plot of cumulative residuals should oscillate around 0, end close to 0, and not exceed the ± 2 standard deviation.

3. SAFETY PERFORMANCE IN DIGITAL URBAN NETWORK

Lord and Persaud (2004) represented road networks as simplified digital networks using the transportation modeling package EMME/2, which allowed the estimation of flow on the network links. They applied developed SPF for links and nodes by Lord (2000) in this digital network. The results indicated that it is possible to predict accidents on digital transport networks using SPF, but confirmed the fact that forecast accuracy depends on the traffic flow estimates provided by the modeling tool.

The Indiana Department of Transportation (INDOT) has been trying to link SPF to the long-term planning process of the state network through the GIS-based planning tools. The main idea is safety prediction with SPF as a process executed in parallel to the traffic demand prediction. The addition of the safety prediction component allows evaluating alternative planning solutions from the standpoint of traffic and safety (Tarko, 2006).

In Safety Management System, one of the first steps is to estimate the number of trips on network. A product of the estimation process is the so-called origin-destination matrix (OD matrix). This information corresponds to the number of trips between pairs of zones in a geographic region in a

reference time period. Traditionally, the OD matrix has been estimated through direct methods, such as home-based surveys, road-side interviews and license plate automatic recognition. These direct methods require large samples to achieve a target statistical error, which may be technically or economically infeasible. In an attempt to reduce these problems, alternatively, one can use a statistical model to indirectly estimate the OD matrix from observed traffic volumes on links of the transportation network.

The purpose of using the synthetic methods is to suppress the disadvantages through the use of traffic flow information along the road network, as described by Ortuzar and Willumsen (2011) is a very attractive source of data, since its obtaining is performed at relatively low cost and can be done automatically and requiring little amount of human resources, as in the case of networks monitored by a central traffic control.

Lord and Persaud (2004) demonstrated some important pitfalls and limitations in the application of SPF on digital transportation networks. The principal shows the volumes flows of transportation planning software programs can be inaccurate and this, of course, will lead to an inaccurate appraisal of network safety. Therefore, if several alternative scenarios are being evaluated, and the number of predicted collisions is one of the evaluation criteria, it is advisable to conduct a sensitivity analysis that reflects the uncertainty in the estimates of predicted flow and, therefore, predicted collisions.

4. METHODOLOGY

This study proposes, initially, a database consolidation, on a Geographic Information System (GIS) platform, with crash data, observed volume, physical and operational attributes. This dataset is then applied for calibrating SPF for links (road segments) and nodes (intersections) of the urban road network of Fortaleza city, Brazil. These functions were implemented on a sample network modeled using macroscopic model TransCAD. A residual analysis was performed using observed and estimated crash frequency. Finally, tree hypothetical scenarios were applied to the network in order to explore the sensitivity of the safety performance obtained from this modeling exercise. Figure 1 shows a methodology process used in this paper and safety prediction with SPF as a process executed in parallel to the traffic demand prediction.

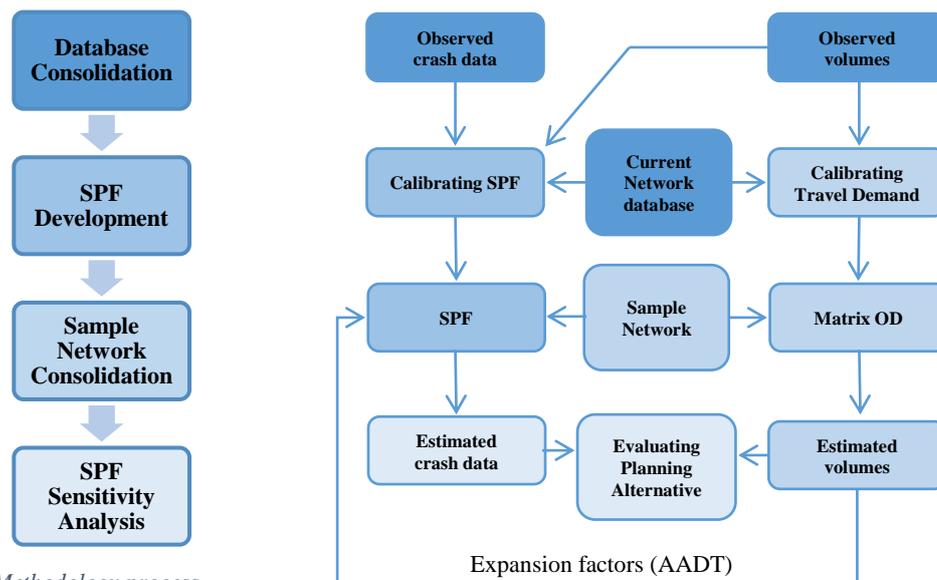


Figure 1: Methodology process

4.1. Database Consolidation

Crash data for 2011 were obtained from the Accident Data System (ADS) of the Traffic Division of Fortaleza city, Brazil. These data were geocoded on a newly updated road base on a Geographic



Information System (GIS) platform, resulting in a high and accurate georeferencing rate data (Gomes et al., 2015). The road database also has information on the physical characteristics of the road network of Fortaleza city such as number of lanes, median configuration, etc.

Traffic volumes (2011-2014) were obtained from the Traffic Division of Fortaleza City. Such data was collected from 642 loop detectors located throughout the city. The data included the annual average daily traffic (AADT) based on permanent 15-minute counts from inductive loops. The database used for the development of SPF included 151 signalized intersections, 128 unsignalized intersections, 103 urban two way segments, and 275 urban one way segments. Table 1 and 2 provide a summary of characteristics of the sample used in the study.

Table 1: Descriptive analysis of Crashes.

Group	Number of observations	Crashes			
		Avg	Min.	Max	S.D.
Signalized Intersection	151	11.7	0	54	11.16
Unsignalized Intersection	128	6.83	0	28	6.81
Two way	103	3.84	0	25	4.76
One way	275	1.16	0	6	1.36

Table 2: Descriptive analysis of data.

Group	AADT				Number of lanes				Lenght (m)			
	Avg.	Min.	Max	S.D.	Avg.	Min.	Max	S.D.	Avg.	Min.	Max	S.D.
Signalized Intersection	32,981	3,455	69,963	12,613	11.64	8.00	20.00	3.25	-	-	-	-
Unsignalized Intersection	15,989	1,071	34,428	7,801	8.48	8.00	16.00	1.72	-	-	-	-
Two way segment road	27,453	12,570	43,355	7,009	4.63	2.00	8.00	1.29	160.58	9.15	1010.57	137.69
One way road segment road	10,747	137	22,993	4,454	2.25	2.00	5.00	0.61	110.72	18.57	289.65	37.95

4.2. Model Development

Four different model types were developed and applied. The first and second model types were used for predicting crashes at nodes that represent signalized and unsignalized intersections, respectively. The third and fourth types were utilized for predicting crashes on links that represents two way and one way urban road segments, respectively.

In this research effort the SPM were developed assuming both standard Poisson and negative binomial model error structure. The overdispersion parameter (σ_d) was applied to indicate the most adequate error structure. Values of σ_d greater than 1 indicate higher data dispersion in the assumed distribution (Poisson or negative binomial). The results indicated σ_d values between 2.01 and 7.42 for models assuming Poisson distribution and 1.13 and 1.19 for models with the negative binomial distribution. Hence, NB model proved to better perform and more appropriate in this analysis.

The SPF parameters were estimated by maximum likelihood method (Hauer, 2002; Lord, 2006). The final models specification was obtained by systematically removing statistically insignificant variables. The goodness-of-fit was evaluated with Pearson Product Moment Coefficient (r) and Cureplots (Figure 3 to 7). Table 3 provides a summary of best performance models for each group used in the study.

Table 3: Models Parameter estimation.

Variable		Model			
		1	2	3	4
alfa	ln(alfa)	-3.20	-4.04	-7.62	-7.41
	Coef.	0.0409	0.0177	0.0005	0.001
	$\hat{\sigma}_\beta^{(*)}$	0.20	1.48	3.34	1.33
AADT	Coef.	0.40	0.63	0.82	0.60
	$\hat{\sigma}_\beta$	0.16	0.15	0.32	0.15
Number of lanes	Coef.	0.12	-	-	0.46
	$\hat{\sigma}_\beta$	0.021	-	-	0.09
Lenght	Coef.	-	-	0.0033	0.008
	$\hat{\sigma}_\beta$	-	-	0.0007	0.001
σ_σ		1.15	1.19	1.14	1.13
r		0.73	0.23	0.33	0.50

coefficients statistically significant ($\alpha=0.05$)

(*) standard-error

The average annual daily traffic (AADT) is the principal variable in all models, followed by the length (segment models) and number of lanes (signalized intersection and one-way segment models). Analyzing the Pearson Product Moment Coefficient the signalized intersections model showed the best goodness-of-fit followed by one-way road segment model.

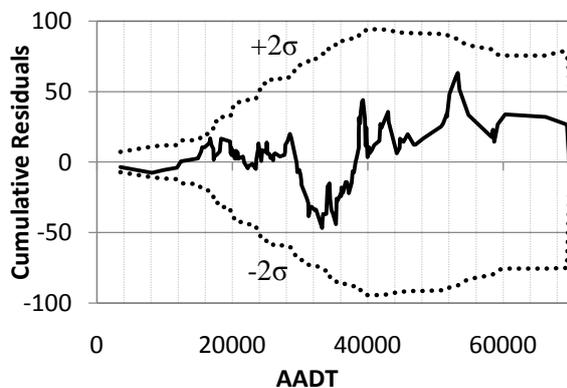


Figure 1: Cumulative Residuals signalized intersections

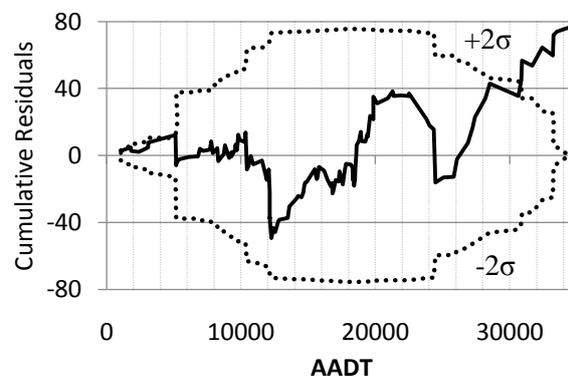


Figure 2: Cumulative Residuals unsignalized intersections

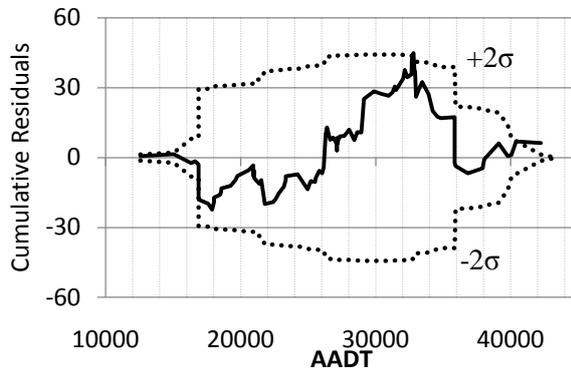


Figure 3: Cumulative Residuals for 2 way roads segments

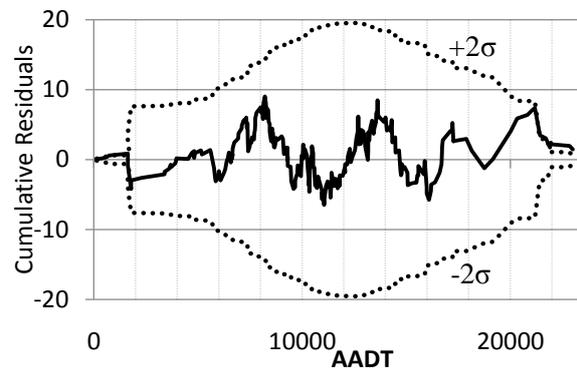


Figure 4: Cumulative Residuals for 1 way roads segments

In general, plot of cumulative residuals should oscillate around 0, end close to 0, and not exceed the ± 2 standard deviation (σ). If there are ranges of a variable where the CURE plot is consistently increasing or consistently decreasing, the fit in that range is poor and may be improved by a suitable modification of the functional form. A vertical jump in the CURE plot indicates an outlier. This should trigger a detailed investigation of that data point. All developed SPF showed adequate performance evaluating CurePlots except the model of unsignalized intersections, that presented an overestimation for $30,000 < \text{AADT}$. The endpoint is not near 0, indicates that there is something wrong with the estimated regression constant. In this case the SPF is not appropriate and needs to be replaced by a function that can rise more steeply near the origin and will have lower values for larger AADT. The CurePlot Signalized model show that for $30,000 < \text{AADT} < 40,000$ the count of accidents tends to be larger than the predicted values, and the opposite is true when $40,000 < \text{AADT}$.

4.3. Sample Network

The sample network selected has its signalized intersections controlled using a scoot system available at the Traffic Control Center (CTAFOR). A synthetic OD matrix estimation was obtained using CTAFOR traffic flow information and the Nielsen method (1993), implemented in TransCAD 4.5, which is an important demand modeling tool based on GIS-T platform (Geographic Information System for transport) used in planning and transport operation. This method rebuilding the synthetic OD matrix based on minimizing the absolute difference between the observed volume and the volumes allocated from the OD matrix reconstructed. It is an iterative process, dependent on prior knowledge of a seed OD matrix, and in a first iteration, the allocated volumes correspond to this seed, this method is dependent on a seed OD matrix; if not provided there will be no reconstruction.

There was no information on the seed matrix area, then an unitary OD matrix seed (0-1) was applied on the first interaction. The limitation of this assumption is to consider the same proportion of travel between the OD pairs. The synthetic OD matrix was subsequently applied to estimate observed traffic volumes on links of the transportation network. This methodology resulted in the reconstruction of all network link flows. Figure 7 shows the sample network layout, its major components as well as a comparison among observed and modeled traffic flows.

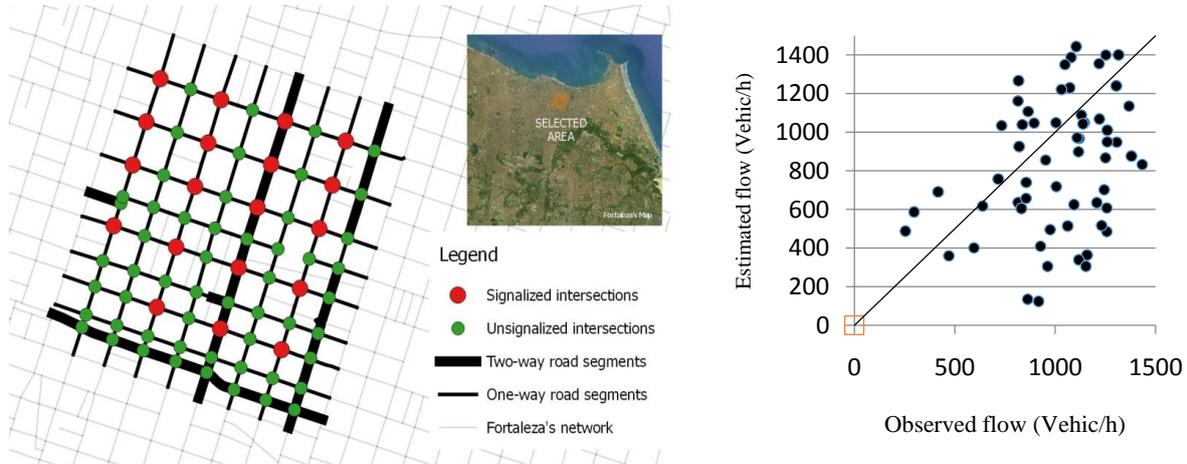


Figure 5: Sample network

The results show a trend of underestimation link flows. A hypothesis for this difference is associated with the limitations of TransCAD on the volumes reconstruction when there is little or no information about the area regarding the seed matrix. In practice, the Nielsen method has been studied in some work and some researchers have claimed that achieved good results with its use. However, in some situations in an attempt to ensure balance in the user network, the values of estimated and observed flows are different, not even respecting the restrictions on maximum permissible error. Also, it is possible to observe in extreme situations that travel no longer estimated that the equilibrium conditions are obeyed (Nielsen, 1998).

The peak hour predicted flows (travel demand output) were expanded to AADT values using expansion factors computed from traffic counts on the physical network. Since the values are estimates computed from actual counts, the sum of inflows at intersections does not exactly equal the sum of outflows for each intersection. Nonetheless, they were deemed to be close enough for the purpose of this study. These AADT were used as input in the SPF. The number of crashes at nodes was estimated with the signalized and unsignalized intersections models. Moreover, the number of crashes for the links was estimated with the one-way and two-way road segments models. The application results of the models on sample network are presented in Table 4.

Table 4: Predicted and actual number of crashes on sample network

Component	Observed	Accidents		Accidents/ Component		
		Estimated	Difference	Observed	Estimated	Difference
Signalized						
Intersection (25) ¹	107	141.88 (10.83) ²	-34.88	4.28	5.68	-1.40
Unsignalized						
Intersection (48)	138	233.74 (5.45)	-95.74	2.88	4.87	-1.99
Two way road segment (46)	34	50.66 (1.95)	-16.66	0.74	1.10	-0.36
One way road segment (212)	91	104.95 (1.87)	-13.95	0.43	0.50	-0.07
Total	370	531.22	-161.22			

(¹) number of components

(²) standard deviation.



The results show that, for this sample network, the models overestimated the number of accidents for all groups. A possible reason for the problem is the excess of “zero accidents” that the model cannot predict. The difference between observed and estimated crash frequency can be attributed to possible bias brought from the stage of reconstruction of flows as well as the expansion factors used in the output data of the travel demand modeling.

4.4. Sensitivity Analysis

Within the urban planning process, evaluating different scenarios is an important step in order to explore different strategies to be implemented. This different strategies need to be compared using different transportation dimensions such as mobility, safety and environmental aspects. This study have also focused on investigating the sensibility of SPF applied to different transportation scenarios for urban digital networks. In this exercise, four hypothetical scenarios were evaluated.

Scenario 0 represents the original layout for the sample network. In scenario 1 was implemented a tactical intervention. It has changed the configuration of two corridors, which are no longer two-way and have become one-way. The major corridor was planned to receive an exclusive bus lane. In this new configuration, this corridor has three lanes in the north-south direction. The other corridor has two lanes in the south- north direction and six new signalized intersections.

Scenario 2 comprises the implementation of an urban traffic generator which led to an increase in the number of vehicle-trips in the area. A total of 3.300 vehicle-trips were added to those of the original scenario representing an increase around 25% in vehicle trips. This intervention has a more strategic level (long-range planning). In both scenarios and their combinations, the new flows were assigned under the assumption that the estimated flows were predicted accurately by TransCAD. The product of this assignment was expanded to AADT flows with an average factor computed from the Fortaleza data. The predicted number of crashes from the two-, one-way road, unsignalized and signalized intersection models were applied on scenarios. Table 5 presents the predicted number of crashes in original layout and the proposed scenarios. The last column of the table shows the combined deployment scenario 1 and 2.

Table 5: Predicted number on accidents

Component	Scenario 0	Scenario 1	Scenario 2	Scenario 1+2
Signalized Intersection	141.88	163.28	154.65	200.81
Unsignalized Intersection	233.74	213.66	284.98	320.16
Two way road segment	50.66	21.63	59.21	38.40
One way road segment	104.95	121.65	110.65	176.73
Total	531.22	520.22	609.49	736.10

Based on the results shown in Table 5, it would be possible to plan for the implementation of additional measures to minimize the increase in crashes for the critically affected links and nodes. One could plan various localized interventions (site specific) on the physical network to improve safety, such as at scenario 1. Alternately, one could, for example, plan measures that would redistribute the flow of traffic within the transportation network, such as at scenario 2. In scenario 1, the models were sensitive to change the configuration and network geometry. As expected, there was an increase in the number of accidents at signalized intersections and one-way road segments and decreased in others. In scenario 2 is also perceived sensitivity of the SPF, with the increase in volume was also expected to increase in the number of accidents in all groups. This difference was more representative, an increase of 3.300 vehicle-trips leads to an increase of about 13% in the predicted crashes on sample network.



The biggest increases occur on unsignalized intersection the hypothesis is the same as already mentioned previously, the vast amounts of zeros that the model cannot estimate.

5. CONCLUSION

This research recognizes that safety analysts need methodologies to predict safety similar to the quantitative methodologies that traffic operations engineers have available to assess capacity and level of service from specific traffic operational service measures. Given the increased liability of transportation agencies for traffic safety problems, it is important that they take action in this framework, which will allow them to show that proper steps were taken to reduce the number and severity of crashes.

This paper investigated the use of SPF as a tool to evaluate different transportation planning scenarios for urban road networks. Based on the results, it would be possible to plan for the implementation of additional measures to minimize the increase in crashes for the critically affected in road network, links and nodes within SPF. The SPF can also be used to quantify safety at the planning stage for forecasted traffic flows. The aim is to estimate in general terms, the safety of different scenarios without knowing all the detailed characteristics of the physical network that, more often than not, are unavailable for long-term planning projects. With the use of SPFs that account for time trend in accident occurrence the safety implications of different scenarios could also be estimated for short to mid-range planning projects (Lord and Persaud, 2004).

In general the expected results of this research were likely to contribute to the development of a more comprehensive methodology that incorporates the road safety dimension into traditional process of transportation planning. Furthermore, the analysis can provide indication of the usefulness of traditional SPF as a tool for estimating crash frequency in macroscopically modeled networks as well as possible improvements in modeling premises and model structure to increase its scope in this type of application. The tools developed and demonstrated in this research would allow planners to add a very useful criterion to the evaluation of different alternatives.

However, the results demonstrated some important pitfalls and limitations in the application of SPF on computerized transportation networks. The most important is the dependence of estimation of accidents with AADT of the estimation process. The error accumulation generated in the flow reconstruction process and the calculation of expansion factors can generate inaccurate results in the SPF implementation phase. It is advisable to conduct a sensitivity analysis that reflects the uncertainty in the estimates of predicted flow and, therefore, predicted collisions.

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REFERENCES

- AASHTO. (2010). Highway Safety Manual (HSM), 1st edition.
- Badran, A., Anowar, S., & Miranda-Moreno, L. F. (2015). A Safety Planning Tool for Evaluating Safety Impacts of Road Infrastructure Projects at the Link and Intersection Level. In Transportation Research Board 93rd Annual Meeting (No. 14-4857).
- Caliper (1996) Travel Demand Modeling with TransCAD 3.0. Caliper Corporation, Newton, USA



- Hadayeghi, A., Shalaby, A.S. & Persaud, B. (2003). Macro-level accident prediction models for evaluating safety of urban transportation systems. *Transportation Research Record*, v. 1840, n. 1, p. 87-95.
- Hadayeghi, A., Shalaby, A. & Persaud, B. (2010). Development of planning level transportation safety tools using Geographically Weighted Poisson Regression. *Accident Analysis and Prevention*, v. 42, 676-688.
- Hauer, E. (2015). *The Art of Regression Modeling in Road Safety*. (1a ed). Springer. Toronto, Canadá.
- Hauer, E. (2002). *Observational Before-after Studies in Road Safety*. (1a ed). Pergamon. Toronto, Canadá
- Hauer, E., & J. Bamfo (1997). Two Tools for Finding What Function Links the Dependent Variable to Explanatory Variables. *Proc., ICTCT 97 (International Cooperation on Theories and Concepts in Traffic Safety)*, Lund, Sweden, pp. 1-7.
- Lord, D., & Persaud, B. (2000). Accident prediction models with and without trend: application of the generalized estimating equations procedure. *Transportation Research Record: Journal of the Transportation Research Board*, (1717), 102-108.
- Lord, D. & Persaud, B.N. (2004). Estimating the safety performance of urban road transportation networks. *Accident Analysis & Prevention* 36 (4), 609-620.
- Lord, D. (2000). *The prediction of accidents on digital networks: characteristics and issues related to the application of accident prediction models* (Doctoral dissertation, University of Toronto).
- Nielsen, O. A.(1993) A New Method for Estimating Trip Matrices from Traffic Counts. Institute of Roads, Traffic, and Town Planning. The Technical University of Denmark, Paper 1993-3.
- Ortuzar, J. D. & Willumsen, L. G. (2011) *Modelling Transport* (4nd ed.). Wiley, NY
- Tarko, A. (2006). Calibration of safety prediction models for planning transportation networks. *Transportation Research Record: Journal of the Transportation Research Board*, (1950), 83-91.
- Zeng, Q., & Huang, H. (2014). Bayesian spatial joint modeling of traffic crashes on an urban road network. *Accident Analysis & Prevention*, 67, 105-112.
- Washington, S., Schalkwyk, I.V., Meyer, M., Dumbaugh, E. & Zoll, M., (2006). Incorporating safety into longrange transportation planning. NCHRP Report n. 546, TRB. National Cooperative Highway Research Program, Washington D.C.
- Sayed, T., deLeur, P., & Sawalha, Z. (2004). Evaluating the Insurance Corporation of British Columbia road-safety improvement program. *Transportation Research Record: Journal of the Transportation Research Board*, (1865), 57-63.
- Song, B., Huang, H., Zeng, Q., Deng, Q., & Abdel-Aty, M. A. (2015). Comparative Analysis of Macro and Micro Models for Zonal Crash Prediction. In *Transportation Research Board 94th Annual Meeting* (No. 15-2774).