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7–9 May 2012, Dubrovnik, Croatia

Road and Rail Infrastructure II

Stjepan Lakušić – EDITOR



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METHODOLOGY FOR SAFETY PERFORMANCE ASSESSMENT OF HIGHWAY INFRASTRUCTURE – ISSUES, RECENT APPLICATIONS AND FUTURE DIRECTIONS

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Abstract

The paper addresses key issues in safety performance assessment of highway infrastructure. The state of research in safety performance assessment methodologies in the us, specifically the Highway Safety Manual crash prediction algorithm, is first presented, with an illustration of how the algorithm can be evaluated for application outside the us. Fundamental to the algorithm's performance are crash modification factors (CMFs) for assessing how safety is affected as a roadway feature is changed. Issues in the development of these CMFs are discussed and illustrated with recent application examples in the development of CMFs for countermeasures targeted at improving intersection safety. Finally, the paper discusses future research directions. The paper is a culmination of several recent research projects, some of which are related the Highway Safety Manual, which was released in 2010, and is already being used worldwide.

Keywords: highway safety, crash prediction models, crash modification factors, Bayesian methods, safety countermeasures

1 Introduction

Explicit consideration of the safety consequences of decisions in designing a new highway facility or in assessing or improving an existing one requires the application of Safety Performance Functions (SPFs) and crash modification factor (CMFs). This is the basic philosophy in the newly released Highway Safety Manual (HSM) [1] which was developed in the United States.

The HSM procedures and associated knowledgebase are of interest around the world, and especially in Europe in the light of the directive (2008/96/EC) recently adopted by the European Commission (EC) that requires the establishment of procedures relating to road safety impact assessments [2]. The HSM will greatly facilitate the EC directive by providing guidance, based on the best available factual knowledge, to professional engineers for quantitative crash analysis and safety evaluation. A key issue in facilitating the worldwide application of the HSM is the transferability of the predictive methodology to data and road networks in environments that may be quite different from those in the us.

Part c of the HSM provides the safety performance assessment algorithm essentials – baseline safety performance functions (SPFs) and CMFs – for segments and intersections for three types of facilities: rural two lane undivided highways, rural multilane highways, and urban and suburban arterials. In the first step of the algorithm, a baseline SPF predicts the expected number of crashes for sites meeting the base conditions. Crash modification factors documented in the HSM are then used to adjust the base SPF prediction to account for the effects of other variables that are subject to design decisions, i.e., for conditions different

from the base conditions. The algorithm provides for the refinement of the estimates using the crash history for an existing site in an empirical Bayes procedure [3], and for adjustments to be made to reflect differences in crash experience across jurisdictions. The algorithm for predicting the number of crashes (N) at a site has the form:

$$N = c \times N_b \times CMF_1 \times CMF_2 \times CMF_3 \times \dots \quad (1)$$

where N_b is the number of crashes predicted by a SPF for base conditions, $CMF_1, CMF_2, CMF_3 \dots$ are crash modification factors for differences from the base conditions and c is a calibration factor for applying a base model from a different jurisdiction and/or time period.

Typically, the base SPF is a function of Annual Average Daily Traffic Volume (AADT), and is calibrated using negative binomial regression modelling that also estimates an overdispersion parameter that serves, among other things, as an indication of how well the model fits the calibration data. The calibration factor can be simply calculated from the total number of crashes for a sample set from the jurisdiction of interest divided by the sum of the predicted crashes for the sample using eqn (1) without the calibration factor.

How well the methodology works for a given jurisdiction anywhere in the world depends on the validity and applicability of its components – the base SPF, the CMFs, and the calibration factor. The rest of the paper touches on issues related to these components. Section 2 addresses the three components as a whole, with a focus on the SPFs, while Section 3 focuses on the CMFs.

2 Issues relating to the calibration and application of the HSM crash prediction algorithm outside the US

Issues in the calibration of the HSM crash prediction model were recently investigated in a research project [4] pertaining to its application for two-lane rural roads in Ontario, Canada. This effort served to demonstrate tools that could be used by jurisdictions around the world for assessing the validity and compatibility of the CMFs and base SPFs, as well as the performance of the whole algorithm.

The basic approach was to apply the HSM recalibration procedure and evaluate the performance of the HSM SPFs and CMFs for two-lane when applied to local data from Ontario, Canada. These data included 483 homogeneous segments with the total length of 77.9 km. In this recalibration procedure, the HSM SPFs and CMFs was applied to a group of sites and the calibration factor in eqn. 1 was calculated as the ratio of the sum of crash counts for the calibration data to the sum of the predictions.

Several goodness-of-prediction measures were used to assess performance, including the value of the recalibrated overdispersion parameter, the mean absolute deviation (MAD) (average value of the absolute value of observed minus predicted crash frequencies), and cumulative residual (CURE) plots.

As noted earlier, the overdispersion parameter can be used to compare model performance when applied to the same data in that the smaller its value the better the model is in general. The overdispersion parameter for recalibrated SPFs was estimated using a specially written maximum likelihood procedure.

How well an SPF fits the data can be judged using a Cumulative Residual (CURE) Plot. In this method, the cumulative residuals (the difference between the observed and predicted crashes for each location) are plotted in increasing order for each covariate, e.g., AADT, separately. Also plotted are graphs of the 95% confidence limits. If there is no bias in the SPF, the plot of cumulative residuals should stay inside of these limits. The graph shows how well the SPF fits the data with respect to range for each individual variable of interest.

In addition to evaluating the performance of the predictive algorithms as a whole it was desired to evaluate the performance of the base condition SPFs and CMFs separately. To evaluate the CMFs the following steps were undertaken, where data were sufficient, separately for each CMF in turn:

- Change the CMF to 1 for all sites
- Group the sites by the levels of the CMF in question
- For each group, divide the sum of observed crashes by the sum of predicted crashes, this is a multiplier for each group
- For each group, divide the multiplier by that for the base condition
- Compare the results from the last step to the original CMFs

Application of the algorithm without recalibration resulted in an overestimation of crash predictions for the Ontario data. The calibration factors for adjusting the HSM models to local conditions of the highways of interest are 0.79 for all severity (total) crashes and 0.74 for fatal plus injury (FI) crashes.

The calibration factors were then applied to the HSM algorithm and crashes predicted again. The Goodness–Of–Fit statistics for these recalibrated model predictions are indicated in Table 1. Also provided are the recalibrated overdispersion parameters on a per kilometer basis. An examination of the goodness–of–fit measures indicates that, overall, the recalibrated models perform reasonably well. The values for MAD (Mean Absolute Deviation) are relatively low as are the overdispersion parameters.

Table 2 shows the ratios of observed to predicted total crashes for different values of two variables. The trend is not consistent, although it should be noted that for some categories the number of crashes is small. The results in Table 2 indicate as follows:

- For lane width, the algorithm tends to over–predict for narrower lane widths and under–predict for lane widths of 3.65 m and above.
- For roadside hazard rating there is no evident trend in over or under–prediction.

Table 1 Goodness–of–fit for Ontario two–lane rural road segments

Observed Crashes		MAD for FI	Calibration Factor		MAD for Total	Recalibrated Overdispersion Parameter	
FI	Total		FI	Total		FI	Total
141	534	0.384	0.74	0.79	1.095	0.11	0.17

Table 2 Observed and Predicted Crashes vs. Design Features

Design Feature	Value	Observed	Predicted	Observed/predicted
Lane Width	3.35	16	24.64	0.65
	3.50	23	85.74	0.27
	3.60	53	79.81	0.66
	3.65	127	91.83	1.38
	3.75	315	251.98	1.25
Roadside Hazard Rating	1	23	85.74	0.27
	3	164	106.38	1.54
	4	204	240.61	0.85
	5	121	88.61	1.37
	6	22	12.66	1.74

Figure 1 provides example CURE plots for grade and driveway density versus total crashes. For grade, the CURE plot shows significant bias, particularly for positive values of grade, for which the graph strays beyond the upper 2 standard deviation boundary. For driveway density the predictions are reasonable, in that the plotted line is within the 2 standard deviation boundaries.

The results for the Ontario study were consistent with a recent Italian two-lane rural road case study [5]. That effort calibrated a local base SPF and found that the AADT coefficient was significantly larger than the HSM value of 1.0 (which assumes, contrary to most research, that crash frequency is proportional to AADT), so it is not surprising that the relative difference in predictions between the two models increased with increasing AADT. This, and other results, suggests that the implementation of the HSM safety assessment techniques across Europe, now promoted with the adoption of the directive 2008/96/EC, should be oriented towards the developing of local SPFs/CMFs for the European context.

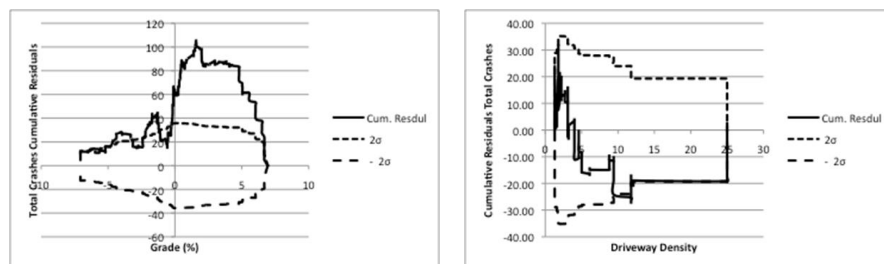


Figure 1 CURE plots of two-lane rural segments: Grade vs. Total Crashes (left); Driveway Density vs. Total Crashes (right)

3 Issues related to the development of CMFs

Key issues in CMF development have been documented in a recent guidebook [6] which first discusses the strengths and weaknesses of the two key methods used for developing CMFs – before–after and cross–sectional studies. Cross–sectional designs compare the crash frequencies of a group of sites with the treatment of interest to similar sites without the treatment at a single point in time and so are particularly useful for estimating CMFs where there are insufficient instances where a countermeasure is actually applied and for the preferred before–after study to be conducted.

The main problem with the before–after design is that the observed change in crash frequencies after a treatment may be due not only to the countermeasure, but to other factors such as changes in traffic volume, crash reporting or weather, and to regression–to–the–mean. Many past studies did not control for these other changes. In the case of regression to the mean, the effects of countermeasures are overestimated since this phenomenon tends to result in reduced crash frequencies when, as is often the case, sites are selected for treatment due to a randomly high crash count [3]. The empirical Bayes methodology [3] resolves the regression to the mean problem with the use of safety performance functions that, conveniently, are also used to account for traffic volume and time trend changes. Another key issue with the before–after design is that typically there are insufficient sample sizes of treatment sites to investigate how the CMF varies with various factors. It is well recognized that many countermeasures are more effective under certain application conditions, so the inability of a before–after design to investigate this variability can be a crucial limitation. Despite its limitations, the cross–sectional design can overcome this limitation.

CMFs derived from cross–sectional data are based on the assumption that the ratio of crash frequencies for sites with and without a feature is an estimate of the CMF for implementing

that feature. The problem with this assumption is that differences in crash frequencies between two groups may be due to factors other than the measure of interest. These other factors may be controlled for by accounting for their effects and that of the measure of interest in a multiple regression model, whereby the coefficient of a variable is indicative of the CMF for a unit change in that variable. The problem with this is that these coefficients will be inaccurate, and perhaps even have the incorrect sign, due to correlated or omitted variables. The result is that CMFs from cross-sectional designs tend to indicate smaller crash reductions than those derived from before-after studies.

4 Illustrative recent application examples in CMF development

Two recent studies [7] [8] pertaining to countermeasures for signalized intersections serve to illustrate the issues discussed above and their resolution.

The first study [7] estimated CMFs from before-after evaluations (using the EB methodology primarily) of two treatments targeted at left turn crashes at signalized intersections: (1) changing from permissive to protected-permissive phasing, and (2) implementation of flashing yellow arrow (FYA) for permissive left turns. Results of the first evaluation, which was based on a total of 71 intersections indicated a substantial reduction in left turn opposing through crashes, especially at intersections where more than one leg was treated, and a small percentage increase in rear end crashes. For the second evaluation (FYA), which was based on data from 51 signalized intersections, results indicated a safety benefit at locations with some kind of permissive left turn operation before, and a disbenefit where there was protected only operation before. A key aspect of the study was the estimation of the standard deviation of the distribution of the CMF. For several CMFs, the standard deviation of the distribution was larger than the standard error of the mean value of the CMF, indicating substantial variation in the treatment effect across sites. This indicates the need for the development of crash modification functions instead of crash modification factors. Equally important, it emphasizes the importance of providing more explicit consideration of CMF variability in future editions of the Highway Safety Manual.

CMF variability can be investigated with caution, as noted earlier, where CMFs are derived from cross-sectional multiple regression models. This was the case for the second illustrative study [8] which also investigated the issue of the compatibility of results from cross-sectional and before-after studies in developing CMFs for two treatments for reducing crashes related to traffic signal change intervals: modifying the change interval (i.e., the yellow and or all-red interval) and installing dynamic signal warning flashers (DSWF). Evaluation methods used included the empirical Bayes (EB) before-after method and cross sectional multiple regression models. A secondary objective of using cross-section models for some evaluations was to examine the comparability of before-after and cross-sectional studies, a subject of topical interest in CMF development. There was a general safety benefit for installing dynamic signal warning flashers, with indications that crash reductions can be obtained overall, and for several crash types, including injury, angle, and heavy vehicle crashes. For the change interval modification, the before-after study results showed significant reductions (at the 5% level) in total, injury, and rear-end crashes under various scenarios. For both treatments, the results from cross-sectional analyses were relatively consistent with those from the before-after analyses. This consistency is of particular interest when comparing the difference in the total change interval. Based on the results of the cross-sectional analysis, there is a u-shaped trend in the expected CMF as shown in Figure 2. Specifically, there appears to be a safety benefit as the difference between the actual and Institute for Transportation Engineers (ITE) recommended change interval [9] approaches zero. (The ITE recommended interval minimizes the dilemma zone that exists where a driver cannot stop safely or proceed through the intersection in the change interval.) The results from the EB analysis also indicated a benefit as the change interval is increased and approaches the ITE recommended one and a less pronounced benefit as the total change interval is increased and exceeds the ITE recommended practice (i.e., a u-shaped trend).

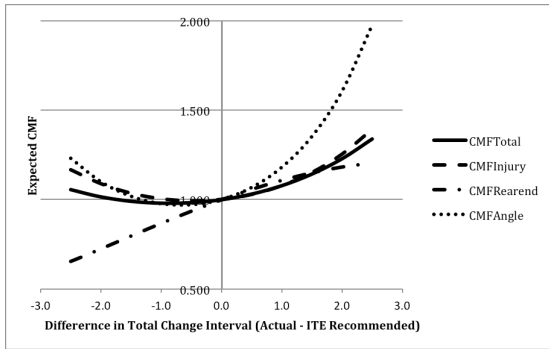


Figure 2 CMF trend for difference between actual and ITE change interval

5 Future directions

Methods used for developing CMFs fall under two broad categories: cross-section and before-after studies. The latter type is preferred and many advances have been made, specifically in the application of empirical and Full Bayes methods [3] [10]. Nevertheless, there remains a dearth of knowledge on quality CMFs, largely because existing methods may have reached their limits. As a result, there has of late been renewed interest in enhancing methods for developing crash modification factors, particularly for situations where conventional methods are found wanting. In late 2008, a workshop titled 'Future Directions in Highway Crash Data Modeling' brought together selected, prominent safety researchers to explore promising directions in crash data modeling and to develop a program of advanced safety research that provides a theoretic foundation for explaining crash causation. Goals of the research program recommended at the workshop [11] are to promote the further development of science-based safety evaluation and to facilitate the development of more stable, reliable, and transferrable highway safety predictive models. The call was issued for the development of new methods, and the refinement of existing methods for either quantifying the safety of a facility, or estimating the relationship between a change in facility condition and a change in facility safety. Structural models [12] for explaining crash causation were seen as a promising approach for accomplishing these objectives. Other promising, emerging approaches include Bayesian model averaging [13] and the application of surrogate driver performance measures where there are insufficient data for crash based evaluations. In the latter case, there has been substantial research of late, but establishing a strong relationship between safety surrogates and crashes has, by and large, eluded researchers, as is the defining and developing of surrogates that can be related to crashes, and so more research is needed on the application of this approach safety estimation.

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