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ABSTRACT:

Longitudinal rumble strips have proven to be an effective treatment on paved shoulders in preventing roadway departure crashes on two lane rural roads.

In 2009, the Government of Puerto Rico started the implementation of longitudinal shoulder rumble strips on freeways. In 2010, the Highway Safety Manual (HSM) was published by AASHTO providing tools for decision making and to estimate how effective a countermeasure or set of countermeasures will be in reducing crashes at a specific location. Crash Modification Factors (CMF) are used to quantify the effect of a particular treatment on expected crash frequency adjusting the estimate of crash frequency from a base condition defined by a Safety Performance Function (SPF) to the specific conditions present at a site. In the first edition of 2010 HSM, CMF's for freeway applications using non-continuous longitudinal rumble strips on shoulders were not included.

This paper documents the process of developing CMF for non-continuous rumble strips on urban and rural freeway segments, in rolling to mountainous topography, and the first phase of the development of SPF's. The study area is PR-52, a 108.3 km toll freeway facility which is part of the United States National Highway System (NHS), and includes level, rolling and mountainous areas with an ADT ranging from 26,700 vpd to as high as 166,500 vpd.

Development of Safety Performance Functions for Freeways in Puerto Rico

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INTRODUCTION

The road network of the Commonwealth of Puerto Rico consists of 26,866 centerline kms of which 26,720 are paved and 146 unpaved. In 2012, the Federal Highway Administration (FHWA) of the US Department of Transportation (USDOT) reported 29,915 millions of vehicle-kms traveled on the island highway network of which 39.6% corresponded to the National Highway System (NHS). The interstate system, which includes rural and urban freeways with toll facilities, generated 29.6% of all vehicle-kms traveled (FHWA 2013).

During the last decade, approximately 4,397 motor-vehicle crash fatalities were reported in the island of which approximately 25% are roadway departure crashes (TSC 2013). A preliminary analysis of roadway departure crashes, using a 5 year moving average, resulted in 134 fatalities. Furthermore, an alarming 1.96 fatalities/100 million vehicle-miles traveled (MVMT) were reported as compared with 1.13 fatalities/100 MVMT in the continental US (FARS 2013).

Based on these facts, the Puerto Rico Department of Transportation and Public Works (DTPW) concentrated their efforts to improve safety of the highway network by approving the Puerto Rico Strategic Highway Safety Plan (SHSP 2014). In the SHSP, roadway departure crashes have been identified as one of the areas of emphasis, based upon significant contributing causes of traffic fatalities and serious injuries in the island. The revision of roadside safety engineering policies and standards, and education of innovative roadway departure countermeasures, such as non-continuous longitudinal rumble strips, are listed as strategies that have the potential of reducing roadway departures during the next 5 years on high speed freeways within the NHS interstate system.

Even though non-continuous longitudinal rumble strips are perceived as a cost effective countermeasure to reduce roadway departure crashes, the initial edition of the 2010 Highway Safety Manual (HSM) published by AASHTO does not include Safety Performance Functions (SPF's) and Crash Modification Factors (CMF's) for freeway applications. In 2009, Puerto Rico Highway and Transportation Authority (PRHTA) started the implementation of non-continuous longitudinal rumble strips on freeway shoulders.

This paper will focus on the development of SPF's for freeway segments, combining historical crash data with the Highway Performance Monitoring System Database of the Commonwealth of Puerto Rico for a 2 year and 3 year study period.

OBJECTIVES

The objective of this research is three fold:

- Provide an overview of rumble strips to address roadside departure crashes in high speed freeway facilities.
- Develop SPF using exposure and historical crash data from the Puerto Rico HPMS.
- Perform a sensitivity analysis to evaluate the effect of the independent variables, AADT, and segment length on the expected number of crashes for the study period.

LITERATURE REVIEW: RUMBLE STRIPS

Rumble strips are a safety feature or treatment on a paved roadway, capable of alerting drivers that their vehicle is leaving the travel lane. In the United States, this special treatment has proven to be effective (FHWA 2013). Rumble strips can be either permanent or provisional. Examples of permanent installment of rumble strips are along the centerline of a two way roadway or on the shoulder of a roadway. In the case of provisional rumble strips, they are commonly used to alert vehicles of changes in the roadway. Temporary transverse rumble strips in work zones are commonly used in high speed rural freeway facilities to assist in speed reduction of vehicles approaching the work zone. Essentially transverse rumble strip are used to alert drivers of a potential change or hazards in the roadway. Figure 1 illustrates longitudinal and transverse rumble strip applications.

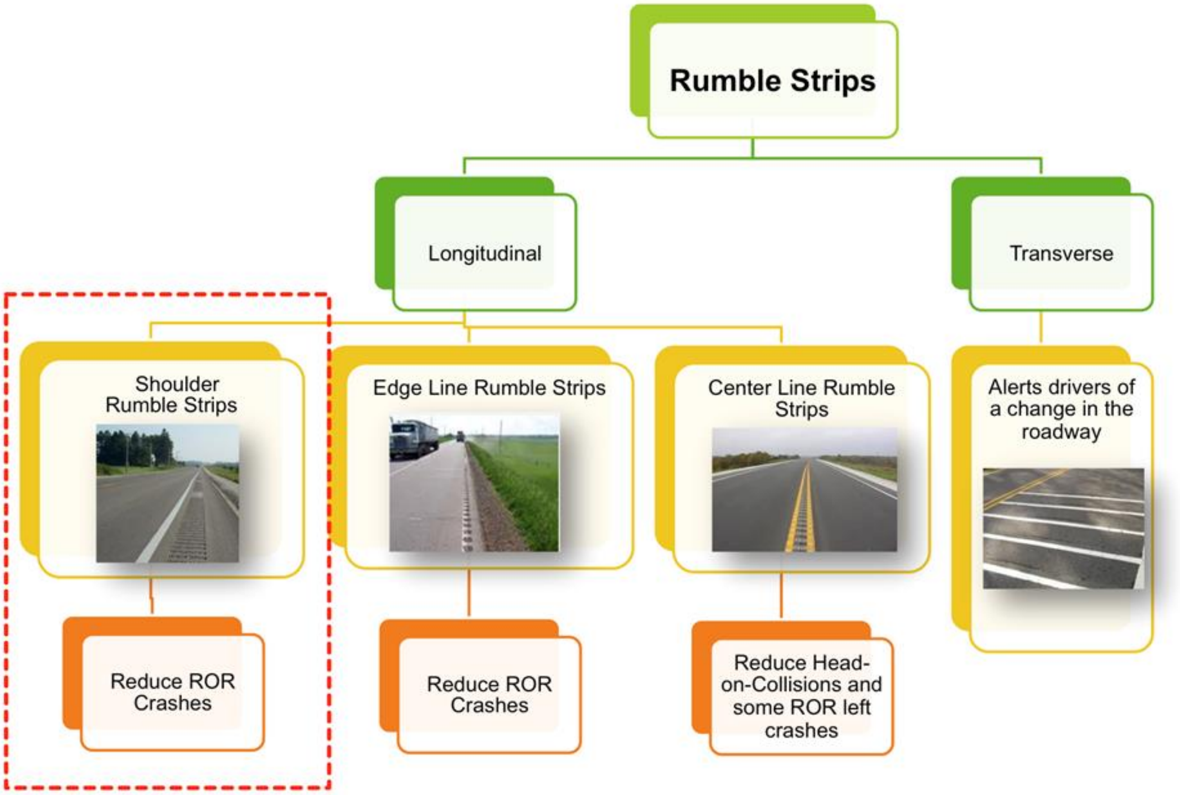

Figure 1. Longitudinal and Transverse Rumble Strips (Source: http://safety.fhwa.dot.gov/)

DESIGN GUIDELINES FOR RUMBLE STRIPS

The PRHTA issued a Design Guidelines No. 409 for the installment of rumble strips in the island highway system (PRHTA, 2012). Table 1 provides a comparison between the FHWA Technical Advisory 5040.39, the National Cooperative Highway Research Program (NCHRP) Report 641, and the PRHTA Design Directive No. 409.

Table 1. Local and National Specifications for Shoulder Rumble Strips

REQUIREMENTS	FHWA (TA 5040.39)	NCHRP (641) Most Common Values	PRHTA (DD#409)
A-Minimum Shoulder Width (feet)	4	4	4
B-Lateral Clearance (inches)	9	12	12
C-Rumble Strips Width (inches)	7	7	7
D-Rumble Strips Length (inches)	16	16	16 to 18
E-Center to Center Spacing (inches)	Not specified	12	12
Rumble Strips Depth (inches)	1/2	½	1/2 to 5/8
Bicycle Gap (feet)	10 to 12	10 to 12	6 to 12
Minimum Posted Speed (mph)	50	45 to 50	Not specified

RESEARCH METHODOLOGY

The development of SPF's are part of a large scale research project that will ultimately develop CMF's for non-continuous shoulder rumble strips on Puerto Rico freeways. The development of SPF's correspond to Phase A of the flowchart shown in Figure 2.

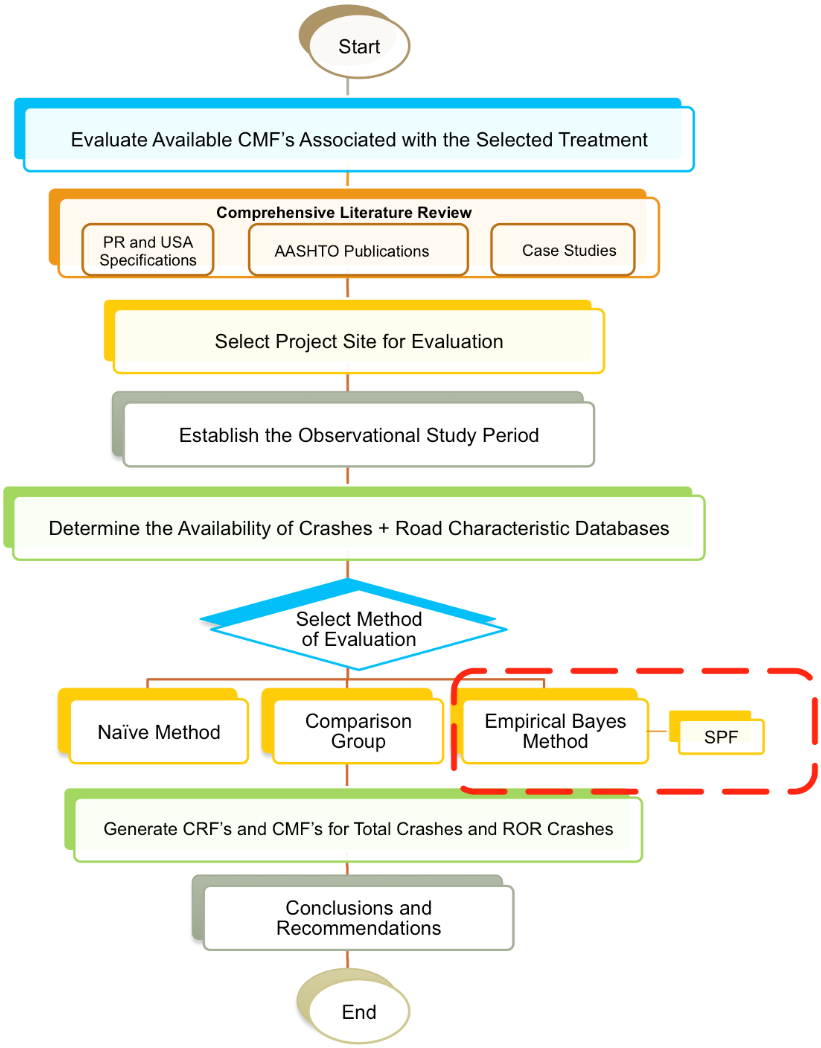

Figure 2. Research Methodology

Two databases were used in Phase A to develop SPF's, namely historical crash and HPMS databases. They provided traffic (AADT, %Trucks), geometric (horizontal curve, grades), and operational (speed limit) characteristics, as well as crash data for a study period covering from 2006 to 2012.

During the summer of 2009, PRHTA performed a pilot project that consisted of the installation of milled-in, non-continuous shoulder rumble strips along the PR-52 freeway. The study area is highway PR-52, a 108.3 kilometers long toll freeway facility that is part of the National Highway System, which originates from the north in San Juan, Capital of Puerto Rico, crossing the central mountain range, and ends in the City of Ponce. Both cities have shipping ports that receive and deliver commercial freight. Its AADT ranges from 165,800 vpd in the origin, an urban area with level to rolling terrain, to a minimum of 18,600 vpd in a rural mountainous region. The maximum speed limit is 65 miles per hour and has approximately 8% of heavy trucks.

Figure 3 shows the warning sign with the rumble strips phrase in Spanish within the text plate, "huella en el paseo", alerting drivers of the presence of longitudinal shoulder rumble strips, followed by a representative longitudinal shoulder rumble strip on NHS PR-52 freeway, and the recommended dimensions of the longitudinal shoulder rumble strip. In our research project, the non-continuous longitudinal shoulder rumble strip installed on this freeway are 5.7 feet (1.74 m) long, 1 feet (0.30 m) wide and 10.8 feet (3.29 m) gap between the strips.

Figure 3: (a) Rumble Strips Sign, (b) Rumble Strips on NHS PR-52 Freeway;
(c) Sketch of the Gap Dimension of the NHS PR-52 Non-continuous Rumble Strips

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS (SPF's)

SPF is a statistical model that is used to predict crashes in the future, at a particular location such as a road, segment or intersection. The first step of the Empirical Bayes Method (EB) was the development of a SPF for both total crashes and injuries. It includes the creation of a reference group that is a collection of untreated segments that have similar characteristics as the treated segments. Table 2 shows the distribution of total crashes for the freeway study segments of the NHS, namely PR-22 and PR-52.

Table 2. Distribution of Total Crashes of NHS PR-22 and PR-52 (Study period 2006-2009)

Road Name		2006		2007		2008		2009		Total Crashes
	Length (km)	Total Crashes	Crashes /km-yr	Total Crashes	Crashes /km-yr	Total Crashes	Crashes /km-yr	Total Crashes	Crashes /km-yr	
PR-22	0.0-83.7	738	8.82	816	9.75	782	9.34	804	9.60	3,140
PR-52	0.0-108.3	970	8.96	933	8.61	831	7.67	909	8.39	3,643

The segment selection for the reference group was a combination of treated segments in the NHS PR-52 and untreated segments of the NHS PR-22 with similar characteristics. The segmentation is based upon the segmentation use in the Highway Performance Monitoring System (HPMS) Database which defines segments for each road in Puerto Rico based upon the Annual Average Daily Traffic (AADT). Table 3 presents the principal characteristics of the segments selected for the reference group of NHS toll freeways using 2009 as the base year.

Table 3. Characteristics of the Segments Selected for the Reference Group

Characteristics of the Segments of the Reference Group	NHS PR-52	NHS PR-22
Number of Lanes	4 to 6 lanes	4 to 6 lanes
Lane Width	12 feet (3.65 m)	12 feet (3.65 m)
Average Segments AADT's (vehicles/day)	70,677	77,438
Average Crashes for Segments (per year)	30	23

The second major task was the data cleaning process in which incomplete records were eliminated from the database. The data cleaning process was performed on all of the segments for both freeways including the reference group. A total of 491 crash records were eliminated because they lacked the exact location of the crash or had errors related to the exact kilometer location.

The calibration of the preliminary SPF was completed using a methodology proposed by Hauer in which he suggests that an SPF can be built by adding the variables in the model equation, one at a time. If the modeler reports every SPF gradually obtained, practitioners then can use the model for which they have the data available (Hauer 2014). Hauer suggests to start the modeling process with a segment length as a simple model equation, and then add the rest of the variables. The development of the SPF's were obtained by using a curve fitting model in combination of a function in Microsoft Excel called the "Solver Parameter Tool" which can solve the parameters of practically any function that would better fit the model.

The SPF's were developed assuming a Negative Binomial Distribution (NBD). In the past, researchers used Poisson Distribution but recently had shown that the Negative Binomial Distribution offers better fitted models than the Poisson Distribution. A pertinent parameter for the development of the EB method is the negative binomial dispersion parameter (Φ) obtained from this regression.

The first preliminary SPF's were performed by fitting a power function. On the first trial, the segment length (kms) was used as the independent variable. The first SPF is represented by equation (1), where $E(\mu)$ is defined as expected crashes, X_1 is the segment length (kms) and β_0 and β_1 are regression parameters.

$$E(\mu) = \beta_0 * X_1^{\beta 1} \qquad (1)$$

Table 4. Results of the Models with Segment Length for 2 to 3 Year Periods

Severity Type	Expected Crash Frequency Model (2 Year Period)				Expected Crash Frequency Model (3 Year Period)			
	regression parameters		over-dispersion parameter	Pearson Function Index	regression parameters		over-dispersion parameter	Pearson Function Index
	β_o	β_1	ϕ		β_o	β_1	ϕ	
Total Crashes	22.245	0.737	1.155	0.57	34.279	0.719	1.129	0.56
Crashes with Injuries	21.899	0.737	1.144	0.57	21.899	0.737	1.144	0.57

Table 4 provides the values of the parameters (β), over-dispersion parameter (Φ) and the value of the Pearson Index obtained by the Microsoft Excel Solver Parameter Tool. The Pearson Function Index can range from -1 to 1 and reflects the relationship between two data sets. On the initial analysis, the Pearson Function Index value was low for all of the models with a SPF based upon segment length. To better improve the SPF, an additional variable, the AADT for each segment, was added. The second SPF is represented by equation (2), where $E(\mu)$ is defined as expected crashes, X_1 is the segment length (kms), X_2 as the AADT (vehicles/day) and β_0, β_1 and β_2 are regression parameters.

$$E(\mu) = \beta_0 * X_1^{\beta 1} * X_2^{\beta 2} \quad (2)$$

Table 5. Results of the Models with Segment Length and AADT's for 2 to 3 Year Periods

Severity Type	Expected Crash Frequency Model (2 Year Period)					Expected Crash Frequency Model (3 Year Period)				
	regression parameters			over-dispersion parameter	Pearson Function Index	regression parameters			over-dispersion parameter	Pearson Function Index
	β_o	β_1	β_2	ϕ		β_o	β_1	β_2	ϕ	
Total Crashes	0.00042	0.847	0.963	2.576	0.85	0.0016	0.781	0.889	2.254	0.85
Crashes with Injuries	0.00037	0.855	0.974	2.554	0.85	0.00169	0.78	0.883	2.185	0.85

Table 5 provides the values of the parameters (β), over-dispersion parameter (Φ), and the value of the Pearson Function Index obtained by Excel for the SPF's that included the segment length and the average AADT's variables. The Pearson Function Index gets closer to 1 and reflects that there is a better relationship between the two data sets (observed vs. fitted values).

In order to evaluate the effect of the independent variables AADT and segment length on the expected crashes, a sensitivity analysis was performed. The study period for this analysis was 2 years. Figure 5 shows the results of the sensitivity analysis with segment lengths varying from 0.5 kms to 5.0 kms, and AADT from 25,000 vpd to 75,000 vpd, which is representative of the traffic exposure in the NHS rural segments, where rumble strips were installed. Based on this analysis, the SPF generates a good fit in terms of increasing the number of expected crashes with an increase in traffic exposure (AADT) and segment length.

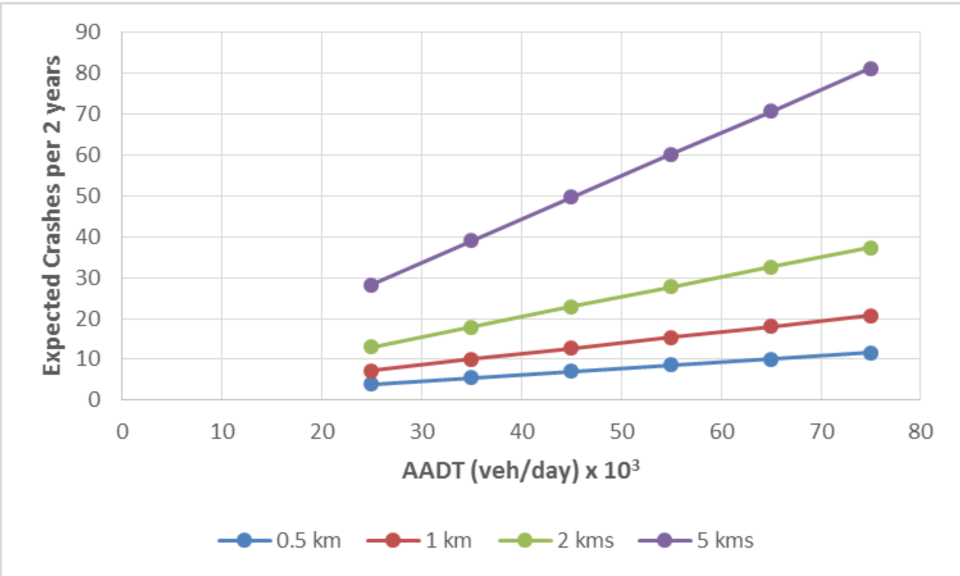

Figure 5. Sensitivity analysis of the effect of AADT (X_2), and segment length (X_1) on the expected number of annual crashes on freeway segments of varying lengths with non-continuous rumble strips 2 year model

CONCLUSIONS

This paper focused on the development of SPF's for freeway segment reference groups, combining historical crash data with the HPMS database provided by the Puerto Rico Department of Transportation and Public Works, and performing a sensitivity analysis to evaluate the effects of the independent variables, segment length and AADT, on the expected number of crashes.

The results of Phase A of the research study showed that in general:

The Microsoft Excel Solver Parameter Tool can be useful in the preliminary stages of developing SPF's by adding independent variables in a step wise fashion. The Solver Parameter Tool is a very flexible and powerful tool since it allows the researcher to calibrate different mathematical functions.

In terms of the first model, with a SPF based upon segment length, it was noted that the Pearson Function Index value was low, therefore, the estimate of the expected number of crashes with only segment length as an independent variable was not reliable.

In terms of the second model, with a SPF based upon segment length and AADT, the Pearson Index gets closer to 1, and reflects that there is a better relationship between two data sets (observed vs. fitted values) to estimate the expected number of crashes in the study period.

In terms of the sensitivity analysis, the model is a powerful tool to assess the fitness of the SPF with two independent variables. Based on the sensitivity analysis, the SPF generates a good fit in terms of increasing the number of expected crashes with an increase in traffic exposure (AADT) and segment length.

Ongoing studies will apply the Empirical Bayes Method to generate CMF's associated with non-continuous shoulder rumble strips for freeway application.

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