Crash Modification Factors for Rumble Strips Treatment in Freeway

by

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ABSTRACT

Longitudinal shoulder rumble strips is a safety feature or treatment on a paved shoulder, capable of alerting drivers that their motor vehicle is departing the traveled lane. This treatment has proven to be effective specially preventing roadway departure crashes.

In 2009, Puerto Rico Highway and Transportation Authority (PRHTA) started the implementation of non-continuous longitudinal rumble strips on the right hand shoulder on freeways on the island. In 2010, the Highway Safety Manual (HSM) was published by AASHTO to provide tools for decision making to estimate how effective a countermeasure or set of countermeasures will be in reducing crashes at a specific location. The Crash Modification Factors (CMF) are used to quantify the effect of a particular treatment on expected crash frequency. On the HSM, CMF's for freeway applications using non-continuous longitudinal rumble strips on shoulders were not included.

This investigation documents the process of the development of CMF for non-continuous longitudinal shoulder rumble strips on freeway segments, in rolling to mountainous topography. The study area is highway PR-52, a 108.3 kilometers toll freeway facility that is part of the National Highway System (NHS) that originates in the north at San Juan, Capital of Puerto Rico, crossing the central mountain range and ends in the city of Ponce. Its AADT ranges from 165,800 vpd in its origin in the urban area with level to rolling terrain to a minimum of 18,600 vpd in a rural mountainous region. The maximum speed limit is 105 km/hr (65 mph) with approximately 8% of heavy trucks. The specific segment evaluated in this research starts on the South Caguas Toll Plaza (km 23.1) and ends at the exit ramp towards the town of Salinas (km 66.3).

An observational study known as Empirical Bayes Method was performed to calculate the effectiveness of this treatment. This method can predict the number of crashes that would occur in the "after" period if the treatment or countermeasure had not been implemented and then compares these values with the actual count of crashes in the "before" period of the treated site. The first step on this method is the development

of a multivariate crash prediction model or "Safety Performance Function" (SPF) specifically adapted to Puerto Rico's jurisdiction for total crashes and run off the road (ROR) crashes for the reference group.

This investigation revealed that, other than length and AADT, the presence of freeway ramps and climate category (dry areas versus moist/wet areas) were statistically significant in the prediction of total crashes. Furthermore, the SPF associated with ROR crashes for the reference group, had statistically significant variables such as segment length, AADT and presence of freeway ramps. No major outliers were detected for both SPF models on the final verification process. In addition, a jurisdictional SPF was calibrated for average crashes on Puerto Rico's freeway network.

The EB Method showed that for longitudinal intermittent shoulder rumble strips in the NHS PR-52 toll freeway there was a decrease on ROR and total crashes by 5% and 2%, respectively. The estimation of CMF for longitudinal intermittent shoulder rumble strips associated with ROR crashes was 0.95 and for total crashes was 0.98. The estimated CMF's had standard errors of less than 0.1 indicating reliable results based on AASHTO guidelines.

RESUMEN

Las huellas longitudinales en los paseos de las carreteras es un tratamiento de seguridad en los paseos capaz de alertar a los conductores que su vehículo de motor se está saliendo de su carril. Este tratamiento ha demostrado ser eficaz especialmente en la prevención de choques asociados a vehículos de motor que salen de la vía de rodaje.

En el 2009, la Autoridad de Carreteras y Transportación (ACT) comenzó la implantación de huellas longitudinales intermitentes en los paseos al lado derecho de las autopistas de la isla. En el 2010, el Manual de Seguridad en las Carreteras (HSM, por sus siglas en inglés) fue publicado por la AASHTO para proporcionar herramientas para la toma de decisiones en términos de estimar la eficacia de una medida o conjunto de medidas correctivas en la reducción de choques en un lugar específico. Los Factores de Modificación de Choques (CMF) son utilizados para cuantificar el efecto de un tratamiento en particular en la frecuencia de choques esperados. En el HSM, no se incluyeron CMFs asociados a huellas intermitentes en paseos de autopistas.

Esta investigación documenta el proceso del desarrollo de CMF para huellas intermitentes en segmentos de autopistas. El área de estudio es la autopista PR-52, una facilidad con cobro de peaje cuya longitud es de 108.3 kms que forma parte del Sistema Nacional de Carreteras (NHS) que se origina en el norte en San Juan, Capital de Puerto Rico, cruzando la cordillera central y terminando en la ciudad de Ponce. Su Volumen Anual Diario Promedio (AADT) oscila entre 165,800 vpd en su origen en el área urbana con el terreno de nivel a ondulado a un mínimo de 18,600 vpd en la región rural montañosa. El límite máximo de velocidad es de 105 kms (65 mph) con aproximadamente 8% de camiones. El segmento específico evaluado en esta investigación se inicia en el sur en el peaje de Caguas (km 23.1) y termina en la rampa de salida hacia la ciudad de Salinas (km 66.3).

Un estudio observacional denominado como el Método Empírico de Bayes se llevó a cabo para calcular la eficiencia de este tratamiento. Este método puede predecir el número de choques que se producirían en el período “después” si no se hubiese

implantado el tratamiento y luego compara estos valores con el número actual de los choques en el periodo de “antes” de que se implantara el tratamiento en el sitio de estudio. El primer paso en este método es el desarrollo de un modelo de predicción de choques multivariado o una Función de Desempeño de Seguridad (SPF), que sea específicamente adaptada a la jurisdicción de Puerto Rico y los posteriores para los choques totales y choques de los vehículos que salen de la vía de rodaje (ROR) para el grupo de referencia.

Esta investigación reveló que, además de la longitud del segmento y al AADT, la presencia de rampas de autopista y la categoría climática (áreas secas versus áreas húmedas) fue estadísticamente significativas en la predicción de los choques totales. Por otra parte, el SPF asociado a choques de vehículos que salen de la vía de rodaje (ROR) para el grupo de referencia, tuvo variables estadísticamente significativas, tales como la longitud del segmento, el AADT y la presencia de rampas de autopistas. No se detectaron valores atípicos para ambos modelos de SPF en el proceso de verificación. En adición, se calibró un SPF jurisdiccional para choques promedio en la red de autopistas en Puerto Rico.

El Método EB demostró que para las huellas intermitentes en los paseos de la autopista de peaje PR-52 que formar parte del NHS hubo una disminución de choques de vehículos que salen de la vía de rodaje (choques del tipo ROR) y de choques totales de un 5% y 2%, respectivamente. El estimado de CMF para huellas longitudinales intermitentes en los paseos asociados a los choques de los vehículos que salen de la vía de rodaje (ROR) fue de 0.95 y de 0.98 para choques totales. Los CMFs estimados tenían errores estándar de menos de 0.1 que indican resultados confiables en base a las guías de la AASHTO.

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LIST OF ACRONYMS

ADT	Average Daily Traffic
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ARAN	Automated Road Analyzer
BEATS	Bayesian Estimation of Accidents in Transportation Studies
CARE	Critical Analysis Reporting Environment
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
CSRS	Continuous Shoulder Rumble Strips
DOT	Department of Transportation
EB	Empirical Bayes
EDR	European Directors of Roads
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
HSM	Highway Safety Manual
HTA	Highway and Transportation Authority
IRI	International Roughness Index
MAP-21	Moving Ahead for Progress in the 21st Century Act
MDOT	Minnesota Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
MVMT	Million Vehicle Miles Travels
NCDC	National Climatic Data Center
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
NHI	National Highway Institute
NHTSA	National Highway Traffic Safety Administration
NSC	National Safety Council
PDO	Property Damage Only
PRDTPW	Puerto Rico Department of Transportation and Public Works
PRHTA	Puerto Rico Highway and Transportation Authority
PRISHSP	Puerto Rico Interim Strategic Highway Safety Plan
PRPD	Puerto Rico Police Department
PRTSC	Puerto Rico Traffic Safety Commission
RDG	Roadside Design Guide
ROR	Run-off-the Road
RSA	Road Safety Audit
SHSP	Strategic Highway Safety Plan
SPF	Safety Performance Functions
SPSS	Statistical Package for Social Science
SRS	Shoulder Rumble Strips
SV ROR	Single Vehicle Run-off-the Road
TA	Technical Advisory
TRB	Transportation Research Board
UPRM	University of Puerto Rico at Mayagüez

USA	United States of America
USDOT	United States Department of Transportation

1.0 INTRODUCTION

1.1 Historical Background

Automobile crashes are random events that have several contributors such as human factors, vehicle factors, roadway and environmental factors (AASHTO, 2010). Human factors associated with crashes are distraction, fatigue, inattention, and poor judgment, distraction related to cell phone use or poor driving behavior. Vehicle factors can be associated with worn or deteriorated tires and brakes. Roadway and environmental factors can be associated with wet surfaces or pavement, polished aggregate, steep terrain and others (AASHTO, 2010). The awareness and understanding of those factors can assist in the process of developing countermeasures able to reduce the incidence of crashes at a specific site.

The Department of Transportation and Public Works (PRDTPW), together with the Puerto Rico Highways and Transportation Authority (PRHTA), in their goal to reduce the number of fatal and injury crashes on the island road network had published the Strategic Highway Safety Plan (SHSP) for the years 2014 to 2018. This plan was required by the Moving Ahead for Progress in the 21st Century Act, also known as MAP-21. The objective of this plan is to coordinate within several governmental agencies numerous safety initiatives that can assist in the reduction of crashes in the island' highway network.

This plan included nine emphasis areas based upon Puerto Rico's historical crash data. The crash history involving fatal crashes is managed by the Traffic Safety Commission, which administrates the Fatality Analysis Reporting System (FARS) and the PRHTA Accident Analysis Office. Figure 1.1 presents the nine emphasis areas of the plan. The yellow emphasis areas are considered core emphasis areas and are a priority for the government of the Commonwealth of Puerto Rico. The green emphasis areas were selected based upon the most significant contributing factors of crashes in the island road network based upon historical crash data analysis.

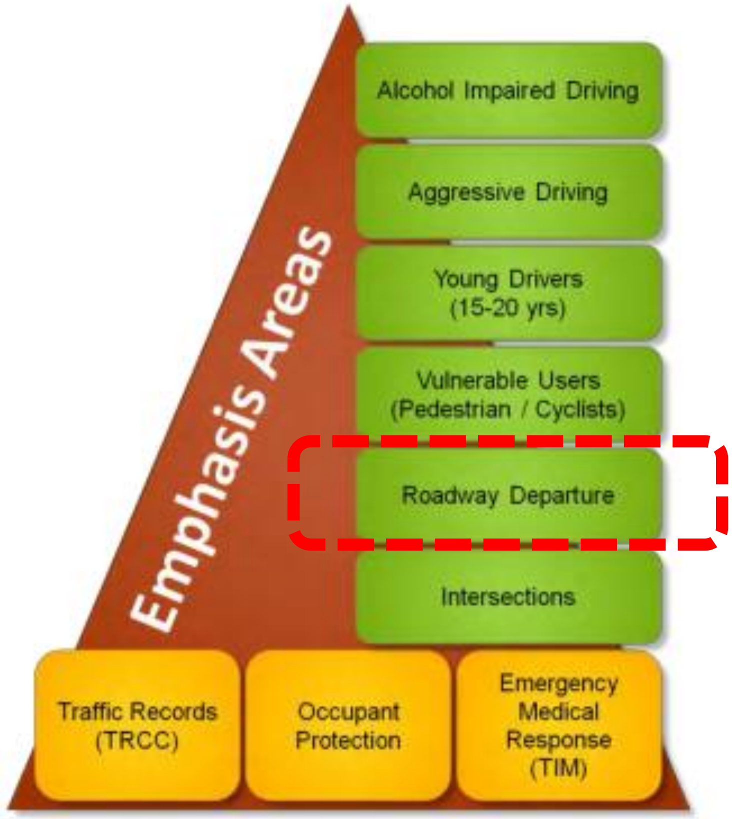


Figure 1.1 SHSP Roadway Departure as an Emphasis Areas (PRHTA, 2014)

In Puerto Rico, the crashes associated with roadway departure represent approximately 25% of the total fatalities caused by traffic crashes (PRHTA, 2014). Contributing factors associated with this type of accidents can be the pavement condition, speeding, driver fatigue or distraction, vehicle defects and others. FARS data exposed speeding and drivers losing control of their vehicles as the top causes for vehicles leaving the roadway.

In the island, during the last 4 years, there has been an increase of 13.7% of run-off-road (ROR) crashes. One of the main goals of the plan is the reduction of fatalities associated by ROR crashes. Some strategies to achieve this goal are the implementation of roadside engineering safety measures, such as shoulder rumble strips, and the removal or shielding of roadside fixed objects.

Meanwhile in the United States, in an effort to decrease the quantity and severity of crashes, the American Association of State Highway Transportation Officials (AASHTO) published in 2010 the first edition of the Highway Safety Manual (HSM). The HSM, serves the transportation practitioners and agencies by offering various tools that can quantitatively assist in the prediction of the impact or effectiveness of safety related projects during the different stages such as planning, design, operations and maintenance. Other applications that can be achieved using the HSM are: the identification of sites with high incidence of crash frequency, identification of contributing factors associated with crashes and potential countermeasures or treatments, economic appraisals for specific improvements or projects to help prioritize them and the estimation of potential effects on crash frequency and severity in the planning or designing process of highway related projects (AASHTO, 2010).

Crash Modification Factor (CMF) is a tool incorporated in Part D of the HSM. CMF can assist practitioners predict quantitatively the change in crash frequency expected for a specific treatment before implementation. Furthermore, CMF can assist government agency officials envision how a specific treatment can either reduce or increase crashes if implemented (AASHTO, 2010).

The Federal Highway Administration (FHWA) has recommended safety countermeasures based on proven effectiveness. Countermeasures such as safety edge, roundabouts, longitudinal rumble strips and strips, road diets, and others have been evaluated to acknowledge the effectiveness in the reduction of crashes. Longitudinal rumble strips for two lane roads have proven effective in the United States with an approximate reduction of 36% of ROR crashes including fatal and injury crashes (FHWA, 2013b).

The PRHTA's Road Safety Audit (RSA) Division is in charge of implementing safety countermeasures to existing roads on the island road network. Countermeasures such as longitudinal rumble strips, crash attenuators, and several projects of pavement rehabilitation that included safety features such as pavement marking, installation safety barriers and sings, have been implemented on our highway system in the past few years.

A total of 250 kilometers of longitudinal rumble strips have been implemented on the island highway network system with an estimate investment of $1.8 million (Rivera, 2014).

In this investigation, a methodology was applied to perform the evaluation of the effectiveness of the first pilot project regarding longitudinal intermittent shoulder rumble strips implemented on Puerto Rico's National Highway System (NHS) PR-52 toll freeway.

1.2 Justification

In August 2014, the PRDTPW published the Strategic Highway Safety Plan 2014 - 2018 as required by the Moving Ahead for Progress in the 21st Century Act (MAP-21). One of the primary objectives of this plan was to implement highway safety countermeasures based upon statistical evaluations or proven effectiveness.

The SHSP reported that in Puerto Rico approximately 25% of all traffic fatalities are related to ROR crashes or roadway departure crashes. One of the main goals of the SHSP is to decrease the 5 year moving average of fatalities involving ROR crashes by 7% by the year 2018 (PRHTA, 2014). One of the strategies they are planning to implement is the installation of rumble strips on high speed or high frequency crash corridors.

A Safety Performance Function (SPF) is an equation that provides a prediction of average crash frequency. Case studies involving the evaluation of effectiveness of shoulder treatments revealed that they only calibrated jurisdictional SPF's containing variables associated with traffic volume and segment length in order to achieve the prediction of crashes. The National Cooperative Highway Research Program (NCHRP) used data from three different states to evaluate the effectiveness of shoulder rumble strips and included a multivariate SPF's with the inclusion of one additional variable involving Road Hazard Ratings. Currently, the HSM does not provide a CMF regarding the installation of longitudinal intermittent shoulder rumble strips.

On 2009, the first pilot project regarding longitudinal intermittent rumble strips along the NHS PR-52 was completed. As a result of this investigation, the first set of multivariate SPF's regarding homogeneous freeways segments where calibrated and an observational study was employed to measure the effectiveness of the intermittent longitudinal shoulder rumble strips. These measures can assist the PRHTA decide the feasibility of incorporating these countermeasures on other highways around the island. The end result of this investigation is the application of a methodology for the evaluation of shoulder treatments, including calibrated multivariate SPF's for freeway segments for the island freeway network and the development of unique CMF's for this specific treatment in Puerto Rico.

1.3 Objectives

The main objective of this research was the application of a methodology to evaluate the effectiveness of road safety measures associated with shoulder treatments implemented in Puerto Rico's freeway system and by doing so, the evaluation of the pilot project associated with the installation of longitudinal intermittent shoulder rumble strips in the NHS PR-52 toll freeway.

The specific objectives of this research are:

- To characterize crashes on Puerto Rico Toll Freeways (2006-2012)
- To develop the Safety Performance Function associated with freeway segments for Total and ROR crashes.
- To evaluate the effectiveness of longitudinal intermittent shoulder rumble strips along the NHS PR-52 by performing the Empirical Bayes Method.
- To generate Crash Modification Factors associated with the implementation of longitudinal intermittent shoulder rumble strips.
- To create recommendations to PRHTA based upon the results of this research investigation.

1.4 Scope of Work

The research study focused on the evaluation of the effectiveness of safety related treatments associated with shoulders on the freeways of the Commonwealth of Puerto Rico. The crash database that covers the periods from 2004 to 2013 was provided by the PRHTA Accident Analysis Office. Exposure data and other general geometric characteristics for freeways were provided by the PRHTA Office of Highway System. Specifications for the project were provided by the RSA Division. The research period was approximately 20 months.

1.5 Contributions to the State of the Art

This investigation creates several contributions to the highway safety field, both theoretical and practical. The first contribution was the calibration of unique SPF's for freeway segments including models for Total and ROR crashes in the estimation of the effectiveness of shoulder rumble strips. The distinctiveness of these models is the integration of new variables related to geometric characteristics of the freeways and also the integration of a climate related variable. The second contribution was the calibration of a jurisdictional SPF for freeway segments in Puerto Rico that can be use by highway safety officials. The third contribution was the development of first generation of CMF's associated with permanent intermittent longitudinal rumble strips along the shoulders on freeways.

1.6 Thesis Organization

The final product of this research will be presented on seven chapters as listed below.

- Chapter 1 includes the introduction, which contains the justification, objectives, the scope of the research, the contributions to the state of the art, as well as a summary of the thesis.
- Chapter 2 includes a literature review including the definitions, types and specifications of shoulder rumble strips, a summary of the CMF's published in the HSM and CMF's Clearinghouse, an overview of before-and-after studies including EB Method and the SPF's needed in order to perform the development of CMF's.
- Chapter 3 includes the methodology of the research study containing the description of the pilot project, the information relating to the data needed for the development of this research, and a detail description of the before-and-after study that was performed to obtain the CMF's.
- Chapter 4 covers an explanation and statistical analysis of the databases that provided the independent variables associated to the SPF.
- Chapter 5 contains a characterization of freeway crash data (dependent variable) covering the study period.
- Chapter 6 describes the preparation of the data for the development of the SPF, including the merging process, the identification of homogeneous segments using

the independent variables explained on the previous chapter, the preliminary clearing of homogeneous segments and the analysis of outliers for measured independent variables.

- Chapter 7 explains the calibration process of the SPF using the negative binomial distribution for Total and ROR crashes of the reference group as well as a jurisdictional SPF for freeway segments.
- Chapter 8 reviews the EB Method developed to obtain the SPF's, index of effectiveness, the percentage of crash reduction and the CMFs associated with the intermittent shoulder rumble strips project.
- Chapter 9 summarizes the conclusions and recommendations associated with this research study.

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter reviewed the literature associated with this investigation. First, there is a summary of the description and technical specifications associated with shoulder rumble strips. Second, a discussion of published CMF's associated with shoulder rumble strips. Finally, an insight of the role of Observational Studies and the EB Method in the evaluation of the effectiveness of shoulder rumble strips.

2.2 Shoulder Rumble Strips

This section addresses the literature associated with the treatment in which the CMF's will be developed. First, a discussion of pertinent definitions based upon technical publications and the types of rumble strips will be discuss. Then the specifications and standard drawing or schematics for shoulder rumble strips will be summarized.

2.2.1 Definition and Types of Rumble Strips

The 2004 version of the AASHTO "A Policy on Geometric Design of Highways and Streets" defines rumble strips applications on shoulders as a safety feature that reduces ROR crashes caused by drivers that can fall to sleep while driving (AASHTO, 2004). The 2011 version includes a particular section for rumble strips treatments that emphasizes that the objective of shoulder rumble strips is to alert drivers to return to the traveled way. It states that rumble strips have been proven effective in reducing crashes, but it has limitations such as the noise levels, possible loss of control for cyclists and motorcyclists and maintenance issues. (AASHTO, 2011). This version considers that rumble strips are part of the cross section elements.

The 2010 HSM defines rumble strips as devices designed to give strong auditory and tactile feedback to errant vehicles leaving the travel way (AASHTO, 2010). In other words, 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 in preventing crashes (FHWA, 2011).

Rumble strips can be either permanent or provisional. Examples of permanent installment of rumble strips are: on the centerline of a two way roadway or in the shoulder of a roadway. In the case of provisional rumble strips, they are commonly used to alert vehicles of changes in the roadway. One of the most common applications for this treatment is on temporary working zones.

There are **longitudinal** and **transverse** rumble strips. Longitudinal rumble strips can be installed either in the center line, edge line or shoulder of a roadway. Edge line rumble strips are placed in the edge line of the pavement and they help prevent vehicles from leaving the road. Shoulder rumble strips have the same functionality as edge line rumble strip but they are usually installed on the shoulder near the outside edge of the lane. Centerline rumble strips are installed on the centerline of a two lanes roadway and they prevent head-on collisions between vehicles that are traveling from two different directions especially, on rural two lane roads.

The purpose of transverse rumble strips is to alert drivers of a potential change or hazards in the roadway. This can be applied on the approaches to intersections, temporary work zones, toll lanes and others. Figure 2.1 represents a diagram with the application categories of rumble strips.

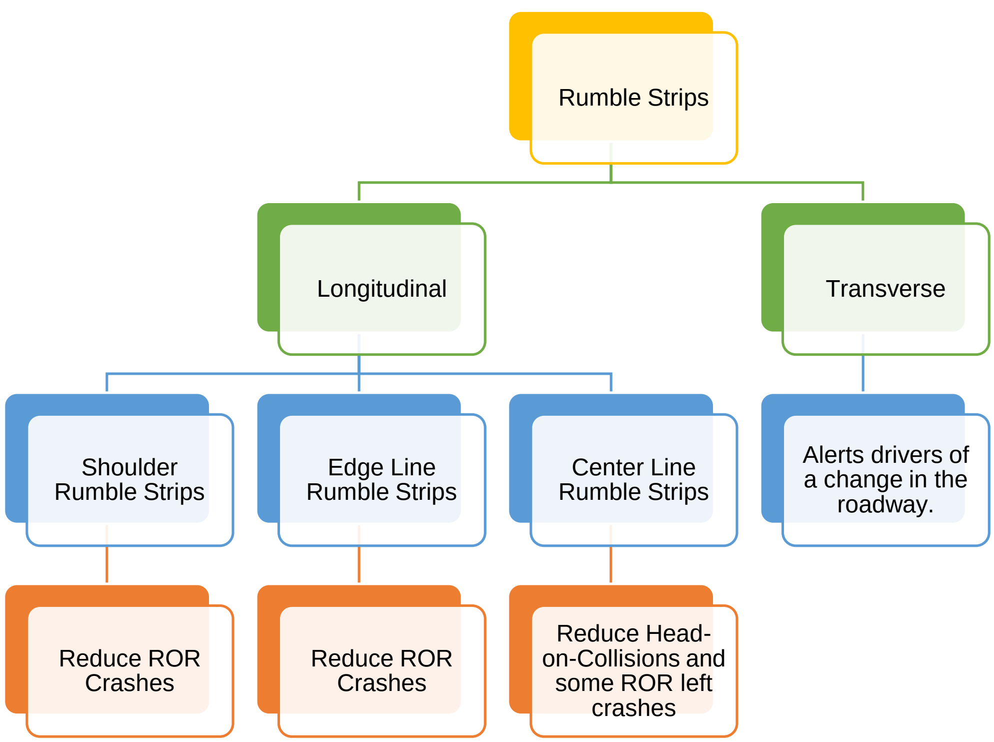


Figure 2.1 Application Categories for Rumble Strips

In PR, the most commonly used rumble strips are the longitudinal shoulder or center line rumble strips. Figure 2.2 presents a picture of a permanent rumble strips on the shoulder of PR-2 highway at the municipality of Yauco.

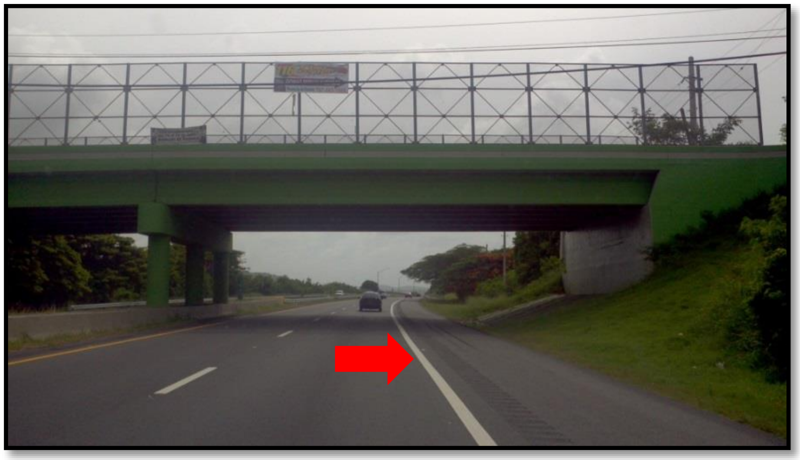


Figure 2.2 Rumble Strips in PR-2 Highway

In terms of shoulder rumble strips, the FHWA recommends the use of the treatment along the entire corridor, instead of partial segments of the corridor. On divided highways, they recommend the use of rumble strips in the right shoulder as well as in the left inner shoulder. FHWA also recommend the installation of rumble strips along the shoulder as well as in the centerline of the roadway to prevent serious injury crashes.

There are four types of rumble strips designs. The first one, the **milled-in** rumble strips, is a texture or groove in the pavement made by a rotary cutting machine. The milled-in has proven to be effective because of its noise level performance. Research shown that milled-in strips produce more vibration and noise than the other types of rumble strips.

Dimensions for milled-in rumble strips depend primarily on road characteristics and operational conditions. The most common dimensions are 17.8 centimeter wide, 40.64 centimeter long and a depth of 1.27 centimeter. Studies have proven that rumble strips installed nearest the edge line or with less offset from the edge line are more effective because they can alert drivers faster and they can recover sooner returning to their travel lane (FHWA, 2011). Another characteristic of milled-in rumble strips is that they can be either continuous or intermittent. The continuous rumble strips is recommended along a corridor because they provide more coverage.

The second design type of rumble strips is the **rolled** rumble strips. Rolled rumble strips are depressions that are made during the process of compaction of the hot asphalt pavement. The noise level on this kind of rumble strips is less than the milled-in rumble strips. To install the rolled rumble strips they use a roller with steel pipes welded to drums that creates depressions on the asphalt surface.

Figure 2.3 Milled in, Rolled or Raised Rumble Strips (Google Images, 2014)

The final two design types of rumble strips are **raised** and **formed**. The **raised** rumble strips can be shaped either round or rectangular and are recommended in warm climates. The raised rumble strips is commonly use in work zones because it can easily adhere to the pavement. The **formed** rumble strips or corrugated is similar to the rolled type but they are typically use in concrete pave shoulders. Figure 2.3 presents pictures of milled- in rumble strips, rolled and raised rumble strips.

In terms of installation FHWA recommend to measure the offset of the rumble strips from the edge of the travel lane. During construction, they have to provide safe accommodations for the vehicles using the roads. Another relevant recommendation is not to install rumble strips in shoulders designed for cyclists. If bicycle lanes exist near the shoulder, special provisions are needed such as gaps of 3.05 to 3.66 meters between the rumble strips to improve bicyclist's movement. To avoid pavement deterioration the installation should be a few centimeters away from the joint.

One concern of shoulder rumble strips is the noise level they produce, which may affect nearby residents. To know the positive effects of this treatment FHWA recommend government agencies to inform the public before the installation of this safety road treatment.

Overall, rumble strips are proven to be cost-effective countermeasures, which save lives and can reduce crash severities. Shoulder rumble strips are an effective low-cost crash mitigation treatment with an estimated installation cost between 30 to 40 cents per foot. This is relatively inexpensive as compared to the social cost of losing a human life.

Other countries have study the effects of longitudinal rumble strips. The European Directors of Roads issued a special report about shoulder and medians rumble strips in April 2010 (EDR, 2010). Sweden reports a reduction of crashes of 10 to 15 percent after implementing shoulder rumble strips. Other countries in Europe have installed rumble strips before the entrance of tunnels to alert drives of the change ahead.

2.2.2 Specifications, Standard Drawings and Construction Equipment regarding Shoulder Rumble Strips

The FHWA Safety Program has developed a Technical Advisory for shoulder and edge line rumble strips (FHWA, 2011). These are the guidelines for the design and installation of this treatment on shoulders and edge lines of roadways across the USA. Figure 2.4 is a schematic of the minimum dimensions required by the Technical Advisory where letter A is the minimum offset of up to 22.86 centimeter, B is the minimum length of 40.6 centimeter, C is the minimum width of 17.8 centimeter and D is the minimum depth of 1.27 centimeter and E the bicycle gap which is between 3.05 to 3.66 meters.

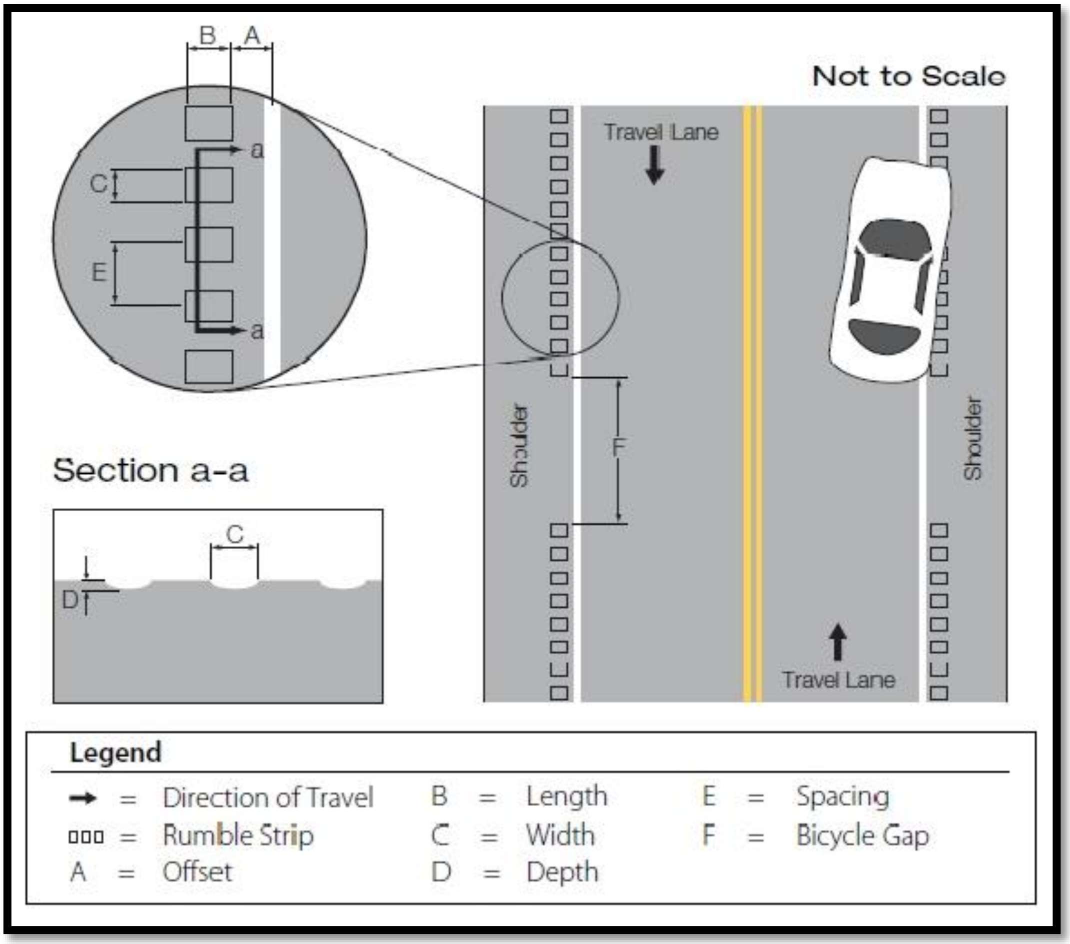


Figure 2.4 Schematic of Shoulder Rumble Strips (FHWA, 2011)

Recommended practices listed on the Technical Advisory related to rumble strips indicates that can be installed on all rural freeways and highways with a minimum posted speed of 80 kilometers per hour, along rural, urban corridors or highways with high incidence of ROR crashes. Furthermore, rumble strips should be located at least a few centimeters away from joints to reduce the pavement deterioration.

The report “Guidance for the Design and Application of Shoulder and Centerline Rumble Strips” presents practical guidelines for the design and construction of both shoulder and centerline rumble strips (NCHRP, 2009). Other main objectives of the report was to perform a complete literature review of previous research and existing policies on rumble strips, evaluate the safety effectiveness of rumble strips and provide a guidance of the effectiveness of the treatment for various locations.

The NCHRP performed an email survey to 27 state transportation agencies and 4 Canadian transportation agencies and quantified the safety effectiveness of shoulder rumble strips placed in various locations with respect to the edge line by performing before-and-after studies such as Empirical Bayes methodology and comparison group analysis. The following guidelines were compiled regarding shoulder rumble strips:

- Minimum Shoulder Width: The most common value is 1.22 meter.
- Minimum Lateral Clearance: This distance is defined as the measurement between the outside edges of the shoulder to the outside edge of the rumble strips and the most common values are 1.22 and 1.8 meters.
- Rumble Strips Width: The minimum requirements ranges from 12.7 to 17.78 centimeters, but the most common value is 17.8 centimeter.
- Rumble Strips Length: It ranges from 15.24 to 40.64 centimeters, but the most common value is 40.6 centimeter.
- Rumble Strips Depth: It ranges from 1.27 to 1.59 centimeters, but the most common value is 1.27 centimeter.
- Center to Center Spacing: 30.48 centimeter for most transportation agencies.
- Bicycle Gap: 3.05 to 3.66 meters gaps for most transportation agencies within 12.2 to 18.3 meters cycles.
- Minimum ADT: It can range from 1,500 to 3,000 vehicles daily.
- Pavement Type: The majority of the agencies install the rumble strips on asphalt surfaces.
- Minimum Pavement Depth: It can range from 25 to 152 millimeters.
- Preferred Area Type: Some agencies only limited the installment of rumble strips on rural areas due to the noise disturbance.
- Minimum Speed Limit: Minimum speed limits varies between transportation agencies. It can range between 72 to 80 kilometers per hour.

Primary recommendation from this report is that shoulder rumble strips located on roads, where no bikes are expected, should be design to produce sounds between 10 to 15 dBA in the passenger compartment to alert drivers that the vehicles is leaving the travel lane. On urban areas, the sound levels shall be between 6 to 12 dBA in the passenger compartment.

The 2009 edition of the Manual of Uniform Traffic Control Devices (MUTCD) has a chapter for rumble strips markings but they do not have provisions concerning the design and installation of longitudinal or transverse rumble strips (FHWA, 2009). The MUTCD only states a standard regarding the color of the rumble strips markings and the color of the edge line or centerline of the roadway (Section 3A.05). In the case of transverse provisional rumble strips, the Manual states that they cannot be the same color of pavement, they shall be white or black.

The PRHTA "Standard Specifications for Road and Bridge Construction" do not provide any specification concerning rumble strips. In 2012, the Authority issued Design Directive No. 409 for the installment of rumble strips in the island highway system (PRHTA, 2012). This document detailed the following guidelines:

- Minimum Shoulder Width: 1.2 meter
- Lateral Clearance: 30.5 centimeter
- Rumble Strips Width: 22.9 centimeter
- Rumble Strips Length: Between 40.6 to 45.7 centimeters
- Rumble Strips Depth: Between 1.3 to 1.6 centimeters
- Center to Center Spacing: 30.5 centimeters
- Bicycle Gaps: 1.8 to 3.66 meters

It also detailed that the rumble strip cannot be installed on any structure or bridge. Rumble strips has to be installed 25 meter before and after any structure. Rumble strips are not permitted over pavement joints and special provisions are detailed for bicycle crossings.

The PRHTA Division of Highway Safety Projects has detail installation plan for shoulder rumble strips. PRHTA do not have an approved standard drawing for rumble strips applications in Puerto Rico. Figure 2.5 shows part of the installation plan of the PRHTA for shoulder rumble strips treatment.

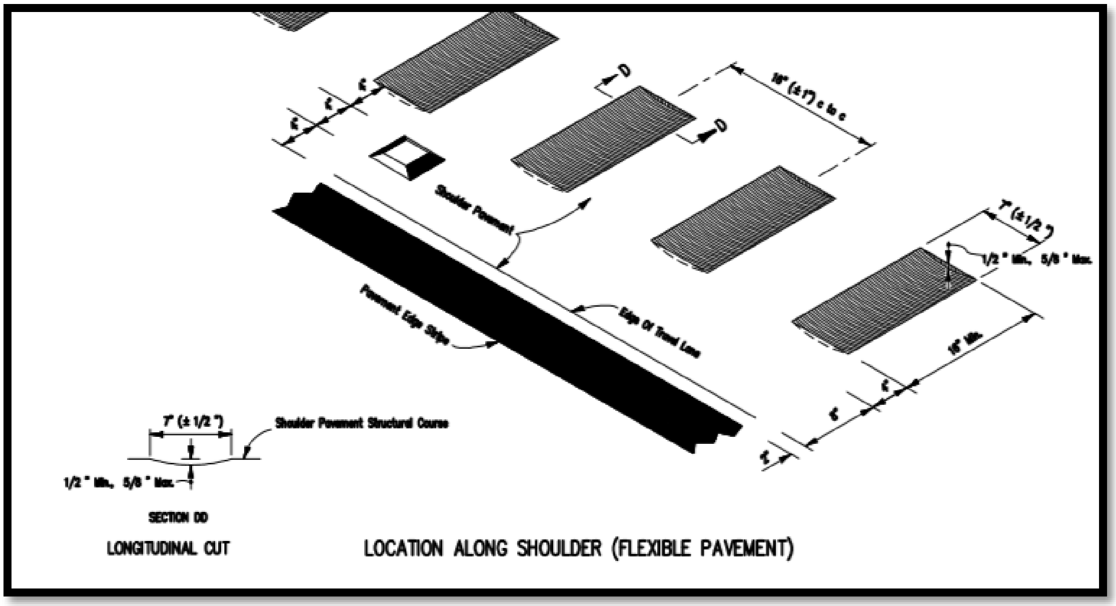


Figure 2.5 PRHTA Installation Plans for Shoulder Rumble Strips (PRHTA, 2013)

Table 2.1 compares the guidelines for the installation of shoulder rumble strip stipulated by the PRHTA and FHWA. The only difference is that in Puerto Rico it has larger lateral clearance between the strips and the edge of the travel lane than in other states and that they have a wider range than the states for the dimension of the bicycle gaps. Puerto Rico design directive do not specified a minimum posted speed requirement for the installation of shoulder rumble strips.

Table 2.1 Comparison of Guidelines between PR and USA

Requirements	FHWA (TA 5040.39)	NCHRP (641) Most Common Values	PRHTA (DD#409)
Minimum Shoulder Width	1.2 m	1.2 m	1.2 m
Lateral Clearance	22.9 cm	5.1 -22.9 cm	30.5 cm
Rumble Strips Width	22.9 cm	22.9 cm	22.9 cm
Rumble Strips Length	40.6 cm	40.6 cm	40.6- 45.7 cm
Rumble Strips Depth	1.27 cm	1.27 cm	1.3 – 1.6 cm
Center to Center Spacing	Not specified	30.5 cm	30.5 cm
Bicycle Gap	25.4-30.5 cm	25.4-30.5 cm	15.2–30.5 cm
Minimum Posted Speed	80 km/h	75-80 km/h	Not specified

In terms of construction equipment, there are a variety of manufactures for different types of machines that are used to install milled-in shoulder rumble strips. One of the most sophisticated rumble strip profiling machines is the Jamaco RS-20B. This machine has a diesel Cummins Engine that operates at 160 HP. (Jamaco, 2014) This pavement rumble strip milling machine surpasses expectations at cutting median rumble strips, with a production rate of up to 5.5 kilometer per hour. Some of the features of this machine are: the cutter assembly can be side shifted from one side of the machine to the other and it's a fully enclosed machine and has lighting for safety purposes during nighttime operations. This machine cuts grooves on the pavement. Behind it, there is a machine that will both sweep the milled asphalt and provides a conveyor belt to ship the asphalt chips into a dump truck. This is an all-in-one pass, leaving the pavement clear of debris.

Wirtgen Group has an adaptable rumble strip kit for cold milling machines. The W 50 DC and W 50 DCi are two types of cold milling machine that offer an adaptable kit for the construction of rumble strips. This adapter can make grooves of up to 2.54 centimeter depth. It offers an interchangeable milling drum which makes the grooves on the pavement and it can rumble up to 1.61 kilometer per hour. (Wirtgen, 2014)

Another manufacturer of adapters for the installation of rumble strips is Thomas Gridding, Inc. This manufacturer offers two types of models the SS-200 and the TR-200. The SS-200 has a production rate of up to 8.05 kilometer and is use for smaller projects. The TR-200 has a production rate of up to 2.4 kilometer per hour and has the advantage of being a machine that can be easily detached from the tow vehicle (Thomas Griding, 2013). Figure 2.6 presents three types of machines that can be used for the production of rumble strips.

Figure 2.6 Rumble Strips Production Equipment's (Jamaco, 2014)

The next section will summarize the locations that have been implementing intermittent pattern shoulder rumble strips

2.3 Intermittent Pattern Shoulder Rumble Strips

Shoulder rumble strips can be intermittent or continuous. Freeway PR-52 has an intermittent shoulder rumble strips with a gap between rumbles of 3.35 meter. In Canada, intermittent shoulder rumbles trips had been implemented since early 2000. The shoulder rumble strips have a pattern of 4 meters gap between rumbles and a length of 4 meters for a group of rumbles. (Behar et al., 2001)

The state of Minnesota policy of shoulder rumble strips indicates that they shall be placed on all rural highway projects where shoulders are constructed, reconstructed, or overlayed and where the posted speed limit is 80 kilometers per hour or greater. In order to meet the concerns of bicyclists, they had been implementing an intermittent pattern with a 3.66 meter gap. (MDOT, 2011) Other states that had implemented the same gap between rumbles are Colorado Missouri and Nuevo Mexico.

The next section will address the CMF's published on the Highway Safety Manual and the CMF Clearinghouse web site.

2.4 Shoulder Rumble Strips CMF's in the Highway Safety Manual and CMF's Clearinghouse

A CMF is a multiplicative factor that is used to estimate the number of crashes after employing a treatment at a specific location. The AASHTO's HSM Chapter 13 has a section related to CMFs for rumble strips treatment. HSM have records concerning CMF's for continuous shoulder rumble strips on multilane highways and freeways. The CMF for continuous shoulder rumble strips on multilane highways for all types of severity is listed as 0.84. The CMF for continuous shoulder rumble strips on multilane highways for ROR crashes is listed as 0.90 (table 13-44 of the HSM). For freeway applications, they have CMF's for milled in shoulder rumble strips that are 0.21 and for rolled in shoulder rumble strips which it is 0.82 both for ROR crashes (table 13-45 of the HSM).

Another source to find CMF's for various treatments or countermeasures is the CMF Clearinghouse Website. This website was funded by the USDOT and is currently maintained by the University of North Carolina Highway Safety Research Center. This website offers transportation agencies and officials a source or database of CMF's and additional information regarding the studies that took place in order to develop the CMF's published by the website. CMF Clearinghouse also provide the possibility to submit new CMF's by submitting investigations or studies regarding the development of new CMF's. At the end of the evaluation process, a score rating is given to each CMF's with the following formula:

$$\text{Score} = (2 * \text{study design}) + (2 * \text{sample size}) + \text{standard error} + \text{potential bias} + \text{data source} \quad (2.1)$$

If the score is between 1 to 2 it is a 1 star CMF, if it is between 3 to 6 it is a 2 star CMF, if it is between 7-10 it is a 3 star CMF, if it is between 11-13 it is a four star CMF and 14 or more it is a five star CMF. Table 2.2 shows the CMF's Clearinghouse points assignment based upon each category under evaluation for the submitted CMF's. The five categories upon evaluation are the study design, the sample size, the standard error, the potential bias and the source of the data that were used to develop the CMF.

Table 2.2 CMF Clearinghouse Rating System

Relative Rating	Excellent (2 Points)	Fair (1 point)	Poor (0 points)
Study Design	Statistically rigorous study design with reference group or randomized experiment and control	Cross sectional study or other coefficient based analysis	Simple before-and-after study
Sample Size	Large sample, multiple years, diversity of sites	Moderate sample size, limited years, and limited diversity of sites	Limited homogeneous sample
Standard Error	Small compared to CRF	Relatively large SE, but confidence interval does not include zero	Large SE and confidence interval includes zero
Potential Bias	Controls for all sources of known potential bias	Controls for some sources of potential bias	No consideration of potential bias
Data Source	Diversity in States representing different geographies	Limited to one State, but diversity in geography within State	Limited to one jurisdiction in one State

The CMF Clearinghouse had published more than 445 CMFs for shoulder, edge line, centerline and transverse rumble strips including their four basic rumble strips designs or types such as milled-in, rolled-in, raised and formed. A variety of research has been conducted to study the safety effectiveness of different types of rumble strips on different locations (FHWA, 2009).

The CMF Clearinghouse has published a total of 321 CMF's for SRS including milled-in and rolled-in SRS types. These CMF's are differentiated by road types, crash types and crash severity. One aspect that the HSM and the Crash Modification Factor Clearinghouse has in common is that they do not provide a specific CMF for intermittent, skip pattern or non-continuous shoulder rumble strips as the one we pretend to evaluate on this research study.

The next section will define a typical design study in the development of quality CMF's. The observational before-and-after studies are generally use to evaluate the effectiveness of treatment or countermeasures.

2.5 The Role of Observational Before and After Studies in the Evaluation of Effectiveness of Shoulder Rumble Strips

Studies design can be either experimental or observational. Experimental studies in road safety are planned before implementing a treatment in randomly assigned sites. In experimental studies, sites randomly selected are either treated or left as an untreated sites for control group purposes. Observational studies cannot be planned beforehand because the treatment has already been implemented. This type of study has to be perform retrospectively by observing the performance of the treatment or countermeasure that was implemented. (FHWA, 2010).

Observational studies can be either cross sectional studies or before-and-after studies. Cross sectional studies compares the safety of a group of locations treated with a group of locations that have not been treated. One limitation of this type of study is that the untreated locations and the treated locations have to share similar characteristics. The before-and-after studies measure the effectiveness of a treatments that have been implemented by estimating the safety performance of similar treatment on the before and comparing with the crashes after it has been treated in a particular location. (FHWA, 2010)

There are three types of before-and-after studies namely, the Naïve Method, the Comparison Group Method and the Empirical Bayes Method. The Naïve Method is the simplest form. The only data needed in order to perform this analysis is the crash count of the period "before" the implementation of the treatment and the crash count for the period of "after" the treatment implementation. This method cannot distinguish between the effect of the treatment and the effect of other factors such as traffic, weather, driver behavior and many others that can affect the effectiveness of the treatment. For this reason, Hauer recommends to include a disclaimer if this type of method is employed in analyzing the effectiveness of a road safety treatment (Hauer, 2002).

The second before-and-after study is the Comparison Group Method, which is an assessment between a group of untreated segments and a group of treated entities. A group of untreated segments are denominated as the comparison group. Hauer suggest two assumptions to take into account when using this methodology (Hauer, 2002):

- During the before and after period the factors that affect safety have change in the same manner on both the treated and comparison group.
- The chance in the factor have influenced both groups in the same way.

This methodology is similar to the EB Method because it uses crash records from untreated sites to perform an estimate of the safety effectiveness of a specific countermeasure to account for all the factors that can influence safety. The major limitation of this methodology is the requirement of having an untreated or comparison group with similar characteristics than the treated group. This means it needs to have similar crash frequencies or similar rate of chance in crashes on the segments selected, as well as similar geometric and traffic characteristics.

Several investigations regarding the measure of the effectiveness of the shoulder rumble strips in which the Naïve Method and the Comparison Group Method had been used. One of the first investigations that studied the effectiveness of continuous milled-in rumble strips on shoulders was conducted on Albany, New York on the year 1998 (Perillo, 1998). This investigation was performed with the *naïve method* by comparing crash data for a 3 year before period with a 2 year after period. The researchers concluded that the continuous milled-in shoulder rumble strips were proven to cause a 65% reduction on ROR crashes on some New York State Highways, including a private toll road called the NY Thruway. This investigation concluded that shoulder rumble strips are an effective way of reducing the number of ROR crashes and it is cost-effective, due in part to their low initial installation and maintenance costs.

Researchers studied the impact of different treatments to prevent crashes, including rumble strips, in the state of Minnesota (Pitale et al., 2009). The researchers in Minnesota focused on the evaluation of the effect of road geometry on curve departure crashes. As part of this study they performed a before-and-after *Naïve Method*, by comparing crash rates to study the effectiveness of rumble strips on shoulders in curve sections. On edge line rumble strips on shoulders for two-lane road on curve sections, the reduction of crashes was 10%. The researchers also evaluated the effect of a rumble strips called the Rumble StripE that is similar in pattern as the milled-in (which has grooves) but is painted in long-lasting, highly reflective paint. One advantage of this treatment is that it performs better at nighttime because the driver can visualize the edge line of the roadway. In curve segments, where they added paved shoulder with rumble strips/stripes (rumble StripE) they reported a reduction of crashes of 37%.

The latest investigation on rumble strips, submitted on April 2013, was performed by the Washington State DOT (Olson et al., 2013). The researchers evaluated the performance of the combination of centerline and rumble strips on two-lane rural highway system by performing a before-and-after *Naïve Method* by comparing the crash rates. A total of 135.88 miles of treated and untreated highways segments were evaluated. Overall, the before-and-after analysis showed that there was a reduction of 66% of lane departure collisions and 56% decrease of this type of collision involving fatal-serious injuries. A reduction of 61.6% of all ROR collisions and 53.7% of this type of collision involving fatal-serious injuries was reported. The researchers concluded that the combination of both treatments is a low cost tool in reducing the ROR and lane departure collisions.

During 2004, investigators studied the effectiveness of shoulder rumble strips on rural multilane divided highways on the state of Minnesota by using *the Naïve Method and the Comparison Group Method* (Carrasco et al., 2004). The Naïve Method showed a reduction of total crashes of approximately 16%, a reduction of ROR crashes of 10% and a reduction of injuries on ROR crashes of 22%. The Comparison Group Method showed a reduction of total crashes of approximately 21%, a reduction of ROR crashes of 22% and a reduction of injuries on ROR crashes of 51%. The researchers concluded that the difference in values obtained by the two methodologies applied could be reduced by utilizing a combined analysis.

Griffith studied the safety effectiveness of rolled-in continuous shoulder rumble strips on freeways on the year 1999 by performing a before-and-after *Comparison Group*

Method (Griffith, 1999). In this specific study, they used data collected from the states of Illinois and California. The evaluation consisted of 63 projects on freeways of the state of Illinois and 28 projects on freeways from the state of California. The rolled-in continuous shoulder rumble strips were installed in both directions including the inside and outside shoulders on the rural freeways. Griffith concluded that for both urban and rural freeways treated with continuous rumble strips there was a reduction of 18.3 percent of ROR crashes. On rural freeways treated with continuous rumble strips there was a reduction of single – vehicles ROR crashes of 21%. On urban freeways treated with continuous rumble strips there was a reduction of single – vehicles ROR crashes of 7.3%.

A study performed on the state of Connecticut intended to evaluate the safety benefits of shoulder rumble strips on freeways (Smith and Ivan, 2005). The researchers performed a before-and-after *Comparison Group Method* for a six year period. (3 before and 3 after) The study included 20 freeways, which included sections with and without the rumble strips treatment. Connecticut DOT provided crash and annual average daily traffic databases. The before-and-after comparison group was performed because it accounted for unidentified factors that can affect in terms of safety for any countermeasure. At the end, they developed crash reduction factors associated with shoulder rumble strips with different characteristics such as presence of illumination, different types of speeds, number of lanes and section types.

The analysis showed a 25% decrease of crashes for segments with no illumination, 38% in segments with illumination, 38.4% on segments with speed limit of 65 mph, 12.8% on segments with speed limits that were less than 105 kilometers per hour, 32.9% on two lanes per direction freeways, 31.6% on three lanes per direction freeways, 29.8% on roadway sections that were between on and off ramps and 48.5% on interchanges sections. In conclusion, an approximate 33% reduction of single – vehicles crashes with fixed object resulted where shoulder rumble strips were installed. In general, each scenario analyzed for different freeway sections resulted in a reduction of crashes proving that the shoulder rumble strips is effective.

There are two guides with recommended protocols for the development of quality CMFs. The first guide was published by FHWA and the second guide was published by the National Cooperative Highway Research Program (NCHRP). Both guides indicates a distinct preference for the EB Method by alleging that this type of design is more complex and robust than other kind of study designs. The next section will summarize the EB Method and studies that have been performed to measure the effectiveness of the shoulder rumble strips by using this type of study design.

2.6 The Role of the Empirical Bayes Method in the Evaluation of Effectiveness of Shoulder Rumble Strips

The EB Method is the most common approach of crash prediction for researchers. Hauer indicated that the EB Method can improve the precision of the estimates of safety effectiveness, taking into account the limited amount of time (usually two to three years period) for the analysis (Hauer, 2002). This method is recommended by experts in the field because when a countermeasure had been implemented, it can account for the observed fluctuations in crash occurrences before-and-after the implementation that may be due to a regression to the mean (RTM). A regression to the mean bias refers to when there is a sudden decrease in crashes, on a specific segment that had not undergone any safety improvements, that is mainly cause by the randomness of the frequency of crashes.

The EB Method consists of four steps: the development of a SPF, the estimation of the relative weights, the estimation of expected crashes and the calculation of the index of effectiveness. These steps will be explained in more detail in the methodology of this investigation.

There are several investigation concerning the evaluation of the effectiveness of shoulder rumble strips that had used the EB Method. The NCHRP 641 “Guidance for the Design and Application of Shoulder and Centerline Rumble Strips” had contributed with a significant number of CMF and CRF published by the CMF Clearinghouse (NCHRP, 2009). The objective of this section was to quantify the safety of milled shoulder rumble strips on different types of roads such as urban freeways, divided and undivided urban multilane highways, rural multilane undivided highways and rural two lane roads. The researchers also evaluate the location of the milled shoulder rumble strips with respect to the edge line. This study evaluated a total of 191 kilometers of shoulder rumble strips on

Missouri, 852.6 kilometers of rumble strips on Minnesota and 265.44 kilometers of shoulder rumble strips on Pennsylvania.

A database was created with information regarding the location (beginning /ending mileposts, route, county, segment, offset), area type (urban/rural), roadway type (freeway, multilane or two lane), number of lanes, lane width, shoulder width, analysis period and average daily traffic. The collected crash data from the three states were covering from the year 1997 through 2006 in order to perform the before and after crash analysis. The crash data provided information such as the crash ID, date of crash, location, number of vehicles involved, crash severity, accident type and indicators of related events during collision.

The researchers had two different approaches in order to convey the analysis. The first approached used was the before-and-after *EB Method* and the second was a Cross-Sectional Generalized Linear Model Analysis. On this investigation a large quantity of crash reduction factors were developed. The reported estimation of reduction for ROR Crashes on Urban/Rural Freeways was 18% and ROR crashes that involved fatal injuries was 13%.

The report concluded that due to the proven effectiveness of shoulder rumble strips on different types of roadways, the low cost of installation and maintenance and the relative few concerns, it is a suitable safety related treatment. The researchers also recommend that on rural freeways the rumble strips most be installed as close to the edgeline to maximize effectiveness.

On 2000, Hanley et al. performed an analysis of accident reduction factors on California State Highways (Hanley et al., 2000). On this investigation, they developed crash reduction factors for different highway safety treatments such as shoulder widening, installation of rumble strips, superelevation correction and curve correction. Only projects that were completed during a period covering from 1988 to 1992 were included on this study. The researchers performed a before-and-after *EB Method*. A special software was employed named BEATS also called Bayesian Estimation of Accidents in Transportation Studies.

The evaluation of two projects that combined the installation of rumble strips with the widening of the shoulder on two different freeways in the state of California was performed. The researchers concluded that on freeways with combined shoulder widening and installation of rumble strips there was a reduction of 19 percent of all crashes and a reduction of 13 percent of ROR crashes.

In 2007, a group of researchers performed a study that quantified the safety benefits of rumble strips on two-lane rural highways in Minnesota (Patel et al., 2007). A before-and-after *EB Method* with reference group was performed. For this specific methodology, SPFs were developed for segments of roads with similar characteristics to the sites were the treatment had been implemented. The researchers use a negative binomial regression including variables such as AADT and length of segments to predict the frequency of crashes, which is the dependent variable. A total of 183 miles or milled in rumble strips were studied during a period covering from 1995 through 2001. The Pearson's chi-square or goodness of fit measured for the models developed were 1.3077 for all crashes and 1.1693 for injury crashes. A value close to one represents that the models have good fit. On two lane rural roads with rumble strips a reduction of all ROR crashes of 13% and a reduction of 18% of injuries from ROR crashes was calculated. The researchers concluded that although rumble strips was an experimental treatment, they were effective reducing ROR crashes on rural two lane roads.

In 2010, a group of investigators studied the impact of rumble strips on highways located on British Columbia (Sayed et al., 2010). A before-and-after *EB Method* with reference group was performed. For this specific methodology, a collision prediction model was developed for segments of roads with similar characteristics to the sites were the treatment was implemented. The researchers developed the models using the generalized linear modeling tool with a negative binomial distribution. The model included variables such as AADT and segment length in order to predict expected collision frequency, which is the dependent variable. Four different collision prediction models for different types of collisions such as severe collisions, ROR crashes, left ROR and head on collisions and right/left ROR collisions and head on collisions were developed. Results indicated that shoulder rumble strips reduce severe collisions 18% and ROR collisions by

22.5%, concluding that shoulder rumble strips are an effective way to reduce the severity of collisions.

On 2014, two studies on the state of Florida and Pennsylvania evaluated the effectiveness of shoulder rumble strips. The Florida study reported a reduction of 17% of total crashes for rural multilane highways. (Park et al., 2014) The Pennsylvania the study reported a reduction of 7% of total crashes on different types of road classifications (Wu et al., 2014)

The next section will discuss the importance of the calibration of SPF as a key step for the development of CMF's by using the EB Method.

2.7 The Role of Safety Performance Function in the Evaluation of Effectiveness of Shoulder Rumble Strip

The AASHTO HSM defines Safety Performance Functions as an equation that is use to estimate or predict the expected average crash frequency at a particular location as a function of exposure and geometric characteristics of a roadway. (AASHTO, 2010) Usually, these functions can predict average crash frequency either for individual roadway segments or intersections.

One of the key steps in order to perform an EB Method evaluation of safety effectiveness is the calibration of a SPF. The safety effectiveness of a treatment or countermeasure can be achieved by calibrating a SPF that can predict the crashes at a specific location and comparing this to the actual crash frequency at the location that the treatment was implemented. The SPF's serves as a key element to achieve the main purpose of the EB Method in safety effectiveness evaluation.

Another application for SPF's Statewide is to assist transportation agencies in their network screening process. SPF's can assist agencies by identifying potential locations were safety improvements are needed. It also can also assist agencies determining the projected safety effects for proposed roadway design changes. For this reason, it is very important that each state can calibrate their own SPF's for all kind of road types including segments and intersections.

States such as Alabama, Illinois and Virginia have calibrated their own SPF's using the exposure data and roadway characteristics from their own road network. In Alabama, researchers calibrated SPF's for two-lane two-way rural roads and four-lane divided highways by using Negative Binomial Distribution models. In Illinois, SPF's were calibrated for the purpose of future network screening and using only the traffic volumes as their independent variable for multiple road types segments and intersections. The state of Virginia calibrated SPF's for total crashes and fatal plus injury crashes for rural and urban intersections using traffic volume as there only independent variable.

There are two types of SPF's the Level I and Level II. Level I is the simplest form of SPF and is a function that determines the crash frequency based solely on the exposure data or traffic volumes. Level II SPF is a multivariate model that incorporates the traffic volumes as well as other road characteristics, and other variables.

The literature review performed for this investigation showed that they are different functional forms applicable to the SPF's. Hauer explains that the modelers assumes the typical form of exponential function in the development of SPF (Hauer, 2014). SPF's are non-lineal because of the variation of segment length as well as other characteristics on the segments such as AADT's and there is not a simple proportionality between the variables. In terms of functions, there is a variety of functions to choose from when modeling a SPF such as:

Power Functions: $E(\mu_i) = X^{\beta}$ (2.2)

Polynomial Functions: $E(\mu_i) = \beta_1 + \beta_2 X^2 + \beta_3 X^3$ (2.3)

Exponential Functions: $E(\mu_i) = e^{\beta x}$ (2.4)

Quadratic Functions: $E(\mu_i) = 1 + \beta_1 X + \beta_2 X^2$ (2.5)

Hoer Function (combination of exponential and power):

$$E(\mu_i) = X^{\beta 1} e^{\beta 2x} \quad (2.6)$$

On SPF, the expected or predicted number of crashes is denominated as $E(\mu_i)$ and is measured in crashes counts per year or per a period of time. The expected or predicted number of crashes is the dependent variable. The independent variables are the X's which can be road characteristics such as: segment length measure in kilometers or the annual average daily traffic of the segment in vehicles per day. Additionally, there are parameters called β_1, β_2, β_q, which are regression parameters.

In terms of the calibration of the SPF's, they are a variety of statistical regression models. In the past, many researchers used Poisson Distribution for calibrating crash count data. This distribution expresses the probability of a certain quantity of events happening in a giving period of time. In the Poisson Distribution, the probability (P) that the count of crashes (y_i) has a distribution equation as follows:

$$P(y_i) = \frac{\exp(-\mu i)(\mu i)^{yi}}{yi!} \qquad (2.7)$$

where μ_i is the expected crashes for a given period. The Poisson Distribution primary assumption is that the mean is equal to the variance. Recently, researchers had shown that the Negative Binomial Distribution (NBD) offers better fitted models than the Poisson Distribution because the NBD compensates in cases in which the variation is higher than the mean. If over-dispersed data is present, estimating a common Poison Distribution Model can result in biased and can lead into inconsistencies in the estimation of the parameters (Lord & Mannering, 2010). The overdispersion indicates how widely the crash counts are distributed around the estimated mean (AASHTO, 2010).

The NBD is able to account for over dispersion because it estimates an additional parameter called the negative binomial dispersion parameter (Φ) obtained from this regression. The probability distribution for the NBD is as follows:

$$P(yi) = \frac{\Gamma\left(yi+\left(\frac{1}{k}\right)\right)}{yi!\Gamma\left(\frac{1}{k}\right)} \quad \frac{\text{k}\mu\text{i}}{1+k\mu i}^{yi} \quad \frac{1}{(1+k\mu i)}^{1/k} \qquad (2.8)$$

where, μ_i is the expected crashes for a given period of time, the Γ is the representation of the gamma function and the count of crashes is denoted as y_i. The NBD is based upon three assumptions which are: crash counts on every unit are Poisson distributed, the measured in crashes counts per year or per a period of time (μ) are different and the frequency of μ's in the population can be well approximated by a Gamma Distribution (Hauer, 2015).

Although the most common approach in the development of SPF's is the NBD, there are other types of statistical regression models such as Zero Inflated Poisson and Zero Negative Binomial that have been use in the calibration of SPFs. These two types of mixed distributions are has been successful in calibrating models in which there is a great number of zeros. Although popular among highway safety analyst, experts argued that this types of models couldn't properly reflect the crash data (Lord & Mannering, 2010). Other models that had been use for modeling crash data such as the Poisson-Lognormal Models and Conway-Maxwell Poisson Model are not recommended for small samples.

In the studies related to evaluating the effectiveness of SRS, many had use the EB method approach and developed SPFs for their jurisdiction. Researchers in the state of Minnesota, performed a study that quantified the safety benefits of rumble strips on two-lane rural highways in Minnesota (Patel et al., 2007). The researchers performed the *EB Method* and calibrated *SPFs* for roads with similar characteristics to the sites were the treatment had been implemented. There SPFs were calibrated for total single vehicle run-off-road crashes by using a NBD, which included AADT as the independent variable. The basic form of the SPF included the fitted parameters α and β. Equation 2.9 represents the SPF calibrated by the researchers in Minnesota.

$$\text{Accidents} = e^{\alpha} * \text{AADT}^{\beta} * \text{yearly factors} \tag{2.9}$$

In British Columbia, a group of investigators studied the impact of rumble strips on highways (Sayed et al., 2010). The researchers performed the *EB Method* and calibrated collision prediction models with segment length and AADT as their independent variables.

Equation 2.10 represents the collision prediction model that the researchers from British Columbia developed.

$$E\ (\lambda i) = a_0 * V^{a1} * L^{a2} \qquad (2.10)$$

where V is the Annual Average Daily Traffic, L is the segment length in kilometers and E (λi) is the expected collision frequency for a 3-year period. Both research studies has limited independent variables. Roadside characteristics that can affect the incidence of crashes were not explored as part of this research.

The NCHRP 641 use data from three different states to evaluate the effectiveness of SRS. The researchers performed the *EB Method* and developed *SPFs* for different types of roads such as urban freeways, divided and undivided urban multilane highways, rural multilane undivided highways and rural two lane roads. The researchers attempted to incorporate the variable Roadside Hazard Rating (RHR) as well as the Average Daily Traffic (ADT). Equation 2.11 shows the SPF for divided highways developed by the researchers of this investigation.

$$\text{Expected Crashes} = \exp\ (a + b \ln\ (ADT) + c\ RHR_{out} + d\ RHR_{in}) \qquad (2.11)$$

where ADT represents the average daily traffic volume for both directions in vehicles per day, RHR_{out} represents the average roadside hazard rating for the outside or right side of the divided highway, RHR_{in} represents the average roadside hazard rating for the median side of the divided highway and the estimated coefficients are denoted by the letters a,b,c and d. In this investigation, similar form of models were developed also for rural two-lane roads.

During 2014, a study evaluating shoulder rumble strips on the state of Florida developed SPF's including variables such as segment length, AADT and median household income. Several models were developed for different types of crashes for rural multilane highways. The next chapter will summarize the methodology for this investigation.

3.0 METHODOLOGY

3.1 Introduction

The objective of this investigation is the application of a compiled methodology to evaluate the safety effectiveness of countermeasures associated with shoulders that can assist in the reduction of crashes along freeways and by doing so, to evaluate the effectiveness of the longitudinal intermittent rumble strips implemented along segments of freeways in Puerto Rico.

An observational study was performed with a before-and-after design. Observational studies are to be used when the treatment is already implemented and data has to be collected retrospectively in order to achieve the analysis required to acquire the effectiveness of the treatment. On this particular type of study, a before-and-after design is recommended by the US Department of Transportation (USDOT). The before-and-after design consists in the estimation of CMF using the change in crash counts between the before and after the implementation of a treatment (FHWA, 2010).

As mention in the literature review, the simplest type of before-and-after study is the Naïve Method. Hauer's defined the Naïve Method as the collection of the counts of crashes "before" the treatment is implemented and use it to predict the expected count of crashes of the "after" period had the treatment not been implemented (Hauer, 2002). The second before-and-after study is the Comparison Group Method. The Comparison Group Method use an untreated group of sites with similar characteristics as the treated sites and compared them to account for changes in crash frequencies. The third before-and-after study is the EB Method which is the most precise and robust of all the methodologies. This method can predict the count of crashes that would occurred in the "after" period if the treatment or countermeasure had not been implemented and then compares this values with the actual count of crashes in the "before" period of the treated site.

Figure 3.1 shows a flowchart of the methodology applied to evaluate safety related treatments implemented on highways around the island. In this investigation, the safety effectiveness of the non-continuous SRS was evaluated using the EB Method from Ezra

Hauer and steps for the calibration of SPF compiled from sources from the literature reviewed.

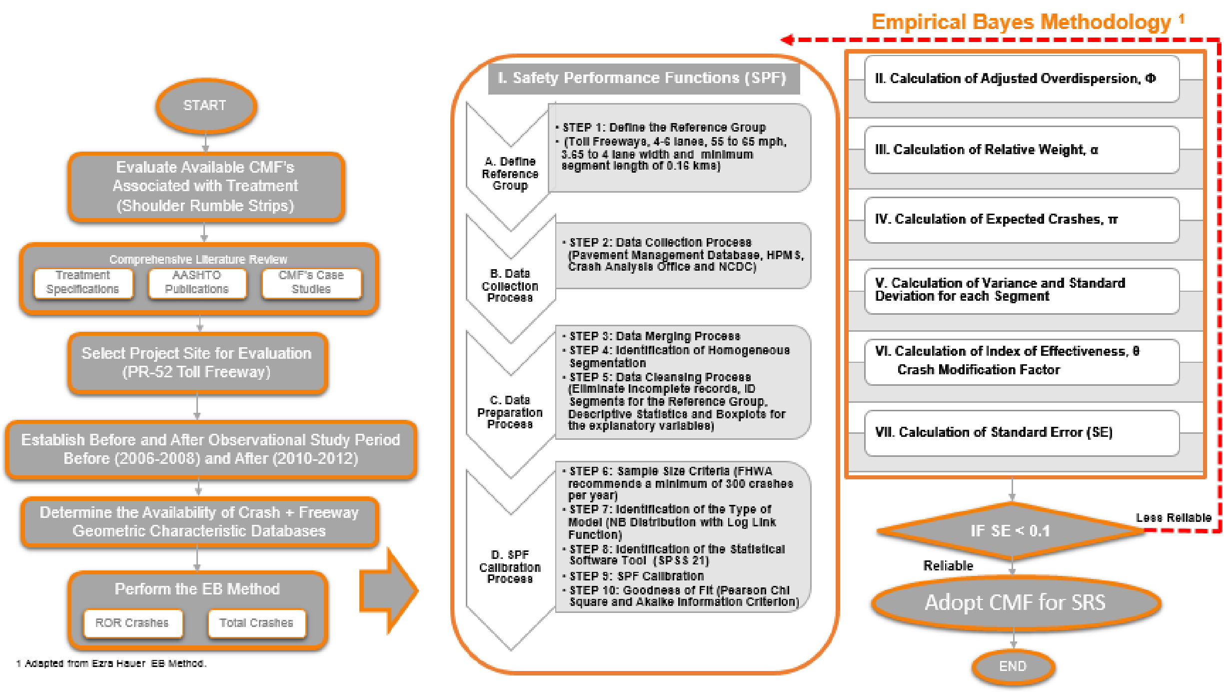


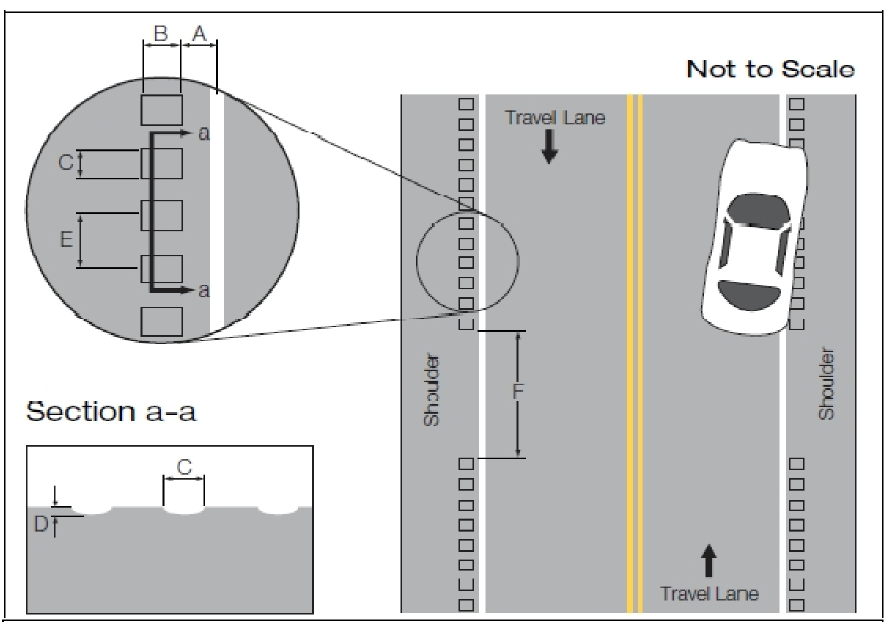
Figure 3.1 Methodology for the Development of CMF's for Non Continuous Shoulder Rumble Strips (NCRS)

3.2 Projects Description: Longitudinal Shoulder Rumble Strips

During the year 2009, the PRDTPW performed a pilot project of installation of milled-in shoulder rumble strips, located on NHS PR-52 freeway. A regional crew did this work. The rumble strips were installed only on the right shoulders from the South Caguas Toll Plaza (km 23.1) through the exit to the town of Salinas (km 66.3). Figure 3.2 shows the location of the shoulder rumble strips project in the PR-52 freeway from an extracted image of google earth.

Figure 3.2 Location of the Pilot SRS on PR-52 Freeway (Source: Google Earth)

Figure 3.3 shows the approximate dimensions of the longitudinal rumble strips on PR-52 freeway. This shoulder rumble strips is not continuous, it have intermittent gaps of approximately 3.35 meter. Personnel of the RSA Division of the PRHTA provided additional information of this specific project.



Legend:

A. Offset = 30.5 cm	C. Width =15.2 cm	E. Gap = 3.35 m
B. Length = 40.6 cm	D. Depth = 1.3 cm	F. Strip Length = 1.83 m

Figure 3.3 Dimensions of SRS on PR-52 (FHWA, 2011)

3.3 Data Collection

In before-and-after studies, information regarding crashes is needed in order to quantify the reduction of crashes per site. The Empirical Bayes Method requires information regarding exposure variables such as AADT's and geometric characteristics for the development of a Safety Performance Function (SPF). Two databases were essential for the completion of this investigation:

- **Crash Database:**

The Traffic Division of the Bureau of Highway Patrol is the entity in charge of monitoring the principal roads in the different police regions of the Island. The Traffic Division have trained and specialized police personal that go to the scene of the crash and gathers the information using a standardized police crash report (PPR-93). This standardized police report was developed in January of 1988 and it provides 112 elements of data of the crash evaluated (PRPD, 1988).

The crash report is divided in four main parts. The first section describes the exact location, date, time; day of the week, municipality, and the event related the collision and the type of collision. The second section describes the vehicles involved in the collision, name of the driver, address, gender, age and personal information related to the driver, type of vehicle, usage of the vehicle, mechanical defect of the vehicle (if applies) and other general information about the vehicles. The third section describes personal information related to the injured or fatally wounded in the crash and the last section involves a detailed written description and a schematic or drawing of the crash site. Additional, the report had blanks for specific generic codes that are provided within the sections of the report.

The PRHTA Crash Analysis Office is in charge of digitalizing and creating a database of all the crashes (including fatal, injuries and property damage) reported by the Traffic Division of the Bureau of Highway Patrol. The PRHTA provided two separate databases needed in order to complete our analysis, a crash database from a period covering 2004-2006 and a database from a period covering 2007-2013. The information withdrawn to perform the before-and-after study was the crash case ID, municipality, road number, kilometer and type of crash.

- **Highway Performance Monitoring System Database:**

The HPMS Database managed by the Office of Highway System of the PRHTA is a yearly report with information regarding the island's highway network system. PRHTA provided the report starting from the year 2006 through 2012.

This database provides information regarding physical features, surface data features and traffic related information for each highway section. Detail information that this report provides are: route number, county code, municipality, description, begin and end stations, functional classification, segment length, annual average daily traffic, %of trucks, directional factor, speed limit, design speed and information regarding the highway geometric characteristics such as lane and shoulder width, median width and type, number of lanes and other pertinent information. This information will be used in the development of the crash prediction models or SPF.

- **Other pertinent information:**

The PRHTA Office of Pavement Management provided information regarding super elevation, curve radius along the freeways, grades and surface type for both freeways. Information regarding annual mean precipitation was provided by the National Climatic Data Center.

3.4 Characterization of Crash Data

A characterization of the PRHTA crash data regarding freeways in Puerto Rico was performed in order to quantify the frequency of crashes during the study period for both freeways. A comparison between PR-52 and PR-22 was executed in terms of Total and ROR crashes.

3.5 Description of the Empirical Bayes Method

There are three types of before-and-after studies namely, the Naïve Method, the Comparison Group Method and the EB Method. The selected method of observational before-and-after study for this research is the EB Method. The study period for this EB Method will be 3 years for the before period and 3 years for the after period. This method is the most common approach of crash prediction used by researchers and is recommended by experts in the field because when a countermeasure had been implemented, it can account for the observed fluctuations in crash occurrences before and after the implementation that may be due to a regression to the mean (RTM). A regression to the mean bias refers to when there is a sudden decrease in crashes, on a specific segment that had not undergone any safety improvements, that is mainly cause by the randomness of the frequency of crashes.

Another advantage of the EB Method is that besides considering the crash data, it also accounts for traffic patterns on the specific site under evaluation. By reducing the RTM effect and taking under consideration the traffic patterns on a specific site, this method can better predict the number of crashes expected to occur during the after period for a specific treatment or countermeasure.

The EB Method consists of several steps, including: the development of SPFs for several types of crashes, the estimation of the relative weights, the estimation of expected crashes and the calculation of the index of effectiveness. The steps are summarize below:

Step #1: Development of Safety Performance Functions (SPF)

A SPF is a statistical model used to predict crashes in the future at a particular location such a road, segment or intersections. There are two types of SPF the simple and the full SPF's.

The simple (Level I) SPF is a model that includes variables such as segment length and annual average daily traffic (AADT) which expresses exposure measures. The full (Level II) SPF predicts crashes based upon traffic volumes and roadway geometric characteristics. The FHA recommends AADT and segment length as significant factor when developing SPF's (FHWA, 2013b). There are several steps when developing a SPF. In this investigation a full SPF will be developed. Figure 3.4 shows the steps towards the development of SPF's used on this research.

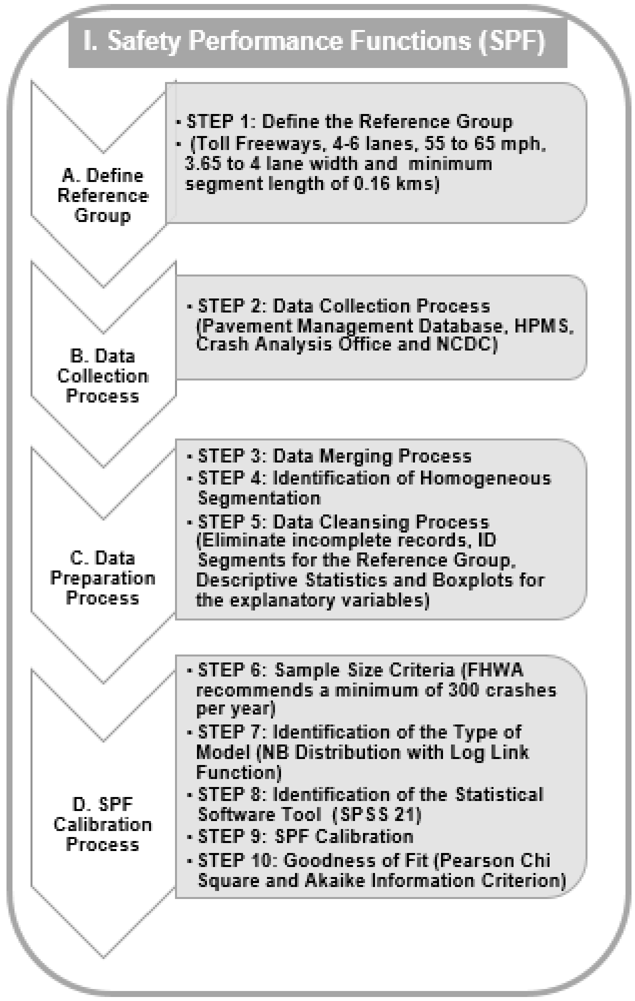


Figure 3.4 SPF Development Steps

One essential part in developing SPF, is to define the reference group. Hauer defines the reference group as the group of entities with the same physical characteristics and the same crash history as the study site (Hauer, 2002). On a publication called “A Guide to Developing Quality Crash Modification Factors” the authors express that currently, there is no formal method for determining a sample size for a reference group on an EB method. This publication suggests that the investigator should ensure that there is sufficient crash data to detect a statistically sound change in safety (FHWA, 2010). There are several steps in order to achieve a proper development of a SPF.

The *first step* in the development of a SPF, is the definition of the reference group for toll freeways in Puerto Rico. Only non-treated segments were considered on the reference group. Segments for the reference group were selected based upon several parameters such as speed limits ranging from 90 to 105 kilometers per hour and the total number of travel lanes ranging from 4 to 6 lanes. Another characteristic of the reference group is that all the segments will have 4 meters wide lanes. Only two of the island's toll freeways, NHS PR-52 and NHS PR-22, were considered on the reference group. FHWA recommends a size sample for SPF of 160.9 to 321.9 kilometers of road segments to be incorporated in the reference group. (FHWA, 2013)

The *second step* was the data collection process or compilation of necessary data in order to prepare a database that includes the proposed variables. For this specific study the PRHTA Crash Database from the year 2006-2012, HPMS Database from the year 2006-2012 and other additional data was compiled into one master database for the reference group. Table 3.1 summarizes the variables used for the calibration process and the source and contact information for each variable.

The *third and fourth steps* for development of the SPF was the data merging process and segmentation process based on homogenous segments. In this step, the HPMS Database (which provides most of the road characteristics) and other additional data was assembled manually using Microsoft Excel and engineering judgment. Homogenous segmentation is the art of dividing the roadway into individual segments with a set of unique attributes. A new segment begins when there is a change on any explanatory variables. The segment length for each segment was defined in kilometers. Segments that are equal or less than 0.16 kilometers were neglected to avoid small counts of crash data for such small segments.

Once the homogeneous segments were identified, then crash counts were assigned to each segment depending on their start and end location. Total and ROR crashes are count on two separate datasets for the calibration of two specific models associated with the reference group. The PRHTA defines ROR crashes on their database as the crashes that involved a vehicle that went off from a cliff, crashed with a fixed object such as a barrier, tree, post, traffic sign, structure, fence or any other object located on the roadside.

Table 3.1 Summary of Variables used on this Investigation

Variable Type	Variable	Variable Description	Source
Y (Response Variable)	Crashes per 3 Year Period	Crashes for a 3 year period for each freeway segments	Crash Analysis Office (PRHTA)
X (Explanatory Variable)	Annual Average Daily Traffic (AADT)	Exposure Variable measured in vehicles/day. It varies yearly.	HPMS Database - Office of Highway System (PRHTA)
X (Explanatory Variable)	Percent of Average Daily Trucks	Percentage of Average Daily Single Unit Trucks + Combination Trucks	HPMS Database -Office of Highway System (PRHTA)
X (Explanatory Variable)	Speed Limit	Posted speed limit for each segment in km/h.	HPMS Database - Office of Highway System (PRHTA)
X (Explanatory Variable)	Number of Lanes	Total number of lanes in both directions per segment.	HPMS Database - Office of Highway System (PRHTA)
X (Explanatory Variable)	Surface or Pavement Type	Bituminous Surface or Portland Cement Concrete	HPMS Database - Office of Highway System (PRHTA)
X (Explanatory Variable)	Median Width	Measurement of existing median width in meters.	HPMS Database managed by the Office of Highway System (PRHTA)
X (Explanatory Variable)	Median Type	Guardrail or Concrete Barrier versus unprotected	HPMS Database -Office of Highway System (PRHTA)
X (Explanatory Variable)	Right Shoulder Width	Measurement of existing shoulder width in meters.	HPMS Database - Office of Highway System (PRHTA)
X (Explanatory Variable)	International Roughness Index (IRI)	Measurement of the pavement surface roughness. (m/km)	HPMS Database - Office of Highway System (PRHTA)
X (Explanatory Variable)	Precipitation	Annual Mean Precipitation in inches.	National Climatic Data Center (NCDC)
X (Explanatory Variable)	Segment Length	Segment length based upon homogeneous segment. (kms)	The last variable establish by the segmentation process.
X (Explanatory Variable)	Presence of Lighting/ Freeway Ramps	Presence of lighting systems and ramps along freeways	Field visit to PR-52 and PR-22 to establish the locations of lighting systems.
X (Explanatory Variable)	Other road characteristics	Grades, Curve Radius and Superelevation	Office of Pavement Management (PRHTA)

The *fifth step* was the master database cleanup. Inaccurate or incomplete records were eliminated from the database. Crash records that lack the exact location of the crash or had errors related to the exact kilometer location were not considered. Basic descriptive statistics were performed for each of the proposed variables to corroborate there location (mean) and there variability (variance or standard deviation). The minimum and maximum values for each variable could assist, by identifying if the variables are between their individual acceptable value ranges. Another relevant statistic, is the identification of outliers by generating boxplots on SPSS. Finally, the selection of homogeneous segments that meets the criteria and definition of the reference group was carefully chosen.

The *sixth step* was the evaluation of the minimum criteria for the sample size. FHWA guidelines for the development of SPF indicates a minimum sample of 300 crashes per year and at least 3 years of data for the development of the prediction models.

The *seventh step* was to identifying the type of model that applies for the dataset. Crash data is variable or random. Due to the non-normality of the crash data, SPF are usually log-linear models with an assume Negative Binomial Distribution. In the past, many researchers used Poisson Distribution but recently researchers had shown that the Negative Binomial Distribution offers better fitted models than the Poisson Distribution. The Negative Binomial Distribution is based upon three assumptions which are: crash counts on every unit are Poisson distributed, the measured in crashes counts per year or per a period of time (μ) are different and the frequency of μ's in the population can be well approximated by a Gamma Distribution (Hauer, 2015).

The *eighth step* was the selection of a statistical package tool for the calibration of the models. The tool selected is the statistical software package called Statistical Package for the Social Sciences (SPSS) version 19. This software has a tool called “Generalized Linear Models” which can generate models in which the dependent variable is linearly connected to the factors and covariates with a specific link function. This tool can generate Negative Binomial with log link models as well as the overdispersion parameter.

The *ninth step* was the calibration of the SPF model. As mention before, the models were calibrated based upon crash types using a Negative Binomial Distribution (NBD) which generates an additional parameter called the overdispersion parameter (Φ). The mathematical form of the model is given below:

$$E(\mu_i) = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots + \beta_n X_n) \qquad (3.1)$$

where the dependent variable $E(\mu_i)$ is the expected or predicted number of crashes and measured in crashes counts per year or per a period of time, the X's are the independent variables that includes exposure and road characteristics and the β_0, β_1, β_2, β_n are regression parameters.

The modelling process was performed using a technique called the Backward Elimination Process. This technique involves starting with all candidate variables, testing the deletion of each variable using a criterion such as a statistical significant test such as the p-value and finally eliminate the variable that does not significantly degrade the model. This process is repeated until the variables that significantly contribute to the model remain.

The *tenth step* was the measurement of the goodness of fit of the model. The goodness of fit is the measurement of how well the model fits the observed data. It shows is there are discrepancies between the observed and the fitted values. The two measures for goodness of fit used in this research investigation were the Mean Deviance and the Pearson chi-square statistic. These values are often estimated by statistical software packages. Mean Deviance is the division between the deviance and the degrees of freedom of the model. This statistic provides a test for overdispersion and a measure of fit of the model. This value tends toward 1. The Pearson chi-square statistic (Person chi-square/ (degrees of freedom)) provides another measure of fit of the model and also it value tends toward 1.

The *eleventh and final step* is the validation of the model. This process is performed to decide whether the results obtain by the calibration of the SPF are acceptable as the description of the data in other words to identify the prediction performance of the calibrated models. Cross validation is when a data set is divided randomly in two datasets; one part to calibrate the SPF's and the other part to validate the model. FHWA has a report summarizing validation techniques for crash prediction models. This report summarizes model performance measures that are commonly use in the validation process of crash prediction models. The Mean Absolute Deviation (MAD) is commonly used to evaluate the prediction performance of the model. The Mean Square Prediction Error (MSPE) and Mean Squared Error (MSE) evaluate the error associated with the validation data set and the Mean Prediction Bias (MPB) measures the magnitude and direction of the model bias. The formulas are described below:

$$MAD = \frac{1}{n2} \times \Sigma\ /\hat{Y}_i - Y_i/ \qquad (3.2)$$

$$MSE = = \frac{1}{n1-p} \times \Sigma\ (Y_i - \hat{Y}_i)^2 \qquad (3.3)$$

$$MPSE = = \frac{1}{n2} \times \Sigma\ (Yi - \hat{Y}i)^2 \qquad (3.4)$$

$$MBP = \frac{1}{n2} \times \Sigma\ (\hat{Y}_i - Y_i) \qquad (3.5)$$

The variables are: n_2 is the validation dataset sample size, n_1 is the estimation dataset sample size, Y_i is the observed crash counts for segment i, and $\hat{Y}_i$ is the predicted crash count for segment i. The MAD gives the measurement of the average magnitude of variability of prediction (Washington et al., 2005). When the MSPE is higher than MSE it can show that the models may been overfitted and important variables where absent from the calibration process. If both have similar values indicates that the validation data and estimation data fit the model. If the MBP has a positive value signifies that the model overpredicts the observed validation data and if is negative value indicates that there can be underprediction. In this particular investigation, the lack of sufficient comparable freeway segments meant that this process was not achieved.

Summarizing, it is intended to calibrate two different full SPF for Toll Freeways in PR. The SPF's are listed below:

- SPF for injuries + fatalities of all types of crashes
- SPF for injuries + fatalities for ROR crashes

Listed below are the rest of the EB Method steps used to achieve the evaluation of the effectiveness of SRS on freeways in Puerto Rico:

Step #2: Determine the Overdispersion parameter, Φ_i for the roadway segment i and adjustment for the overdispersion parameter.

When modeling SPF researchers assume a Negative Binomial Distribution to represent the crash frequencies. One of the parameters of this distribution is called the overdispersion parameter Φ. Previous studies on EB Methodology indicates that an adjustment for each segment based on the results of the calibrated SPF per segment has to be performed using the overdispersion parameter by applying the following formula where Φ is the overall overdispersion parameter and β is a constant between 0 and 1. (Powers and Carson, 2004)

$$\Phi_i = \Phi * SPF^{\beta} \qquad (3.6)$$

Step #3: Determine the relative weight (α) for each roadway segment i

This step requires the calculation of a relative weight (α) for each specific segment. The following formula was used to calculate the relative weight where the relative weight per each segment is denominated as (α_i), the predicted crashes are denominated as (μ_i) and the adjusted *overdispersion parameter for each segment is denominated as (Φ_i)*:

$$\alpha_i = 1 / (1 + \mu_i / \Phi_i) \qquad (3.7)$$

Step #4: Determine the Expected Number of Crashes for roadway segment i.

This step requires the calculation for the total expected crashes on the “after period” per segment. The following formula was used to calculate the *expected number of crashes per segment on the “after period” is commonly denominated as (π_i)*, where the *relative weight is denominated as (α_i), the predicted crashes using the SPF are denominated as (μi) and the actual count of crashes per year or per period of time is denominated as (λ_i)*:

$$\pi_i = (\alpha_i) * (\mu_i) + (1-\alpha_i) *(\lambda_i) \qquad (3.8)$$

Step #5: Determine the Variance for the Roadway Segment i.

There are two possible ways to calculate the variance for each roadway segment. The following formulas are to determine the variance for each segment. The variable L_i *is the length of the segment*.

$$\sigma_i^2 = (1-\alpha_i) * \pi_i \quad \text{or} \quad \sigma_i^2 = \mu_i * (1 + (\mu_i / (\Phi_i * L_i)) \qquad (3.9)$$

Step #6: Determine the Index of Effectiveness

The *Index of Effectiveness is denominated as (θ)* and is a function containing all of the parameters that were earlier defined. The following formula was used to determine the index of effectiveness:

$$\theta = (\lambda_i / \pi_i) / (1 + (\sigma_i^2 / \pi_i^2)) \qquad (3.10)$$

Step #7: Determine the standard error for each CMF (Hauer, 2002).

$$Var(\theta) = \theta_{total}^2 \{[\sum\lambda / \sum\lambda^2] + [\sum\sigma_i^2 / \sum\pi^2]\} / [1 + (\sum\sigma_i^2 / \sum\pi^2)]^2 \qquad (3.11)$$

$$\text{Standard Error} = SQRT(Var(\theta)) \qquad (3.12)$$

where θ is the total effectiveness index, λ is sum of the actual crashes, π is the calculated expected crashes, σi_2 is the variance of the calculated expected crashes. A small standard error means greater certainty. The HSM defines the most reliable CMF's those that have standard errors of 0.1 or less and less reliable CMF's those that have standard errors between 0.2 and 0.3.

Step #8: Determine the relative difference in crash occurrences for roadway segment i or the percentage of reduction of crashes.

This refers as the **percentage of reduction** or increase of the occurrence of crashes from the before to the after period and is calculated using the following formula:

$$\text{Percent difference in crash} = \Delta = 100(1-\theta) \qquad (3.13)$$

Table 3.2 provides a summary of the EB Method. The EB Method is the most robust methodology and is known by practitioners as one of the best tools to obtain defensible crash reduction factors. This methodology employs the development of a SPF that can estimate crashes by including variables such as traffic and other geometric characteristics. The result of this methodology is the measurement of the percentage of reduction or increase of the occurrence of crashes.

Table 3.2 Summary of the EB Method

ID	Segment Length, L_i	$AADT_i$	Actual Crashes (λ_i)	Predicted Crashes $E(\mu_i)$	Adjusted (Φ_i)	Relative Weight (α_i)	Expected Crashes (π_i)	Variance (σ_i^2)	Index of Effectiveness (Θ_i)
i				SPF	$\Phi_i = \Phi * L^{\beta 1}$	$\alpha_i = 1/(1+\mu_i/\Phi_i)$	$\pi_i = \alpha i * \mu_i + (1-\alpha_i) * \lambda_i$	$\sigma_i^2 = (1-\alpha_i) * \pi_i$	$\Theta_i = (\lambda_i / \pi_i) / (1 + (\sigma_i^2 / \pi_i^2))$
			∑ Actual Crashes, λi				∑ Expected Crashes, π_i	∑Variance, σ_i^2	$\Theta_{Total} = (\sum\lambda_i / \sum\pi_i)/(1+(\sum\sigma_i^2 / \sum\pi_i^2))$

This chapter summarized the steps towards the development of unique SPF's for Total and ROR crashes as well as the methodology to achieve the development of CMF's associated with intermittent shoulder rumble strips. The next chapter addressed the data sources used on this investigation.

4.0 DATA COLLECTION: OVERVIEW OF DATA SOURCES

4.1 Introduction

The main objective of this research was to applicate a methodology to evaluate the effectiveness of road safety measures associated with shoulder treatments implemented in PR's freeway system and by doing so, evaluate the pilot project associated with the installation of longitudinal intermittent shoulder rumble strips in the NHS PR-52 toll freeway. The EB Method is a robust tool to evaluate the effectiveness of the longitudinal intermittent shoulder rumble strips on toll freeways.

The first step in the EB Method is the calibration of SPFs. A SPF is a statistical model that is used to predict crashes in the future at a particular location such a road, segment or intersections. It predicts crashes based upon traffic volumes and roadway geometric characteristics. In order to develop the models it is necessary to collect data regarding traffic volumes and roadway geometric characteristics. Other characteristics of the region such as weather (precipitation) will be incorporated to the model to assess its relevance with the incidence of crashes in the island. This chapter will address two of the main databases used in the development of the SPF's; the HPMS Database and the Pavement Management Database. The crash database will be address in more detail in chapter 5. The next section will describe the first database called the HPMS Database.

4.2 Highway Performance Monitoring System Database

The HPMS data was developed in 1978 by the USDOT and the FHWA to assess the highway system performance in the United States and there territories. This database is required by law specifically the Government Performance and Results Act and the Transportation Equity Act for the 21st Century (TEA-21).

The HPMS is the official source of data for the federal government in areas such as geometric, performance and operating highway characteristics. The FHWA provides a HPMS Field Manual that describes in detail the data collection process and reporting requirement. The chapter IV of the HPMS Field Manual describes in detail each variable collected in the database (FHWA, 2005).

In Puerto Rico, the agency in charge of the HPMS program is the PRHTA specifically the Office of Highway Systems. This office provided the HPMS Database for the only two toll freeways in Puerto Rico for the study period covering from 2006 to 2012. In the HPMS the two toll freeways PR-22 and PR-52 are divided into 29 segments with variable length. A description and statistical analysis of the independent variables that we obtain from the HPMS are describe bellow.

- **Annual Average Daily Traffic (AADT):**

The Annual Average Daily Traffic is defined as the average daily traffic on a roadway or highway including all the days of the week during a period of one year. The AADT provided by the HPMS represents the value of average vehicles per day in both directions of the freeway. This value can be either counted or factored meaning a value estimated using a growth factor. The HPMS manual recommends that states should offer count based AADT's values. Table 4.1 shows a descriptive statistical analysis for the AADT's for the study period of this investigation.

Table 4.1 Descriptive Statistical Analysis of Annual Average Daily (vehicles per day) Traffic for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	35,500	258,100	104,028	62,041	29,800	169,000	72,210	38,890
2007	35,500	259,600	104,862	62,042	23,900	170,000	70,466	39,587
2008	35,000	257,000	105,897	60,993	23,800	168,300	69,897	39,031
2009	33,700	256,200	107,269	60,723	21,000	167,800	70,231	38,273
2010	24,800	254,900	104,066	62,634	18,800	167,000	69,259	39,130
2011	24,300	251,600	99,366	62,249	18,700	164,800	69,014	38,187
2012	24,500	253,100	101,083	66,779	18,600	165,800	69,366	38,238

Table 4.1 shows that for both freeways the average of the AADT's has been decreasing over the years. The freeway PR-22 has more daily traffic than PR-52. PR-22 has a higher range of values of AADT's than PR-52.

- **Percent Average Daily Single Unit Truck (%):**

The percentage of average daily single unit truck represents the nearest whole percent of the daily single unit truck activity. Chapter III of the HMPS Field Manual defines single unit trucks as vehicles such as buses, two-axle six-tire single unit trucks, three-axle single unit trucks and four or more axles single unit trucks. Table 4.2 shows a descriptive statistical analysis of the Percent Average Daily Single Unit Truck (%).

Table 4.2 Descriptive Statistical Analysis of Percent Average Daily Single Unit Truck for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min. (%)	Max. (%)	Average (%)	Standard Deviation (%)	Min. (%)	Max. (%)	Average (%)	Standard Deviation (%)
2006	1	5	3.41	1.02	3	6	3.90	1.01
2007	3	9	4.72	1.56	4	8	5.28	1.49
2008	3	9	4.73	1.56	4	8	5.28	1.49
2009	4	8	5.59	1.18	4	12	6.55	2.81
2010	4	8	5.59	1.18	4	12	6.55	2.81
2011	3	5	3.86	0.58	4	12	5.07	2.43
2012	3	5	3.86	0.58	4	12	5.07	2.43

The statistical analysis in a seven year period showed small fluctuation within the values of single unit truck. The maximum percentage of single unit trucks (value of 12%) was reported on the PR-52 freeway near the town of Salinas which host the only truck weight station in the island.

- **Percent Average Daily Combination Truck (%):**

The percentage of average daily combination truck represents the nearest whole percent of the daily combination truck traffic. Chapter III of the HMPS Field Manual defines single unit trucks as vehicles such as buses, four or less axle single trailer trucks, five-axle single trailer truck, six or more axle single trailer truck, five or less axle multi-trailer truck, six-axle multi-trailer truck and seven or more axle multi-trailer truck. Table 4.3 shows a descriptive statistical analysis of the Percent Average Daily Combination Truck (%).

Table 4.3 Descriptive Statistical Analysis of Percent Average Daily Combination Truck for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min. (%)	Max. (%)	Average (%)	Standard Deviation (%)	Min. (%)	Max. (%)	Average (%)	Standard Deviation (%)
2006	0	4	1.59	1.05	1	4	1.72	0.96
2007	1	5	2.41	1.05	1	5	3.17	1.28
2008	1	5	2.41	1.05	1	5	3.17	1.28
2009	3	5	4.86	0.52	3	7	4.66	0.90
2010	3	5	4.86	0.52	3	7	4.66	0.90
2011	0	4	2.86	1.68	2	5	3.62	0.98
2012	0	4	2.86	1.68	2	5	3.62	0.98

The statistical analysis showed that the values of percent average daily combination truck is estimated every two years. The maximum percentage of combination trucks (value of 7%) was reported on the PR-52 freeway near the city of Ponce. The addition of the values of the percent average daily single trucks with the percent average combination truck equals the total percentage of trucks.

- **Directional Factor (%):**

The Directional Factor is a percent of design hour volume traveling in the peak direction for each sample segment. The directional factor ranges from 50 to 70 percent. Table 4.4 shows a descriptive statistical analysis of the Directional Factor(%).

Table 4.4 Descriptive Statistical Analysis of Directional Factor for PR-22 & PR-52 Freeways (Same Direction)

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min. (%)	Max. (%)	Average (%)	Standard Deviation (%)	Min. (%)	Max. (%)	Average (%)	Standard Deviation (%)
2006	55	65	61.21	3.45	50	65	58.28	5.05
2007	55	65	61.21	3.45	50	65	58.28	5.05
2008	55	60	58.62	2.27	55	70	59.48	2.79
2009	55	60	58.62	2.27	55	70	59.48	2.79
2010	55	60	58.62	2.27	55	70	59.48	2.79
2011	55	60	58.62	2.27	55	70	59.48	2.79
2012	55	70	61.25	3.18	60	60	60	0

The values for both freeways varies from 50 to 70 percent. The maximum values of Directional Factor was reported on the PR-52 freeway on a segment between the town of Juana Diaz and the city of Ponce.

- **Design Speed (km/hr):**

During a freeway design process, the designer selects a speed that will be later used to determine several geometric design elements of the freeway. This speed is called the design speed. The HPMS Field Manual describes that the design speed is calculated by the HPMS software by taking into account the length of individual horizontal curves, the tangents for each segment or the functional classification of the facility. The values of provided by the HPMS for design speed of both freeways varies from 105 to 110 kilometers per hour. Table 4.5 shows a descriptive statistical analysis of the Design Speed (km/hr).

Table 4.5 Descriptive Statistical Analysis of Design Speed (km/hr) for PR-22 & PR-52 Freeways

Years	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006-12	105	110	109.66	1.29	105	110	109.48	1.55

- **Speed Limit (km/hr):**

The speed limit refers to the posted speed limit for each segment on the freeway. It varies from 80 to 105 kilometers per hour for freeway PR-22 and from 90 to 105 kilometers per hour for freeway PR-52. Table 4.6 shows a descriptive statistical analysis of the Speed Limit (km/hr). The Speed Limit and the Design Speed were provided by PRHTA. The year 2009, some segments in San Juan increase from 80 to 90 kilometers per hour.

Table 4.6 Descriptive Statistical Analysis of Speed Limit (km/hr) for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	80	105	97.07	10.13	90	105	100.34	7.06
2007	80	105	97.07	10.13	90	105	100.34	7.06
2008	80	105	97.07	10.13	90	105	100.34	7.06
2009	80	105	97.24	9.22	90	105	100.34	7.06
2010	80	105	97.24	9.22	90	105	100.34	7.06
2011	80	105	97.24	9.22	90	105	100.34	7.06
2012	80	105	97.76	9.22	90	105	100.34	7.06

- **Number of Lanes**

The number of lanes is the total of lanes in both directions of the freeway. It varies from 4 to 6 lanes for freeway PR-22 and from 4 to 10 lanes for freeway PR-52. Table 4.7 shows the descriptive statistical analysis for number of lanes for both freeways. The number of lanes was considered as one of the 29 independent variables associated with the SPF for the reference group.

Table 4.7 Descriptive Statistical Analysis of Number of Lanes for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	4	6	4.66	0.61	4	8	4.90	1.14
2007	4	6	4.66	0.61	4	8	4.90	1.14
2008	4	6	4.55	0.57	4	8	4.90	1.14
2009	4	6	4.55	0.57	4	8	4.90	1.14
2010	4	6	4.55	0.57	4	10	4.97	1.38
2011	4	6	4.55	0.57	4	10	5.21	1.70
2012	4	6	4.55	0.57	4	10	5.21	1.70

- **Pavement Type**

The pavement type is defined as the pavement surface per segment. For both freeways there are three pavement types namely, high flexible pavement (type 4), high rigid pavement (type 5), high composite pavement (type 6). The high type flexible is a bituminous road on a flexible base with a combined surface and base thickness of 178 millimeters or more. (FHWA, 2005) The high type rigid is a Portland cement concrete pavement and the high type composite is a mixed bituminous on a rigid pavement with a combined surface and a base thickness of 178 millimeters or more. Table 4.8 presents the length of freeways segments for each type of pavement or surface per year.

Table 4.8 Total Length (Kilometers) for Different Pavement Types for PR-22 & PR-52 Freeways

YEAR	Freeway NHS PR-22			Freeway NHS PR-52		
	TYPE 4	TYPE 5	TYPE 6	TYPE 4	TYPE 5	TYPE 6
2006	25.95	49.95	N/A	25.45	68.7	14.15
2007	25.95	49.95	N/A	34.65	63.75	9.90
2008	33.25	45.2	1.40	51.65	56.65	N/A
2009	33.25	45.2	1.40	51.65	56.65	N/A
2010	33.25	45.2	1.40	56.95	51.35	N/A
2011	33.25	45.2	1.40	67.65	40.65	N/A
2012	33.25	45.2	1.40	78.2	30.1	N/A

- **Measured International Roughness Index**

The International Roughness Index (IRI) can be measured either in meters per kilometers or inches per mile (1m/km = 63.36 in/mi). In the period of time evaluated, the IRI varied from 0.98 to 7.14 meters per kilometer for freeway PR-22 and from 1.06 to 3.69 meter per kilometer for freeway PR-52. The last measurement of pavement roughness was performed during the year 2009, because the equipment that measured the pavement performance for the PRHTA stopped working. Table 4.9 shows the descriptive statistical analysis for pavement roughness (m/km) for both freeways.

Table 4.9 Descriptive Statistical Analysis of Pavement Roughness (m/km) for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	1.56	5.3	2.49	0.71	1.46	3.41	2.43	0.51
2007	1.56	3.2	2.38	0.47	1.34	3.61	2.43	0.67
2008	0.98	7.14	2.29	1.16	1.41	3.69	2.34	0.57
2009	1.13	3.78	2.11	0.69	1.06	3.56	2.10	0.55
2010	1.13	3.78	2.11	0.69	1.06	3.56	2.10	0.55
2011	1.13	3.78	2.11	0.69	1.06	3.56	2.10	0.55
2012	1.13	3.78	2.11	0.69	1.06	3.56	2.10	0.55

The segment that reported the highest roughness index (7.14 m/km) was from the kilometer 15.10 through the kilometer 15.57 in the city of Bayamón on the PR-22 freeway. In the PR-52 freeway the highest roughness index (3.69 m/km) reported was on a segment between the Montehiedra Avenue and the kilometer 9.8 just exiting the city of San Juan.

- **Median Width**

The median width measurement includes the width of the two left shoulders on the freeways. This measurement of the median width varies along the way for both freeways. The HPMS Field Manual defines the median type as positive barrier for the majority of the freeway segments. A positive barrier means that the median normally have either a guardrail or a concrete barrier. In the period of time evaluated, the median width varied from 1 to 28.6 meters for freeway PR-22 and from 1.2 to 30 meters for freeway PR-52. Table 4.10 shows the descriptive statistical analysis for the median width (m) for both freeways.

Table 4.10 Descriptive Statistical Analysis of Median Width (m) for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	1.6	28.6	14.53	6.50	1.2	27.5	16.81	7.44
2007	1.6	28.6	14.53	6.50	3.6	30	17.59	7.16
2008	1.6	28.6	14.10	6.52	3.6	30	17.59	7.16
2009	1.6	28.6	13.93	6.67	3.6	30	17.64	7.18
2010	1.6	28.6	13.93	6.67	2	30	17.33	7.66
2011	1.2	28.6	12.27	8.04	2	30	17.33	7.66
2012	1	28.6	12.10	8.24	2	30	17.33	7.66

The median width showed small fluctuation in a 7 year period for both freeways. The shortest median (1 meter) is located between kilometers 6 and 7 (near the exit of PR-165) in the municipality of Guaynabo.

- **Right and Left Shoulder Width**

The right shoulder width is measured in meters. All of the shoulders for both freeways have either bituminous concrete or Portland cement concrete surfaces. In the period of time evaluated, the right shoulder width varied from 2.4 to 3.5 meters for freeway PR-22 and from 2.7 to 3.4 meters for freeway PR-52. Table 4.11 shows the descriptive statistical analysis for the right shoulder width (m) for both freeways.

Table 4.11 Descriptive Statistical Analysis of Right Shoulder Width (m) for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	2.4	3.5	2.97	0.28	2.7	3.4	3.01	0.11
2007	2.4	3.5	2.97	0.28	2.7	3.4	2.99	0.14
2008	2.4	3.4	2.99	0.24	2.7	3.4	2.99	0.14
2009	2.4	3.4	2.99	0.24	2.7	3.4	3.01	0.16
2010	2.4	3.4	3.01	0.22	2.7	3.4	3.01	0.16
2011	2.4	3.4	3.01	0.22	2.7	3.4	3.01	0.16
2012	2.4	3.4	3.02	0.21	2.7	3.4	3.01	0.16

The right shoulder width did not change during the study period. Minimum and maximum values remained the same for both freeways. Table 4.12 shows the descriptive statistical analysis for the left shoulder width (m) for both freeways.

Table 4.12 Descriptive Statistical Analysis of Left Shoulder Width (m) for PR-22 & PR-52 Freeways

Year	Freeway NHS PR-22				Freeway NHS PR-52			
	Min.	Max.	Average	Standard Deviation	Min.	Max.	Average	Standard Deviation
2006	0	2.4	1.03	0.64	0	1.2	1.06	0.30
2007	0	2.4	1.03	0.64	0	2	1.18	0.29
2008	0	2.4	1.09	0.68	0.3	1.6	1.18	0.28
2009	0	2.4	1.09	0.68	0.3	1.6	1.18	0.28
2010	0	2.4	1.09	0.68	0.3	1.6	1.19	0.28
2011	0	2.4	1.00	0.69	0	1.5	1.07	0.40
2012	0	2.3	0.93	0.72	0	1.5	1.07	0.40

The left shoulder width do not report changes during the study period. In the period evaluated, the left shoulder width varied from 0 to 2.4 meters for freeway PR-22 and from 0 to 1.6 meters for freeway PR-52.

- **Other Geometric Characteristics of the HPMS**

The HPMS database reported that for the study period from 2007 to 2012 the lane width for all the segments for both freeways were 4 meters. As mentioned before, the majority of the median type were describe as positive barriers that have either guardrail or concrete barriers. In addition, the majority of the shoulder types are reported as surfaced type shoulders with either bituminous concrete or Portland cement concrete surfaces.

- **Rural or Urban Designation**

The HPMS Field Manual defines four different categories for rural or urban designation. The first is urban area with less than 4,999 population, the second is small urban area with 5,000 to 49,999 population, the third is small-urbanized area with 50,000 to 199,999 population and the fourth is large urbanized area with more than 200,000 population. Table 4.13 will establish the lineal length of freeway (kilometers) per each categorized rural or urban designation.

Table 4.13 Lineal Length (kilometers) for Urban/Rural Designation for PR-22 & PR-52 Freeways

Urban/Rural Designation	Freeway PR-22	Freeway PR-52
1. Rural Area (Less than 4,999 population)	4.45 kms	22 kms
2. Small Urban Area (5,000 to 49,999 population)	0	13.40 kms
3. Small Urbanized Area (50,000 to 199,999 population)	27.45 kms	21.8 kms
4. Large Urbanized Area (More than 200,000 population)	47.95 kms	51.10 kms
Total HPMS Freeway Length	79.85 kms	108.3 kms

The next database reviewed in this chapter is the Pavement Management Database. This database includes in detail the superelevation, grade and curve radius for both freeways.

4.3 Pavement Management Database

The Pavement Management Database was provided by the PRHTA Pavement Management Office. PRHTA provided two databases; one for the before period and one for the after period. These databases contain information regarding the geometric characteristics for both freeways emphasizing in the curve radius, superelevation and grade of the freeways. These measurements were taken by using a special equipment called Automated Road Analyzer (ARAN).

The ARAN is a vehicle that has technology such as sensors, laser reflectometers, global positioning systems, video, computers and other that provides information about the roadways and right of ways. The ARAN measures the geometric characteristics of the roadways in 20 meters (0.02 kilometers) intervals. In the freeways of this investigation, measurements starts from San Juan (km 0.0) to Arecibo (km 83.9) for the PR-22 freeway and from San Juan (km 0.0) to Ponce (km 108.3) for the PR-52 freeway.

- **Curve Radius**

On freeways where speed is high and uniform, horizontal curves are generally balanced to provide a smooth-riding experience. It is important to distinguish if the curve radius comply with the minimum radius. The minimum radius is a limiting value of curvature for a given design speed and is determined from the maximum rate of superelevation and the maximum side friction factor selected for design (limiting value of f). (AASHTO, 2011) Equation 4.1 is used to calculate the minimum radius for both freeways.

$$R_{min} = \frac{V2}{(127*(0.01emax+fmax))} \qquad (4.1)$$

On this equation the V represents the design speed in kilometers per hour, e_{max} represents the superelevation in percent and f_{max} represents the maximum allowable side friction factor. The design speed for both freeways is 110 km/hr, a maximum supeelevation of 8% and a friction factor of 0.11 obtain from table 3.7 of AASHTO “A Policy on Geometric Design of Highways and Streets”. The calculated minimum radius was 501 meters. A total of 95.3% of the radius for both freeways comply with the minimum radius.

Table 4.14 shows the descriptive statistics for curve radius (meters) for each freeway for the before and after periods of this investigation. The count row summarizes the number of curves for each freeway. During the period of 2006-2008 a total of 132 measurements of curve radius were obtained for the PR-22 freeway and a total of 139 measurements of curve radius were obtained for the PR-52 freeway. During the period of 2010 to 2012 a total of 129 measurements of curve radius were obtained for the PR-22 freeway and a total of 156 measurements of curve radius were obtained for the PR-52 freeway. *The asterisk (*) in the tables of this section corresponding to the values of the freeway PR-22 for the period (2010-2012) indicates that the measurements for curve* *radius, grade or slope and superelevation started from the kilometer 10.24 instead of starting from the kilometer 0.0.*

Table 4.14 Descriptive Statistical Analysis of Curve Radius (m) for PR-22 & PR-52 Freeways

Descriptive Statistic	Period (2006-2008)		Period (2010-2012)	
	PR-22	PR-52	PR-22*	PR-52
Minimum Value	262	308	266	276
Maximum Value	3,929	4,473	4,125	3,896.0
Average	1,853.66	1,368.81	2,009.6	1,444.8
Standard Deviation	896.16	832.478	823.1	833.10
Count	132	139	129	156

Table 4.15 shows the descriptive statistics for grade or slope (%) for each freeway for the before and after periods of this investigation. For the purpose of this analysis, an absolute value of grade was considered. The PR-52 freeway shows greater maximum value, average and standard deviation than the PR-22 freeway, which is rational considering the mountainous topography of the region.

Table 4.15 Descriptive Statistical Analysis of Grades (%) for PR-22 & PR-52 Freeways

Descriptive Statistic	Period (2006-2008)		Period (2010-2012)	
	PR-22	PR-52	PR-22*	PR-52
Minimum Value	0	0	0	0
Maximum Value	6.5	7.4	6.1	7.2
Average	1.65	2.25	1.6	2.25
Standard Deviation	1.37	1.79	1.32	1.79
Count	4,196	5,412	3,395	5,440

Table 4.16 shows the descriptive statistics for superelevation (%) for each freeway for the before and after periods of this investigation. For the purpose of this analysis, an absolute value of grade was considered.

Table 4.16 Descriptive Statistical Analysis of Superelevation (%) for PR-22 & PR-52 Freeways

Descriptive Statistic	Period (2006-2008)		Period (2010-2012)	
	PR-22	PR-52	PR-22*	PR-52
Minimum Value	0	0	0	0
Maximum Value	14	9.9	17.1	16.9
Average	3.04	3.01	3.02	3.16
Standard Deviation	1.69	2.07	1.99	2.09
Count	4196	5412	3,395	5,440

During the period of 2010 to 2012 the PR-22 freeway reported a maximum value of superelevation of 17.1% located in the kilometer 26.24. During the same period, the PR-52 reported a maximum value of superelevation of 16.9% located in the kilometer 30.1. The average of the superelevation remains around the 3% value for both freeways in both periods of time.

Additional relevant roadway characteristics are the location of bridges and illumination systems. In PR-22, the Pavement Management Office reported a total of 62 bridges from San Juan to Arecibo. In the PR-52, the same office reported a total 75 of bridges from San Juan to Ponce.

In terms of the illumination system, PR-22 reported a total of **38.48 kilometers** of illumination system located in different areas of the freeway. PR-52 reported a total of **51.3 kilometers** of illumination system located mainly on urban areas on different locations of the freeway.

The PRHTA Pavement Management Office provided elevations for both freeways that will be use as an explanatory variable associated with acknowledging the upward or downward position of each segment. The elevations were measured by using the ARAN road survey vehicle and were reported on meters.

The next section will summarizes other variables considered for this investigation. These variables are the location of ramps and weather conditions.

4.4 Additional Variables: Ramps and Precipitation

- **Location of Freeway Ramps**

The Highway Capacity Manual provides a volume for facilities that have uninterrupted flow. Volume 2 has a chapter dedicated to freeway facilities, basic freeway segments, freeway weaving segments, freeway merge and diverge segments, multilane highways and two lane highways.

An inventory of the location of each ramp was performed to locate the exact location in both freeways. Google Earth was used to calculate an approximate length for each ramp. The variable freeway ramps was defined as the 457 meters (1,500 feet) of diverge and merge area and the weaving length when individually evaluated. Figure 4.1 shows the Influence Areas of Merge, Diverge and Weaving segments on freeways.

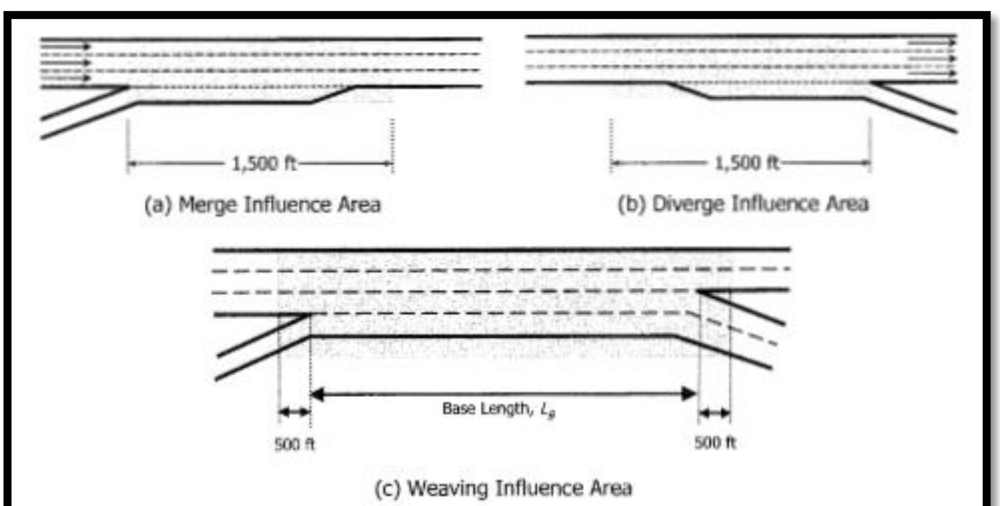


Figure 4.1 Influence Areas of Merge, Diverge and Weaving (AASHTO, 2010)

- **Precipitation**

In order to account for the weather conditions in both freeways the inclusion of the average annual precipitation to account for the amount of rainfall. The average annual precipitation was provided by the National Climatic Data Center (NCDC) for particular regions of the island. Table 4.17 shows the descriptive statistics for average annual precipitation (cm) for each freeway for the before and after periods of this investigation.

Table 4.17 Descriptive Statistical Analysis of Average Annual Precipitation (cm) for PR-22 & PR-52 Freeways

Descriptive Statistic	Period (2006-2008)		Period (2010-2012)	
	PR-22	PR-52	PR-22	PR-52
Minimum Value	148.54	87.78	197.11	90.79
Maximum Value	210.90	193.07	255.35	218.43
Average	187.22	138.08	224.96	158.08
Standard Deviation	21.0	45.04	23.03	56.68

The statistical analysis shows that in the period of 2010 to 2012 the reported average annual precipitation was higher than the period of 2006-2008. It also shows that the minimum values of average annual precipitation were reported on the PR-52 freeway that goes through a dry location on the south part of the island. Figure 4.2 shows the correlation of the precipitation for the before and after period by region.

PR-22 Region	Precipitation (cm) 2006-2008	Precipitation (cm) 2010-2012
San Juan	148.54	197.11
Bayamon	184.73	203.33
Bay-VA	184.73	203.33
VA-VB	168.78	234.07
VB- Barc	192.53	219.63
Bar-Arec	210.90	255.35
Arecibo	210.90	255.35
Ar-Hatillo	196.62	231.53

PR-52 Region	Precipitation (cm) 2006-2008	Precipitation (cm) 2010-2012
Rio Piedras	148.54	197.112
RP-Caguas	148.54	197.112
Caguas	193.07	218.432
Cag-Cayey	193.07	218.432
Cayey	193.07	218.432
Cay-Sal	193.07	218.432
Cay-Sal	87.78	90.792
Salinas	87.78	90.792
Sal-SI	104.01	106.185
SI-JDiaz	106.53	106.185
JDiaz-Ponce	100.79	117.543
Ponce	100.79	117.543

Figure 4.2 Summary of Precipitation (cm) by Region

The next chapter will summarize the characterization of the crash data for both freeways covering the periods from 2006 to 2012. A characterization of the ROR crashes for both freeways.

5.0 CRASH DATA OF FREEWAYS PR-52 AND PR-22

5.1 Introduction

The objective of this investigation was the evaluation of the effectiveness of the first pilot project associated with the installation of longitudinal intermittent shoulder rumble strips in the NHS PR-52 toll freeway. To achieve this objective an observational three year before-and-after study was performed. The longitudinal intermittent shoulder rumble strip was installed during the summer of the year 2009. The year 2009 was set as the buffer year for the study period. The before period for this study is defined as the period covering from the years 2006 to 2008 and the after period is defined as the period covering from the years 2010 to 2012.

The EB Method is the most precise and robust type of observational study for safety effectiveness evaluation. The first step in the EB Method is the development of SPF or a mathematical model that predict crashes per freeway segment. In this investigation, two types of models were developed in order to predict total and ROR crashes. This section will address the statistics of total and ROR crashes for the study period.

5.2 Total Crashes on Freeways PR-52 and PR-22

The freeways PR-52 and PR-22 are the most traveled tollways in the island of PR. The PR-52 was the first toll freeway in the island and was built in 1975. It has a total longitude of 108 kilometers. It is currently the second most traveled tollway on the island. It goes from the north side of the island (city of San Juan) to the south part of the island (city of Ponce). This freeway has a section that passes through a mountain system called Cordillera Central that has lower visibility because of the fog due the altitude of the section.

PR-22 is currently the most traveled tollway on the island. It has a longitude of 83 kilometers and it connects San Juan with the town of Hatillo in the north side of the island. It is the first toll freeway in Puerto Rico that is a highway concession comprise of two companies "Arbertis Infraestructuras" and Goldman Sachs Infrastructure. (Arbertis, 2011)

In terms of total crashes per year, during the study period, the freeway PR-52 has higher count of crashes than the PR-22. Figure 5.1 shows the total crashes per year for both freeways.

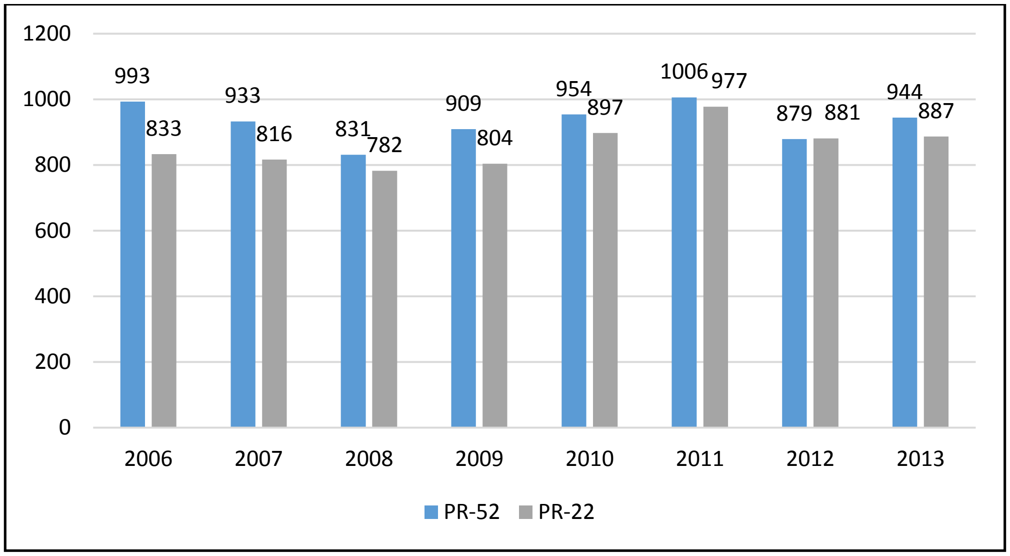


Figure 5.1 Total Crashes on Freeways PR-52 & PR-22

In terms of fatal crashes, the freeway PR-52 has higher count of fatal crashes than the PR-22, except during the year 2007. Figure 5.2 shows the fatal crashes per year for both freeways.

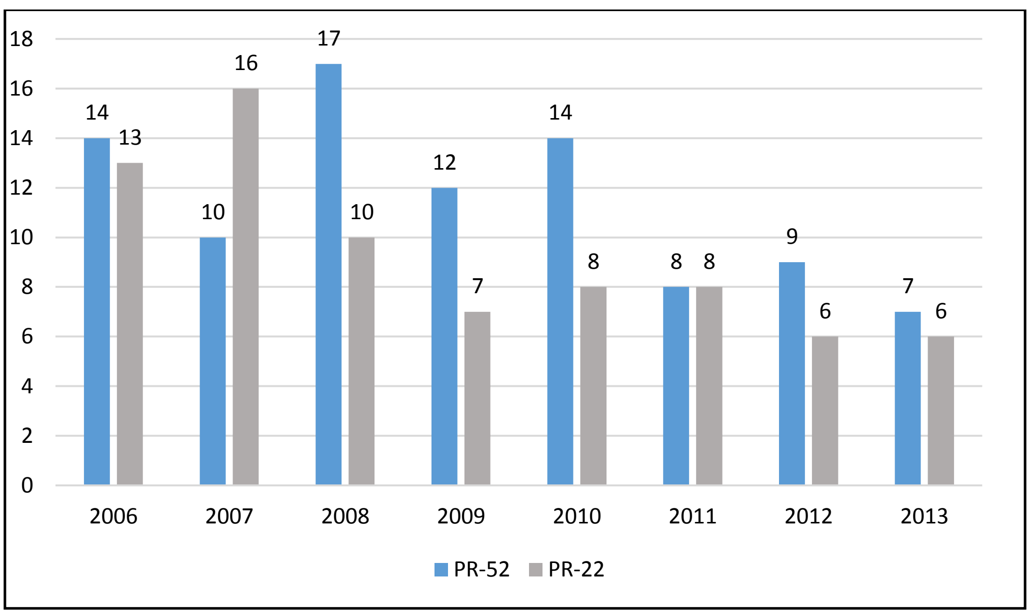


Figure 5.2 Crash Fatalities on Freeways PR-52 & PR-22

Overall, freeway PR-52 has more counts of total crashes and fatalities. Although PR-22 is the most travelled freeway PR-52 has the highest longitude and covers two large metropolitan areas. The next section will address the ROR crashes for both freeways.

5.3 ROR Crashes on Freeways PR-52 and PR-22

The PRHTA classifies ROR crashes as crashes involving vehicles that went off cliffs or roadside slopes, that crash with a fix object on the roadside such as illumination poles, barriers, trees, traffic signs, fences or other fixed objects. The intermittent shoulder rumble strips were installed to prevent ROR crashes.

Figure 5.3 shows ROR crashes count per year for both freeways PR-52 and PR-22. The freeway PR-52 has higher frequency of ROR crashes than PR-22 per year basis.

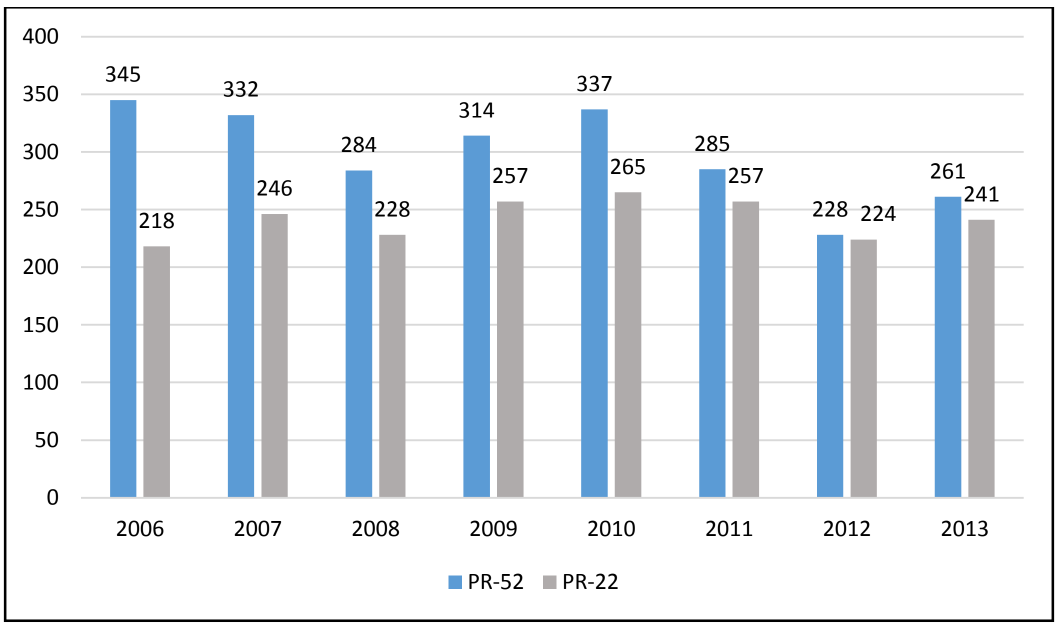


Figure 5.3 ROR Crashes on Freeways PR-52 & PR-22

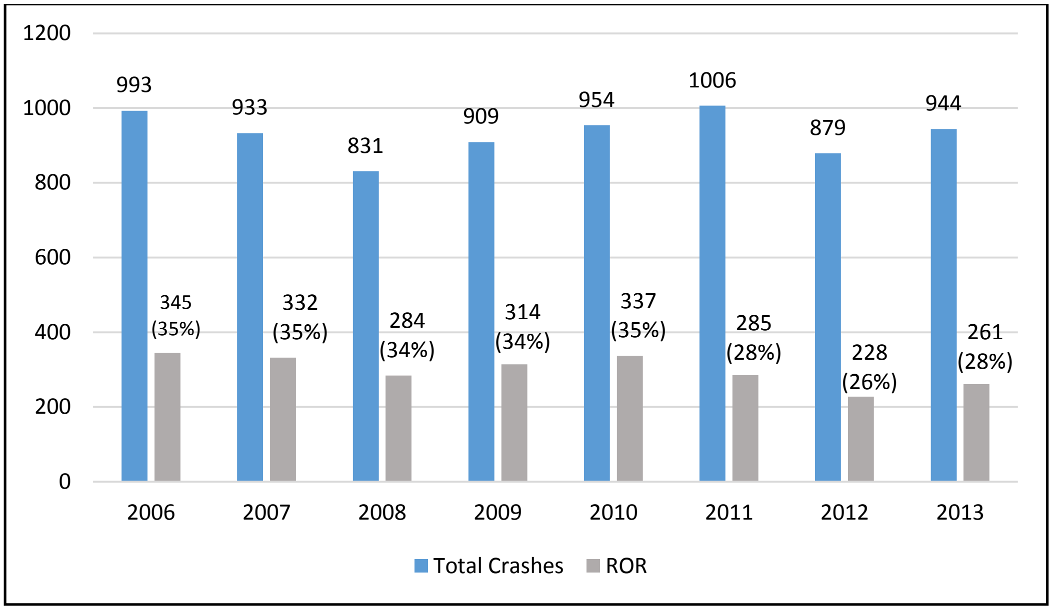


Figure 5.4 Percentage of ROR Crashes on Freeways PR-52

Figure 5.4 and Figure 5.5 respectively shows the percentage attributed to ROR crashes for both freeways. The tendency in Puerto Rico is that one out of three crashes are ROR crashes.

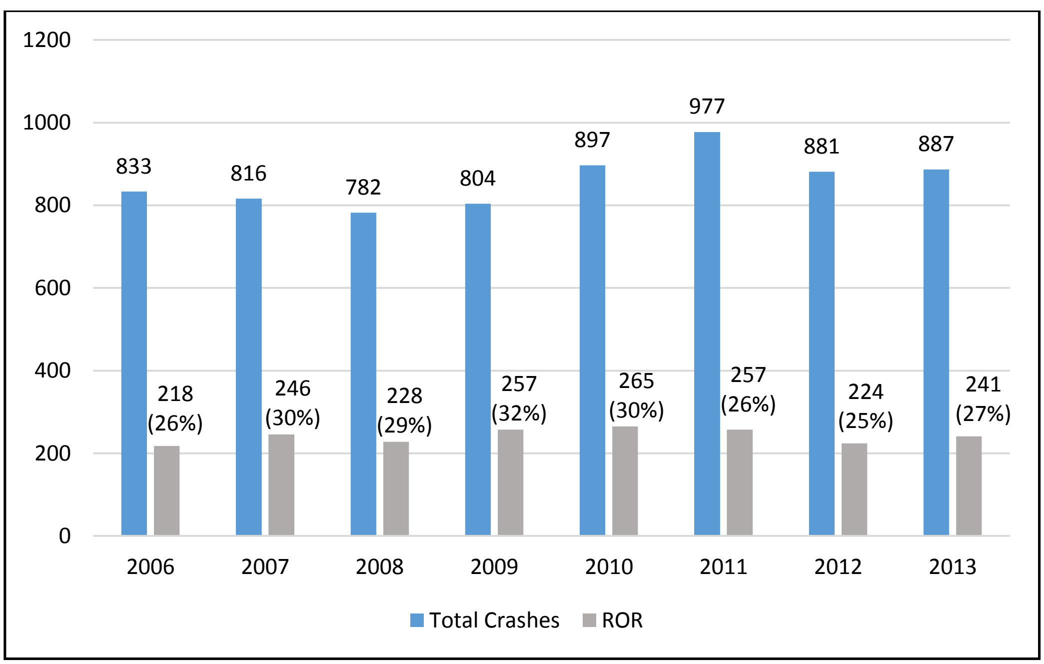


Figure 5.5 Percentage of ROR Crashes on Freeways PR-22

5.4 Crash Trends – Comparison between Freeway PR-52 and PR-22

This section will compare both freeways in terms of crash counts and crash trends. Table 5.1 shows the total count of Total and ROR crashes as well as the difference in crashes between one year and the next. Notice that the before period is highlighted with red and the after period is highlighted in blue.

The highest count in total crashes on the before period was reported on year 2006 and on the after period was reported during the year 2011 for both freeways. The PR-52 has higher counts of Total and ROR crashes during the 8-year period that is reported on the table.

Table 5.1 Crashes for the Study Period on Freeways PR-22 & PR-52

	Year	Freeway PR-52					Freeway PR-22				
		Total Crashes	∆Total Crashes	ROR Crashes	∆ROR Crashes	Percentage (%)	Total Crashes	∆Total Crashes	ROR Crashes	∆ROR Crashes	Percentage (%)
Before	2006	993	-60	345	-13	34.7%	833	-17	218	28	26.2%
Before	2007	933	-102	332	-48	35.6%	816	-34	246	-18	30.1%
Before	2008	831	78	284	30	34.2%	782	22	228	29	29.2%
Buffer	2009	909	45	314	23	34.5%	804	93	257	8	32.0%
After	2010	954	52	337	-52	35.3%	897	80	265	-8	29.5%
After	2011	1006	-127	285	-57	28.3%	977	-96	257	-33	26.3%
After	2012	879	65	228	33	25.9%	881	6	224	17	25.4%
	2013	944	N/A	261	N/A	27.6%	887	N/A	241	N/A	27.2%
	Totals	7,449		2,386		32.0%	6,877		1,936		28.2%

Table 5.2 shows the quantity of average crashes per kilometer for both freeways on the before and after period. The two freeways reported an increase in crashes from the before to the after period. The freeway PR-22 has higher quantity of average crashes per kilometer than freeway PR-52.

Table 5.2 Crashes per Kilometer for the Before and After Period

Freeway	Before Period (2006-2008)	After Period (2010-2012)
PR-52	8.5 crashes/km	8.8 crashes/km
PR-22	9.8 crashes/km	11.1 crashes/km

Table 5.3 shows descriptive statistics for total and ROR crashes based only in the before (years 2006-2008) and after (2009-2012) period. There is an increase in Total and ROR crashes for both freeways when comparing the before period with the after period with the exception of ROR crashes on freeway PR-52 that shows a reduction.

Table 5.3 Descriptive Statistics for the Before and After Period

		Freeway PR-52		Freeway PR-22	
		Total Crashes	ROR Crashes	Total Crashes	ROR Crashes
Before	Total	2757	961	2431	692
	Average	919.0	320.3	810.3	230.7
	Min	831	284.0	782.0	218.0
	Max	993	345.0	833.0	246.0
After	Total	2839	850	2755	746
	Average	946.3	283.3	918.3	248.7
	Min	879	228	881	224
	Max	1006	337	977	265

Figure 5.6 shows the crash trends for total crashes for both freeways. The crash trend line reflects that the total crashes has been reducing on PR-52 and has been increasing on PR-22.

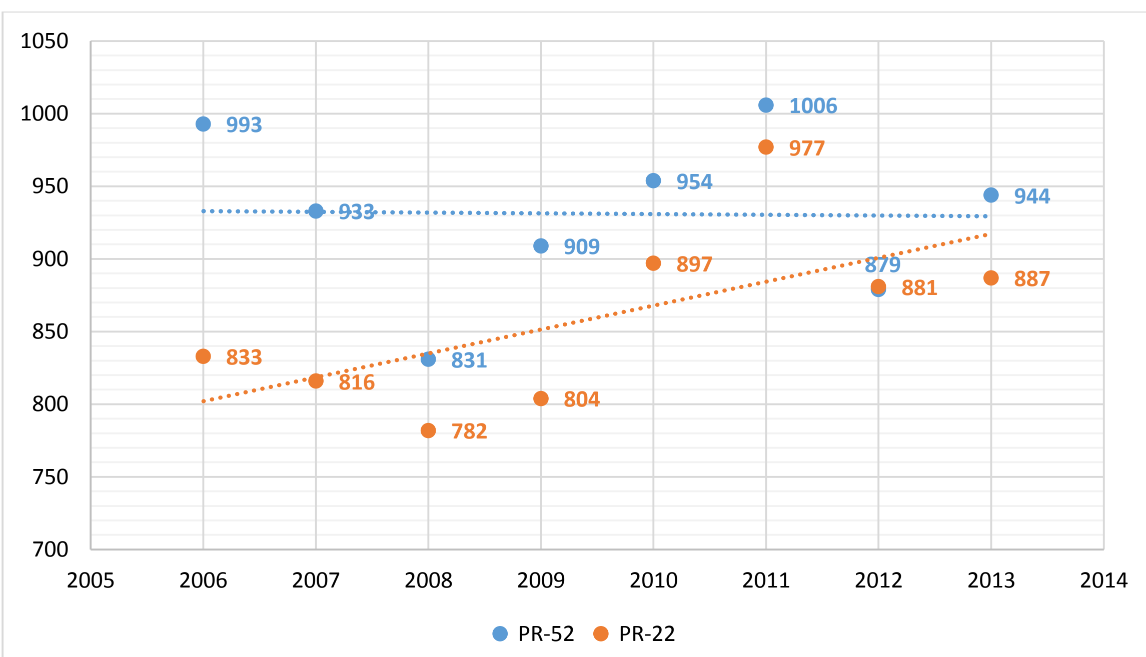


Figure 5.6 Crash Trends for Total Crashes on Freeways PR-52 & PR-22

Figure 5.7 shows the crash trends for ROR crashes for both freeways. The crash trend line reflects that the ROR crashes has been reducing drastically on PR-52 and has been increasing on PR-22. Crash rate analysis validates a reduction of ROR crashes associated to PR-52 freeway (Table 5.4). The PRDOT installed rumble strips on various segments of PR-52 from the year 2009 to 2011, which could cause a reduction of ROR crashes on those segments treated.

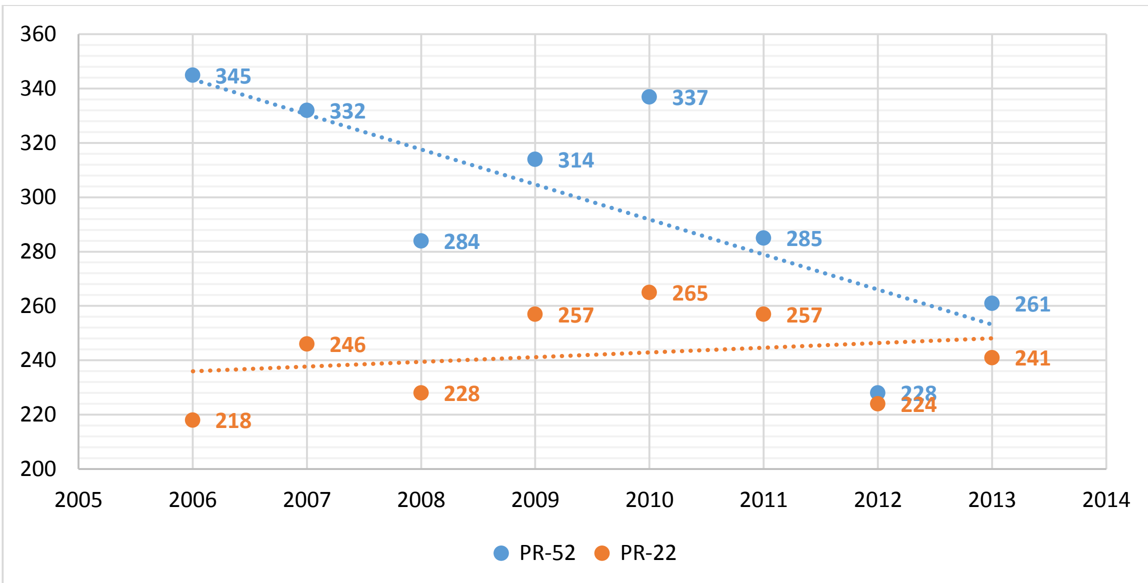


Figure 5.7 Crash Trends for ROR Crashes on Freeways PR-52 & PR-22

Crash rates is a tool to evaluate safety and takes into account the exposure data of the freeway segments. Equation 5.1 describes how the crash rates are calculated. The C is the Total Number of crashes in the period, V represents the AADT, N is the number of years and L the length of segments in miles.

$$R= \frac{C \times 100{,}000{,}000}{V \times 365 \times N \times L} \tag{5.1}$$

Table 5.4 Crash Rate Analysis for PR-52 & PR-22

Year	Freeway PR-52					Freeway PR-22				
	AADT (vpd)	Total Crashes	Crash Rate (100 million veh-miles)	ROR Crashes	ROR Crash Rate (100 million veh-	AADT (vpd)	Total Crashes	Crash Rate (100 million veh-miles)	ROR Crashes	ROR Crash Rate (100 million veh-
2006	72,210	993	56.15	345	19.51	104,028	833	42.03	218	11.00
2007	70,466	933	54.06	332	19.24	104,862	816	40.84	246	12.31
2008	69,897	831	48.54	284	16.59	105,897	782	38.76	228	11.30
2009	70,231	909	52.85	314	18.26	107,269	804	39.34	251	12.28
2010	69,259	954	56.24	337	19.87	104,066	897	45.24	265	13.37
2011	69,014	1006	59.52	285	16.86	99,366	977	51.61	257	13.57
2012	69,366	879	51.74	228	13.42	101,083	887	46.06	224	11.63

Table 5.4 shows the estimated crash rates for both freeways. In the estimates of crash rates we used the average of AADT's and the total length in miles for both freeways. Crash rates for total crashes and ROR crashes are higher on freeway PR-52. Freeway PR-52 and PR-22 reported a peak value of crash rates associated to total crashes during the year 2011. The next section will address the characterization of ROR crashes for both freeways for a 7 year period.

5.5 Characterization of ROR Crashes on Freeways PR-52 and PR-22

A characterization of a period from 2007 to 2013 was performed to identify he circumstances of this type of crashes along PR-22 and PR-52. The year 2006 was not part of this analysis due to a difference in the coding of some of the characteristics associated to crashes in the database. Figure 5.8 shows the characterization of ROR crashes by month for both freeways. The month of May reported the highest value of ROR crash counts for the PR-52 freeway. The month of March reported the highest value of ROR crashes count for freeway PR-22.

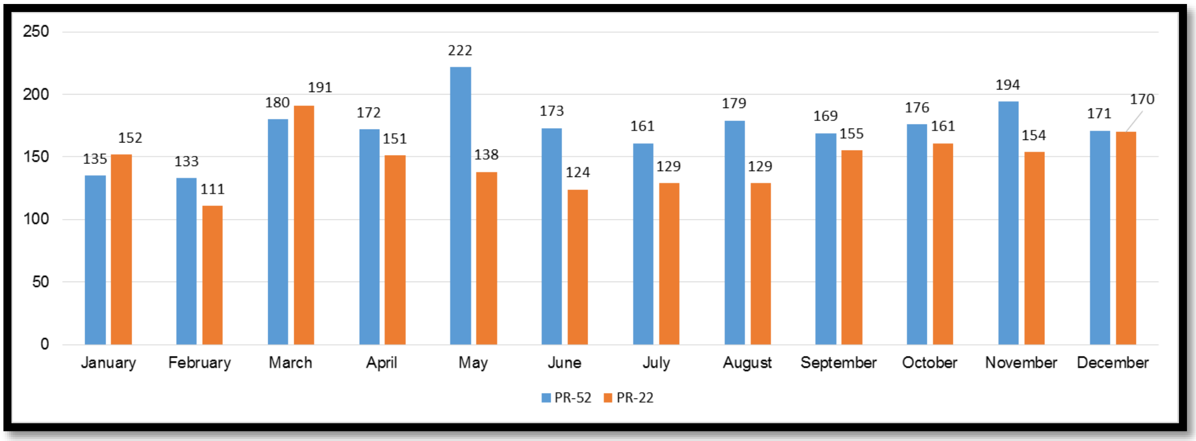


Figure 5.8 ROR Crashes by Month for Freeways PR-52 & PR-22

Figure 5.9 shows the characterization of ROR crashes by day of the week for both freeways. Both freeways reported the highest values of ROR crashes during the weekends.

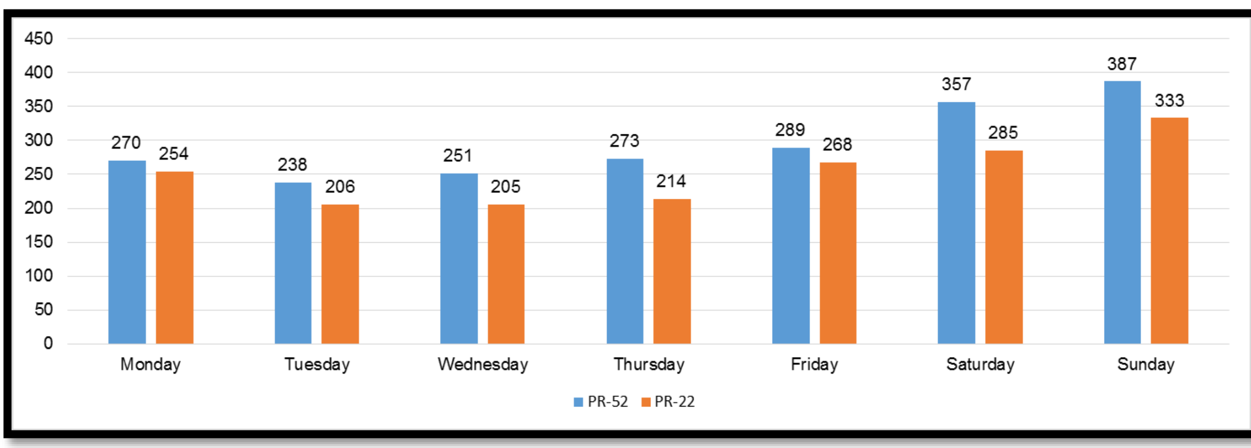


Figure 5.9 ROR Crashes by Day of the Week for Freeways PR-52 & PR-22

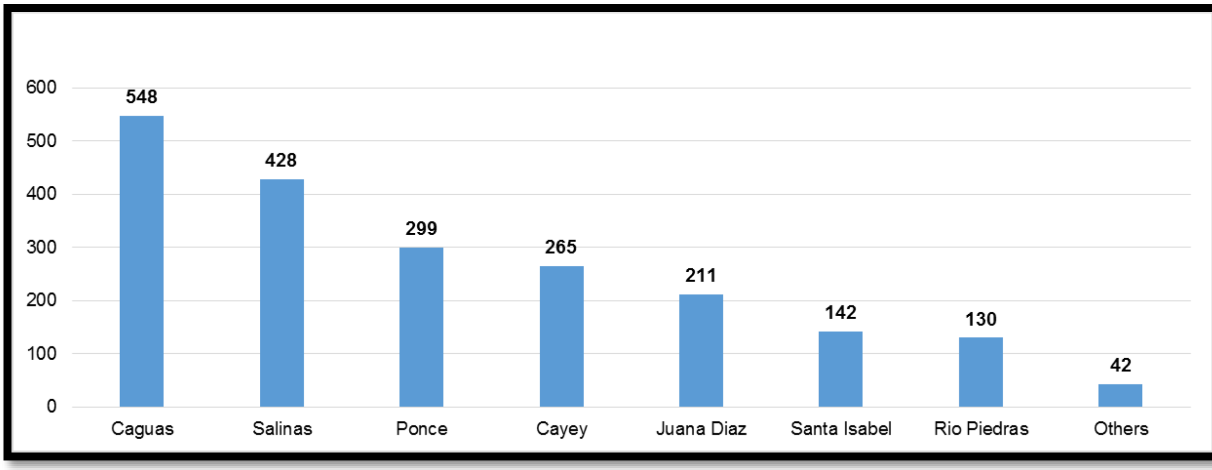


Figure 5.10 ROR Crashes by Municipality for Freeways PR-52

Figure 5.10 and 5.11 shows the characterization of ROR crashes by municipality. PR-52 reported the highest value of ROR crashes in the municipality of Caguas and PR-22 on the municipality of Arecibo.

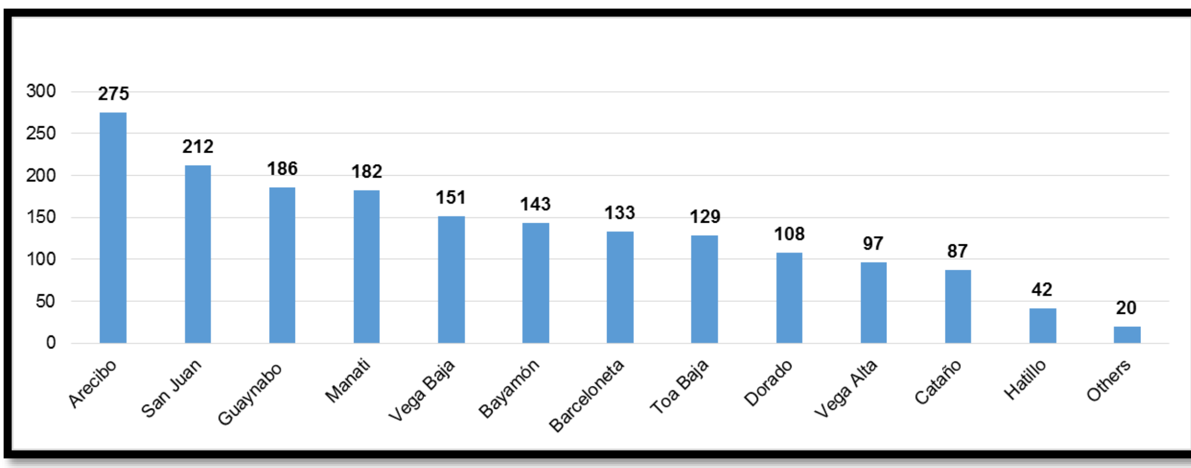


Figure 5.11 ROR Crashes by Municipality for Freeways PR-22

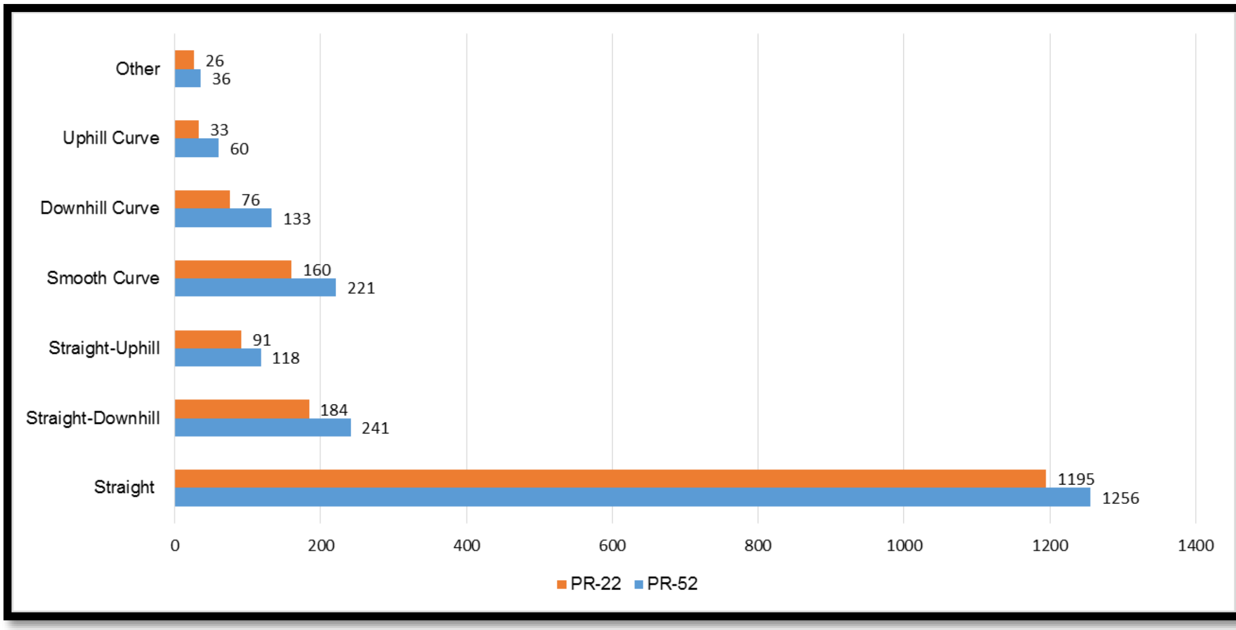


Figure 5.12 ROR Crashes by Freeway Geometric Characteristics PR-52 & PR-22

Figure 5.12 shows the characterization of ROR crashes by freeway geometric characteristics. Approximately, 60% of the ROR crashes occurred on straight freeway segment for both freeways.

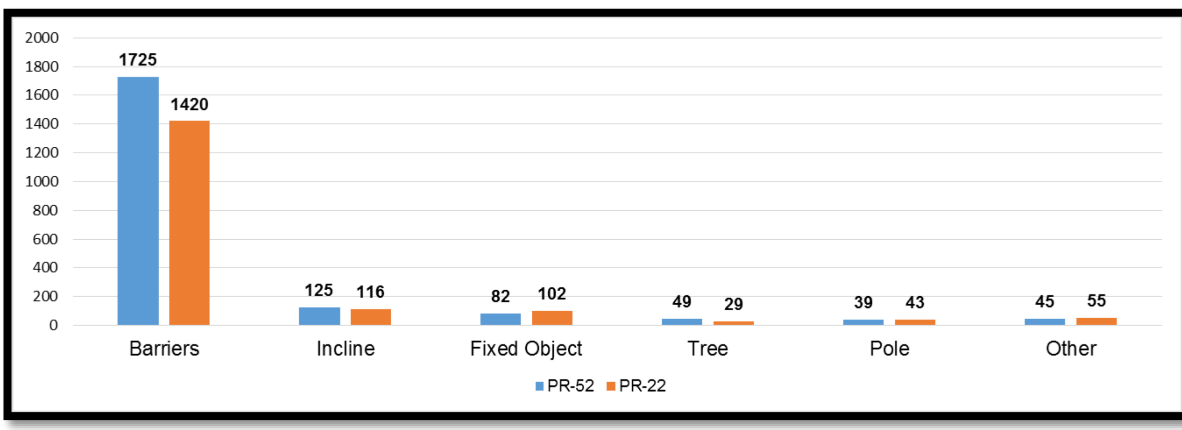


Figure 5.13 ROR Crashes by Related Event for Freeways PR-52 & PR-22

Figure 5.13 shows the characterization of ROR crashes by related event for both freeways. Approximately 80% of the ROR crashes for both freeways involved a collision with a roadside barrier. Figure 5.14 shows the characterization of ROR crashes by visibility for both freeways. The majority of the ROR crashes occurred during day light. The PR-52 reported that 51% of the ROR crashes occurred during daylight. The PR-22 reported that 45% of the crashes occurred during daylight.

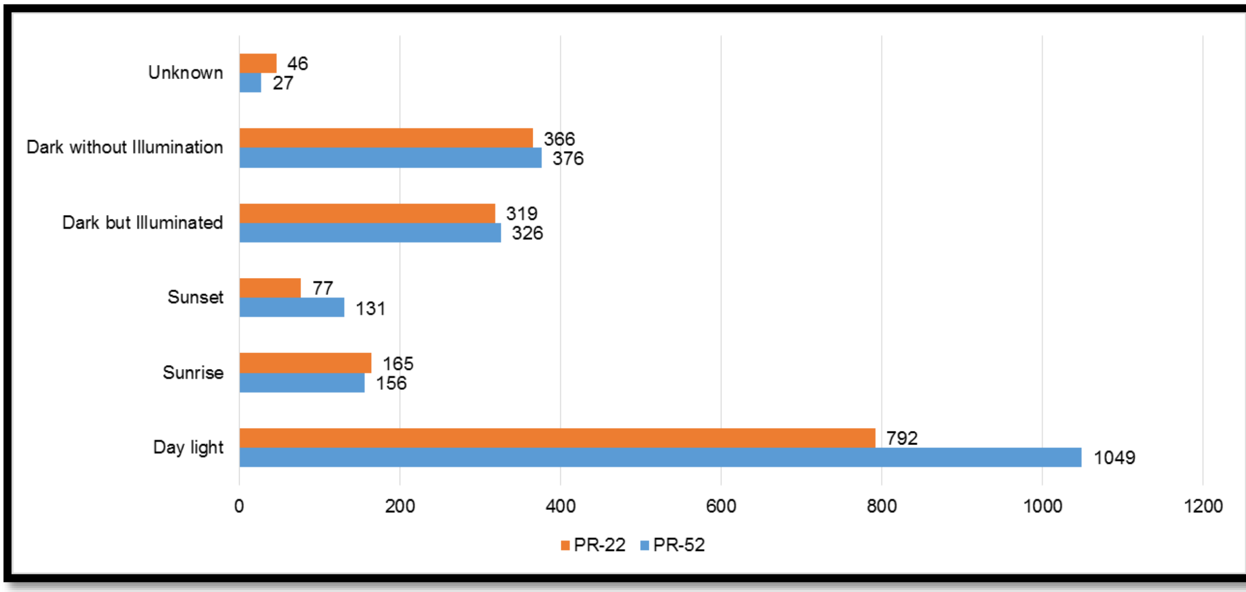


Figure 5.14 ROR Crashes by Visibility for Freeways PR-52 & PR-22

Figure 5.15 shows the characterization of ROR crashes by weather conditions. At least 65% of the ROR crashes on PR-52 occurred during a clear day. The PR-22 reported that 56% of ROR crashes occurred during a clear day.

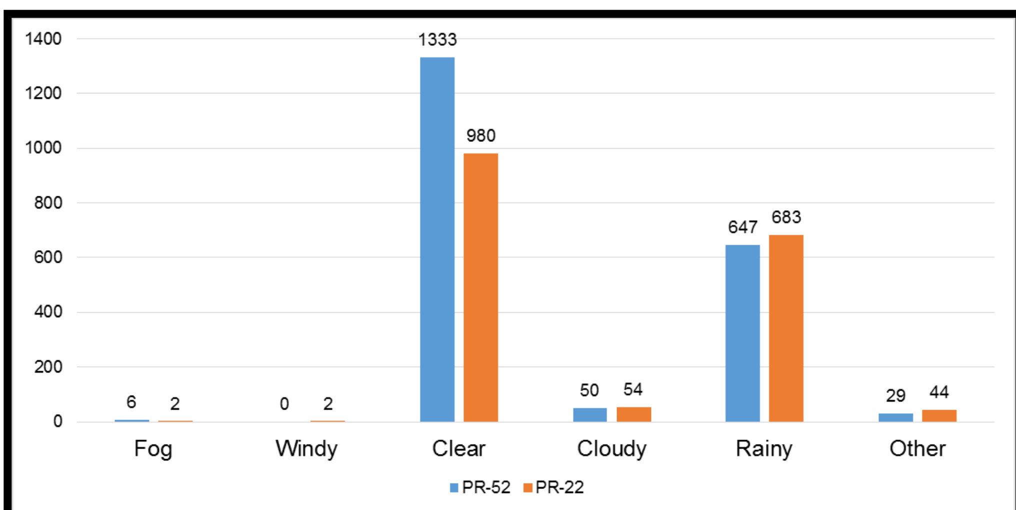


Figure 5.15 ROR Crashes by Weather Conditions for Freeways PR-52 & PR-22

Summarizing the characterization for ROR crashes for both freeways during the period (2007 to 2013) the highest crash counts were at daylight during clear weather conditions. The majority of the crashes occurred when they hit the barriers. The ROR crashes were at their highest during weekends. The next chapter will address the preparation of the database for the development of Safety Performance Functions for freeways in Puerto Rico.

6.0 DATA PREPARATION: MERGING, IDENTIFICATION OF HOMOGENEOUS SEGMENTS AND DATA CLEANSING PROCESS

6.1 Introduction

This chapter will address the preparation of the database for the development of Safety Performance Functions for freeways in Puerto Rico. In the calibration of the SPF, the data of the before period that covers the years from 2006 to 2008 was used. Figure 6.1 shows the steps towards achieving the Data Preparation for the SPF development.

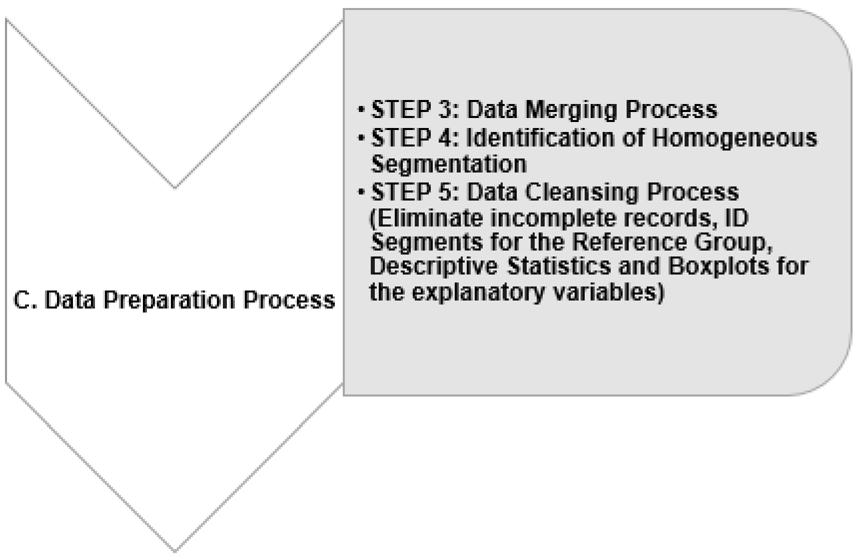


Figure 6.1 Steps for SPF Development – Data Preparation Process

Section 6.2 will summarize the data merging process (step #3) of the two main databases the HPMS and the Pavement Management Office Database described in the previous chapter as well as other relevant variables such as presence of freeway ramps, illumination and weather related information. Section 6.3 will address the identification of homogenous segments (step #4). Section 6.4, 6.5 and 6.6 will summarize the data cleansing process (step #5) based on missed values on the final database and minimum length requirements for the homogeneous segments, the identification of the segments for the reference group and the descriptive statistics associated to the segments of the reference group.

6.2 Data Merging Process

This section summarizes the merging process or data integration process that is defined as a complex process that involves combining datasets from multiple sources into one unified dataset. For the purpose of this investigation, two main databases were used. The HPMS and the Pavement Management Office Database described in the previous chapter as well as other relevant variables such as presence of freeway ramps, illumination and weather related information were merged or unified.

The first dataset included in the unified database was the Pavement Management Office Database. PRHTA provided two databases; one for the before period (2008) and one for the after period (2012). The Pavement Management personnel provided the most complete datasets that they had for each of the periods required for this investigation.

These databases contain information regarding the geometric characteristics for both freeways emphasizing in the curve radius, superelevation and grade of the freeways. These measurements were taken by using a special equipment called Automated Road Analyzer (ARAN).

The ARAN is a vehicle that has technology such as sensors, laser reflectometers, global positioning systems, video, computers and other that provides information about the roadways and right of ways. The ARAN measures the geometric characteristics of the roadways in 20 meters (0.02 kilometers) intervals. In the freeways of this investigation, measurements starts from San Juan (km 0.0) to Arecibo (km 83.9) for the PR-22 freeway and from San Juan (km 0.0) to Ponce (km 108.3) for the PR-52 freeway.

The Microsoft Excel worksheet provided by the Pavement Management Office has the road number, kilometer, measured superelevation, measured grade, measured radius in meters. The radius that are either 99,999 or -99,999 in value signifies that the ARAN did not detect any curve or that it is a straight road. Table 6.1 is an example of the Pavement Management Office database from kilometer 0.02 to 0.24 of the freeway PR-22.

Table 6.1 Pavement Management Office Database for PR-22 Freeway for the Before Period

Road	Start Kilometer	Superelevation (%)	Grade (%)	Radius (meters)
22	0.02	1.9	0.5	99999
22	0.04	-0.9	1	-99999
22	0.06	-1.4	1	-99999
22	0.08	-2.6	0.6	-99999
22	0.1	-2.3	0.3	-99999
22	0.12	-1.2	0.2	-99999
22	0.14	-0.2	0.4	-1231
22	0.16	1.6	0.4	-1231
22	0.18	0.7	1.2	-1231
22	0.2	0.2	1.5	-1231
22	0.22	1.4	1.2	-99999
22	0.24	1.8	1.9	99999

The first step was to eliminate the values 99,999 or -99,999. Using the find and replace command from Microsoft Excel Worksheet a replacement of the values 99,999 and -99,999 for ceros was performed. Then an absolute value of the radius in meters was calculated. The curve length was calculated by adding the number of rows that had each same value of radius and multiplying by 20 meters (0.02 kilometers). Table 6.2 shows a red box with four rows that has the same radius value of 1,231 meters; by multiplying 4 rows by 20 meters the length of the curve is 80 meters which is shown in the last column of the table.

Table 6.2 Sample Calculation of Curve Length for the PR-22 Freeway for the Before Period

Road	Start Kilometer	Superelevation (%)	Grade (%)	Radius (meters)	Absolute Value of Radius (meters)	Radius (meter)	Curve Length (meters)
22	0.02	1.9	0.5	99999	0		0
22	0.04	-0.9	1	-99999	0		0
22	0.06	-1.4	1	-99999	0		0
22	0.08	-2.6	0.6	-99999	0		0
22	0.1	-2.3	0.3	-99999	0		0
22	0.12	-1.2	0.2	-99999	0		0
22	0.14	-0.2	0.4	-1231	1231	1231	80
22	0.16	1.6	0.4	-1231	1231		80
22	0.18	0.7	1.2	-1231	1231		80
22	0.2	0.2	1.5	-1231	1231		80
22	0.22	1.4	1.2	-99999	0		0
22	0.24	1.8	1.9	99999	0		0

Using the horizontal curve radius and the curve length, the second step was calculating the degree of curvature, the deflection angle of the horizontal curve and the curvature change rate. The curvature change rate is the division of the deflection angle by the overall length of the horizontal curve. Chapter 15 of the Traffic and Highway Engineering Textbook has the following formula for calculating the degree of curvature and the deflection angle of the horizontal curves (Garber et al., 2009).

$$\text{Degree of Curve} = D = 5{,}729.6 / \text{Curve Radius} \quad (6.1)$$

$$\text{Deflection Angle} = \Delta = (\text{Curve Length} * 180) / (\text{Curve Radius} * \pi) \quad (6.2)$$

The last step in transforming this database before the merging process was to add a column with the absolute values of superelevation and grade. Table 6.3 shows the final result after adding variables to the existing Pavement Management Office Database.

Table 6.3 Sample of Final Pavement Management Dataset for the PR-22 Freeway for the Before Period

Road	Start Km	Super-elev. (%)	Absolute Value of Supelev. (%)	Grade (%)	Absolute Value of Grade (%)	Radius (mts)	Absolute Value of Radius (meters)	Degree of Curve (mts)	Curve Length (mts)	Central Angle (Δ)	Curve Change Rate (CCR)
22	0.02	1.9	1.9	0.5	0.5	99999	0	0.00	0	0.0	0.000
22	0.04	-0.9	0.9	1	1	-99999	0	0.00	0	0.0	0.000
22	0.06	-1.4	1.4	1	1	-99999	0	0.00	0	0.0	0.000
22	0.08	-2.6	2.6	0.6	0.6	-99999	0	0.00	0	0.0	0.000
22	0.1	-2.3	2.3	0.3	0.3	-99999	0	0.00	0	0.0	0.000
22	0.12	-1.2	1.2	0.2	0.2	-99999	0	0.00	0	0.0	0.000
22	0.14	-0.2	0.2	0.4	0.4	-1231	1231	4.66	80	3.7	0.047
22	0.16	1.6	1.6	0.4	0.4	-1231	1231	4.66	80	3.7	0.047
22	0.18	0.7	0.7	1.2	1.2	-1231	1231	4.66	80	3.7	0.047
22	0.2	0.2	0.2	1.5	1.5	-1231	1231	4.66	80	3.7	0.047
22	0.22	1.4	1.4	1.2	1.2	-99999	0	0.00	0	0.0	0.000
22	0.24	1.8	1.8	1.9	1.9	99999	0	0.00	0	0.0	0.000

The only variables calculated for the purpose of this investigation were from the Pavement Management Office dataset as described earlier. The other variables were obtained using the HPMS, an inventory of freeway ramps and illumination systems and climate related variables obtained by the National Climatic Data Center (NCDC).

The merging process of the Highway Performance Monitoring System (HPMS) begun after completion of the Pavement Management Office dataset. In the HPMS, the two toll freeways PR-22 and PR-52 are divided into 29 segments with variable length. The HPMS was also provided on a Microsoft Excel Worksheet by the Office of Highway Systems.

First, the calculation of averages for variables such as AADT, IRI, Lane Width, Median Width, Right Shoulder Width, Left Shoulder Width, % of Trucks, Directional Factor for the before and after period was completed. Although the HPMS has a total of *98 data items* per segment, for the purpose of this investigation we only used the following data items *(19 data items):*

- Signed Route Number
- Rural or Urban Designation (1- Rural Area, 2-Small Urban Area, 3-Small Urbanized Area, 4-Large Urbanized Area)

- Annual Average Daily Traffic
- Number of Through Lanes
- Measured Pavement Roughness (IRI)
- Pavement Type (4- High Type Flexible, 5- High Type Rigid, 6- High Type Composite)
- Lane Width (meters)
- Median Type (2- Positive Barrier or 3-Unprotected)
- Median Width (meters)
- Right Shoulder Width (meters)
- Left Shoulder Width (meters)
- Design Speed (km/hr)
- Speed Limit (km/hr)
- Peak Single Unit Truck (%)
- Average Single Unit Truck (%)
- Peak Combination Trucks (%)
- Average Combination Trucks (%)
- Average Total Trucks (%)
- Directional Factor (%)

These items listed above had a start and end kilometer to pin point their exact location. These 19 data items from the HPMS Database were inserted to the Pavement Management Office dataset. The inventory of the freeway ramps and the illumination system also recorded the start and end location for both items. With this information, both items were merged to the final dataset.

The Pavement Management Office dataset also included a column that shown the municipality based upon the kilometer location. Using this information, the total precipitation (centimeters) data provided by NCDC was incorporated to the final dataset. The next section will summarize the identification of homogeneous segments in freeways of Puerto Rico.

6.3 Identification of Homogeneous Segments

After merging the data necessary to develop the Safety Performance Functions it is required to divide the data in homogeneous segments. Homogeneous segmentation is the identification of roadway segments that shares the same geometric and traffic characteristics. Segments end when one of the traits or characteristic of the roadway changes. This process is vital for estimating crash prediction models.

Before the segmentation process, two existing variables were recoded to facilitate the identification of homogeneous segments. The first variable added was the presence or lack of presence of curvature. The second variable added was the categorization of grades in types of terrains as suggested on AASHTO "A Policy on Geometric Design of Highways and Streets". Table 6.4 is the metric version of the AASHTO publication with the maximum grades for rural and urban freeways.

Table 6.4 Sample of AASHTO Maximum Grades for Rural and Urban Freeways (AASHTO, 2011)

Type of Terrain	Design Speeds (km/hr)					
	80	90	100	110	120	130
	Grades (%)					
Level	4	4	3	3	3	3
Rolling	5	5	4	4	4	4
Mountainous	6	6	6	5	N/A	N/A

The categorization of the grades was based on table 6.4 requirements using the design speed and grades to categorize level, rolling and mountainous terrains. The majority of the segments on both freeways had either 105 or 110 km/hr design speeds. For 105 km/hr segments, the requirements used were based upon the values in the table above for 100 km/hr.

Using a statistic software package named Statistical Package for the Social Sciences (SPSS) the re-codification of an existing variable to a new variable of terrain was completed by using the terms provided by AASHTO. In terms of the variable that indicated presence or absence of curvature, SPSS recoded into a new variable the radius variable by identifying the cero values as an absence of curvature and the integers as presence of curvature. These two recoded variables made easier the homogeneous segmentation process.

Table 6.5 shows the homogeneous segmentation process. The variable used in HPMS to determine change in the values of the other variables in the HPMS (such as: No. lanes, lane width, median width, type of median, % of truck, IRI) was the Average Annual Daily Traffic (AADT). The HPMS divided the PR-52 freeway in 29 segments; causing the values of all the variables used from this database to change only on 29 occasions through the whole freeway.

Table 6.5 Sample Homogeneous Segmentation Process: PR-52 Freeway

	A	B	C	D	E	F	G	H	I
FHS ID	Freeway	Start Km	Average AADT (vpd)	Right Shoulder Width (m)	Radius (m)	Average Precipitation (cm)	Presence of Illumination	AASHTO Terrain Category	Curvature Presence
FHS 1	52	0.02	169,100	3	0	148.5	YES	LEVEL	NO
	52	0.04	169,100	3	0	148.5	YES	LEVEL	NO
	52	0.06	169,100	3	0	148.5	YES	LEVEL	NO
	52	0.08	169,100	3	0	148.5	YES	LEVEL	NO
FHS 2	52	0.1	169,100	3	952	148.5	YES	LEVEL	YES
FHS 3	52	0.12	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.14	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.16	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.18	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.2	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.22	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.24	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.26	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.28	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.3	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.32	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.34	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.36	169,100	3	952	148.5	YES	ROLLING	YES
	52	0.38	169,100	3	952	148.5	YES	ROLLING	YES

Table 6.5 shows an example of the homogeneous segmentation process for freeway PR-52. The first segment starts at 0.02 km, ends at 0.08 km where the values of the different columns stay continuous, and does not have a curve presence. The second segment starts at 0.10 km where a curve with a total radius of 952 meters (column D) is

reported. This segment is very short (only 0.02 km) because there is a change in terrain denoted by the column H or HSM Grade Category column. The third segment starts at 0.12 and ends at 0.38 km because the terrain changed from a level (with a value of 1) to a rolling terrain (with a value of 2).

Table 6.6 shows the preliminary homogeneous segments derive from the previous example for PR-52 freeway. This table has an additional column (column E) representing the average superelevation for each segment that was calculated during the segmentation process. This is the summary for the three segments identified in the previous table for the PR-52 freeway.

Table 6.6 Summary of the Homogeneous Segments Identified for the PR-52 Freeway from the Previous Sample

FHS ID	A Freeway	B Start Km	C Average AADT (vpd)	D Right Shoulder Width (m)	E Radius (m)	F Average Precipitation (cm)	G Presence of Illumination	H AASHTO Terrain Category	I Curvature Presence
FHS 1	52	0.02	169,100	3	0	148.5	YES	LEVEL	NO
FHS 2	52	0.1	169,100	3	952	148.5	YES	LEVEL	YES
FHS 3	52	0.12	169,100	3	952	148.5	YES	ROLLING	YES

At the end of the process, a total of 775 homogeneous segments were identified for both freeways. The PR-52 freeway reported 395 segments and PR-22 freeway reported 380 segments. The next section will summarize the data cleansing process performed for this investigation.

6.4 Data Cleaning Process

The Data Cleaning Process is defined as the process of detecting inaccurate, incomplete and incorrect records from the dataset and then replacing, modifying or deleting those values to create one unified database. For the purpose of this investigation, two main databases were used, namely the HPMS and the Pavement Management Office Database. There databases were merged for this investigation once reviewed and corrected by the Highway and Transportation Authority (HTA) technical personnel.

The first step towards the data cleaning process was to identify the missing values in the preliminary dataset after the merging process and the homogeneous segment identification process transpired. As previously reported, a total of 775 homogeneous segments were identified for both freeways. The PR-52 freeway reported 395 segments and PR-22 freeway reported 380 segments. Table 6.7 summarizes the missing values identified from the 775 homogeneous segments identified for both freeways.

Table 6.7 Summary of the Homogeneous Segments with Missing Values

Freeway	Original # of Segments	# of Segments with missing values	Start KM	End KM	Length (km)	Source of the Missing Values
PR-22	380	6	0.02	0.64	0.62	HPMS
PR-22		16	7	10.2	3.2	HPMS
PR-52	395	10	36.08	38.8	2.72	HPMS
Total	**775**	**32**			**6.54**	

Table 6.7 indicates that the PR-22 freeway has a total of 22 segments with missing values and PR-52 freeway has a total of 10 segments with missing values. The missing values reported in the dataset were from the Highway Performance Monitoring System information. After the elimination of those segments with missing values the new total segment for PR-52 freeway is 385 segments and PR-22 freeway is 358 segments for a new grand total of 743 homogeneous segments for both freeways.

After eliminating the missing values, a minimum segment length was identified for analysis purposes. *The AASHTO Highway Safety Manual suggests that each homogeneous segment should be at least 0.16 kilometer of length (AASHTO, 2010). Note that segments that are equal or less than 0.16 kilometers will be neglected to avoid small counts of crash data for such small segments.*

First, the segments with less than 0.10 kilometers (0.06 miles) were eliminated. Table 6.8 summarizes the segments that were 0.10 kilometers or less from the two freeways.

The original number of homogeneous segments from both freeways were 743 after elimination of 232 segments that were less than 0.1 kilometers the new total of homogeneous segments for both freeways is 511 segments.

Table 6.8 Summary of the Homogeneous Segments that are Less than 0.1 Kilometers for both Freeways

Freeway	Original # of Segments	# of Segments with less than 0.1 km (Eliminated)	New Total of Segments	Length of segments with less than 0.1 km
PR-22	358	119	**239**	5.42
PR-52	385	113	**272**	5.82
Total	**743**	**232**	**511**	**11.24**

Second, the segments with less than 0.16 kilometers were eliminated. Table 6.9 summarizes the segments that were 0.16 kilometers or less from the two freeways. The original number of homogeneous segments from both freeways were 511 after elimination of 129 segments that were less than 0.16 kilometers the new total of homogeneous segments for both freeways is 382 segments.

Table 6.9 Summary of the Homogeneous Segments that are Less than 0.16 Kilometers for both Freeways

Freeway	Original # of Segments	# of Segments with less than 0.16 km (Eliminated)	New Total of Segments	Length of segments with less than 0.16 km
PR-22	239	60	179	7.2
PR-52	272	69	203	8.12
Total	**511**	**129**	**382**	**15.32**

The PR-52 freeway has a longitude of 108.24 and the PR-22 has a longitude of 83.92. The Pavement Management Office reported that for the PR-52 freeway there were 57.92 kilometers of roadway horizontal curves along the freeway, which represents that 53.5% of this freeway has curves. The PR-22 freeway reported a total of 46.58 kilometers of roadway horizontal curves, which represents 55.5% of roadway curves for this freeway. Both freeways has many topographic changes that varies from level, rolling and steep terrains. This relatively high percentage of curves and topographic changes produce shorter homogeneous segments along both freeways. For that reason, the segments drop from an original value of 743 segments to 382 homogeneous segments in the cleansing data process.

6.5 Identification of the Reference Group

The last step before performing the outlier analysis is to select the homogeneous segments that follows the criteria of the reference group. A reference group is a cluster of entities with similar traits (Hauer, 2002). The selection of homogeneous segments that meets the criteria and definition of the reference group were carefully chosen based upon the criteria in table 6.10.

Table 6.10 Criteria for the Identification of the Reference Group

	Description
Type of Facility	Toll Freeway
Speed Limit	90 to 105 km/hour
Total Lanes	4 to 6 lanes
Lane Width	3.65 to 4 meters
Minimum Segment Length	0.16 kilometers
Maximum Segment Length	2.2 kilometers

Table 6.11 Summary of the Homogeneous Segments that do not comply with the Reference Group

Freeway	Original # of Segments	# of Segments that do not comply with the Reference Group	New Total of Segments	Length of segments eliminated
PR-22	179	20	159	6.72
PR-52	203	2	201	0.44
Total	**382**	**22**	**360**	**7.16**

Table 6.11 summarizes the segments that were eliminated because did not comply with the criteria of the reference group. The original number of homogeneous segments

from both freeways were 382 after elimination of 22 segments that did not comply with the requirements of the reference group the new total of homogeneous segments for both freeways is 360 segments.

After the identification of the segments that comprise the reference group, the segments that were treated with shoulder rumble strips were eliminated to have the final number of segments that will be analyzed. Table 6.12 presents the segments that were eliminated from the kilometer 23.1 to the kilometer 66.3 of the PR-52 freeway. The original number of homogeneous segments from the reference group from both freeways were 360 after elimination of 83 segments that were treated with rumble strips the new *total of homogeneous segments for both freeways is 277 segments*.

Table 6.12 Final Summary of the Homogeneous Segments of the Reference Group

Freeway	Original # of Segments	# of Segments of the Study Area that are excluded	New Total of Segments	Length of segments eliminated
PR-22	159	0	**159**	0
PR-52	201	83	**118**	34.2
Total	**360**	**83**	**277**	**34.2**

Table 6.13 summarizes the segments eliminated during the identification of the reference group and the approximate length in kilometers for each describe item. The total segments for the reference group are 277 that have a total length of 117 kilometers that represent 61% of the total longitude of the two freeways.

Table 6.13 Summary of the Homogeneous Segments Elimination Process

Description of the Eliminated Segments	Total Eliminated Segments	PR-52	PR-22	Total Segments	Total Length of Eliminated Segments (km)	% of the Total Length
Original Quantities	0	395	380	775	192	100%
Segments with missing values	32	385	358	743	6.54	3.4%
Segments that were less than 0.16 kilometers	361	203	179	382	26.56	13.8%
Segments that did not comply with the criteria of the Reference Group	105	118	159	277	41.36	21.5%

The next section will describe the Outlier Analysis of the independent variables in the dataset performed by using IBM SPSS Software.

6.6 Outliers Analysis for Scale Variables

During the Data Cleansing Process and the identification of the segments of the reference group a total of 277 homogeneous segments were identified. Before calibrating the Safety Performance Functions model, a outlier analysis of the independent variables was performed.

The first step towards performing the outlier analysis is to copy the database from Microsoft Excel and pasting it to in the Data View Window of the IBM SPSS software. The second step is to name each variable of the database in the Variable View Window of the IBM SPSS Software. The Variable View Window will specify the name of the variable, the variable type (numeric, dollar, date, string and others), the width of the variable (the number of characters of the variable), the decimals of the variable (the number of decimal places that the software will display), the label of the variable (the detail description of the variable), the variable values (this is used to define the categories for categorical variables), the missing in a variable (is a signal activated by SPSS that can identified missing values assigned by the analyst and ignored it in the subsequent analysis), the width of each column, the alignment of the information, the measure property and the role.

The measure property has three choices: scale, ordinal and nominal. A scale measurement is when the variable has a meaningful metric or can varies and differ in magnitude. SPSS identifies by default every numeric variable as a scale variable. An ordinal variable is a variable that has categories that can be ranked. A nominal variable is a variable that has categories that cannot be ranked or put in an orderly manner.

The role property is the explanation of the role that the variable will be having in the analysis. In our analysis, the variables are either “input variables” or “target variable”. The input variable are the variables that are going to be used as a predictor (independent variables). The target variable are the variables that will be used as a outcome (dependent variable).

After carefully filling the table of the Variable View Screen, the outlier analysis can be perform. The statistic software SPSS has an Explore Option on the Descriptive Statistic Analysis tool that can identify outliers for each quantitative variable. Excluded in this analysis were the quantitative variables number of lanes, Speed Limit and Design Speed. The number of lanes was excluded because there were only two values (4 or 6 lanes). The Speed Limit variable was excluded because there were only two values (105 or 110 km/hr) reported throughout the two freeways. The Design Speed variable was also excluded because two values (90 or 105 km/hr) were reported throughout the two freeways.

Table 6.14 has descriptive statistics such as the maximum and minimum value, range, which is the subtraction between the maximum value and the minimum value, mean and the standard deviation. The standard deviation gives an idea of the amount of dispersion for the set of data values for each variable.

Table 6.14 Summary of the Descriptive Statistics of the Quantitative Variables within the Reference Group

Variable	Units	Descriptive Statistic				
		Max.	Min.	Range	Mean	Std. Dev
Length	km	2.2	.16	2.04	0.425	0.28
AADT	vpd	160,833	25,833	135,000	69,175	30,382
IRI	m/km	3.6	1.7	1.9	2.42	0.47
Median Width	m	27.5	2.8	24.7	17.10	6.11
Right Shoulder Width	m	3.4	2.4	1	2.98	0.20
Left Shoulder Width	m	2.4	0.9	1.5	1.26	0.24
Average Total Truck	%	12	4	8	7.31	2.3
Ave. Directional Factor	%	63.3	51.7	11.6	58.67	2.59
Average Superelevation	cm/cm	7.16	0.52	6.64	2.83	1.47
Absolute Radius *	m	3,423	308	3,115	1,545.2	684.8
Degree of Curvature*	°	18.6	1.7	16.9	4.6	2.48
Curve Length *	m	1,600	60	1,540	635.8	398.5
Central Curve Angle*	°	97.5	1.4	96.1	30.5	24.07
Curvature Change Rate*		0.186	0.017	0.169	0.046	0.025
Average Precipitation	cm	210.9	100.8	110.1	163.4	39.5

*These variables were analyzed using 157 segments that represents the curve segments.

IBM SPSS Software has a procedure for identifying outliers that involve a combination of descriptive statistics and non-parametric graphics called Boxplots. Boxplots can be used to analyze the variation of the sample from a population without assuming a statistical distribution such as normal distribution. Boxplots are nonparametric graphs.

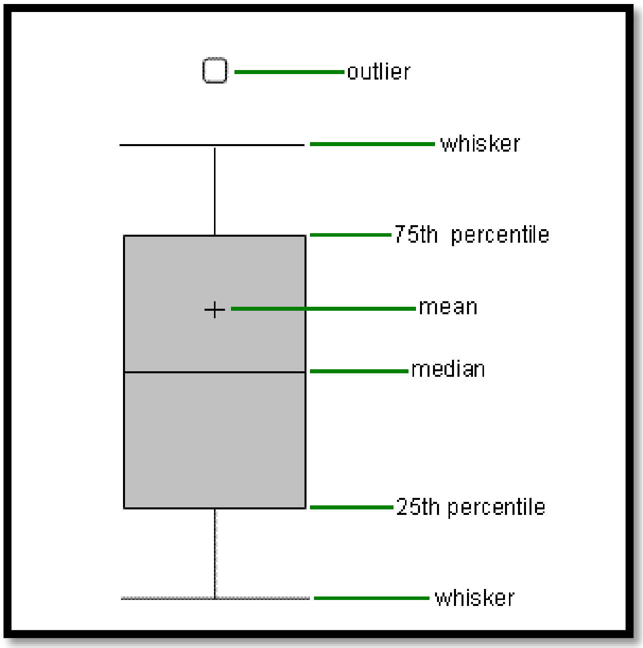


Figure 6.2 Boxplot Sample (SPSS V21)

Figure 6.2, the first quartile or percentile 25 (Q_1) is defined as the average between the smallest and the median number of data set. The second quartile, or percentile 50 (Q_2) is the median of the data. The 75 percentile or third quartile (Q_3) is the mean value between the median and the highest value of the data set. The lower and upper whiskers are calculated using the Equation 6.1. The lower and upper whisker is calculated by multiplying 1.5 by the IQR.

$$\text{Interquartile Range (IQR)} = Q_3 - Q_1 \qquad (6.1)$$

Boxplots for traffic related variables are shown in figure 6.3, 6.4 and 6.5. Neither the AADT nor the Total Annual Truck Percentage showed outliers. The 75th percentile and the 25th percentile represents the values of the upper and lower sides of the box in the boxplot. The AADT has a 75th percentile value of 91,300 vehicles per day and a 25th percentile of 44,833 vehicles per day. In terms of the Total Annual Truck Percentage, it reported a 75th percentile value of 9.3% and a 25th percentile of 5.3% vehicles per day.

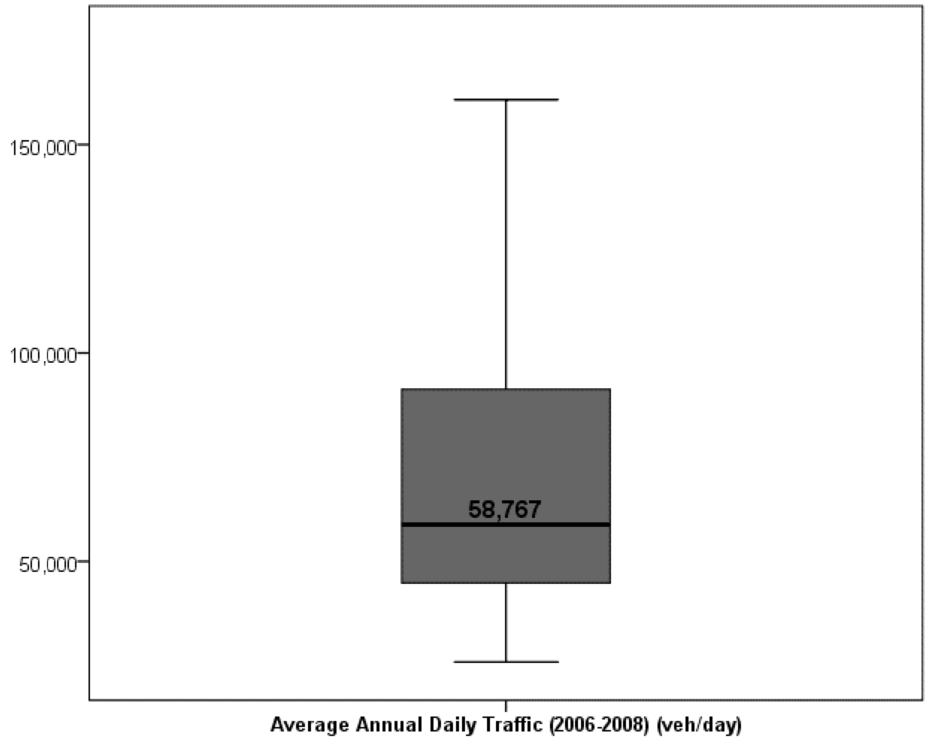


Figure 6.3 Annual Average Daily Traffic for Freeways PR-52 and PR-22 Boxplot

The values shown inside the Boxplots correspond to the median or the middle value of the data set for each variable. The median for AADT is 58,767 vehicles per day and for % of Total Average Trucks is 7.0.

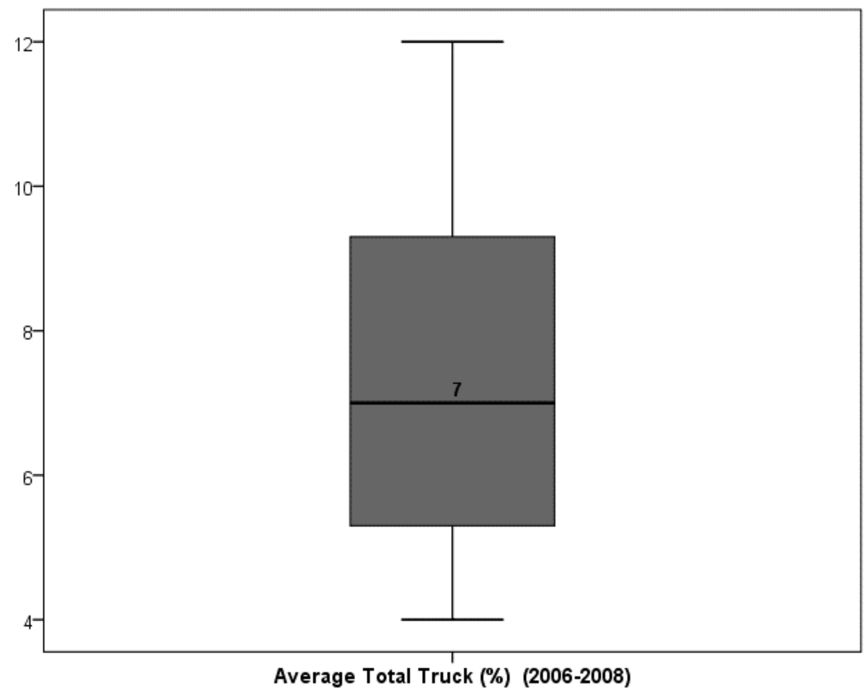


Figure 6.4 Average Annual Truck Percentage for Freeways PR-52 and PR-22 Boxplot

Figure 6.5 represents the boxplot for the average directional factor. The average directional factor has a 25th percentile value of 56.7, a median and 75th percentile value of 60%. The median is represented in the top side of the boxplot. The average directional factor has a minimum value of 51.7% and a maximum value of 63.3%. The boxplot reported segments with outliers represented with circle. In IBM SPSS, an outlier represented in circle signifies that is a mild outlier. AASHTO indicates that Directional Factor varies for rural highways can ranges between 55 to 70%; it also indicates that it can vary between sites and no specific values are describe for freeway segments. The mild outliers represented in the directional factor boxplot will not be eliminated from the final dataset.

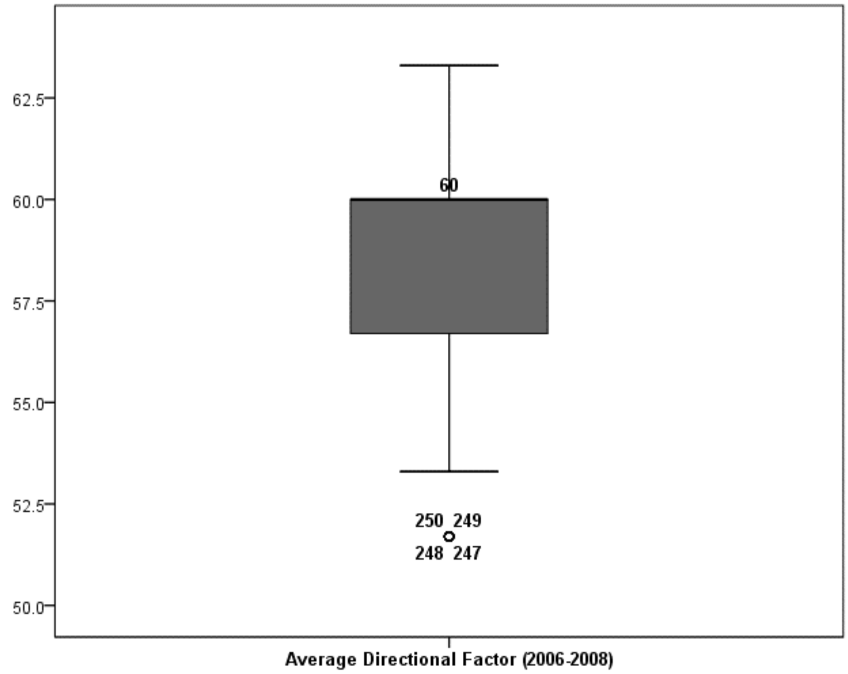


Figure 6.5 Average Directional Factor for Freeways PR-52 and PR-22 Boxplot

Road geometric related variables boxplots and histograms for variables such as median width, right lane width, left lane width are shown in figure 6.6, 6.7 and 6.8. The reference group has freeway segments in urban and rural areas. For urban freeways segments, AASHTO Geometric Design of Highways and Streets recommends medians of at least 3 meters for four lane and 6.6 meters for six or more lanes. For rural segments, AASHTO recommends medians with width between 15 to 30 meters.

Figure 6.6 represents the boxplot for the median width variable. The median width has a 75th percentile value of 22 meters, a 25th percentile of 11.9 meters and a median of 18.9 meters. The boxplot did not reported outliers for this variable.

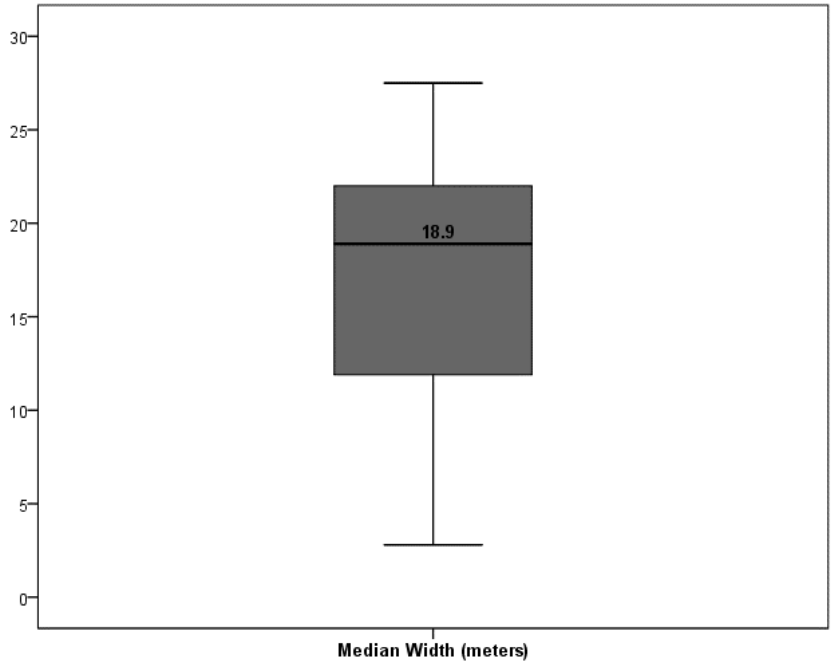


Figure 6.6 Median Width for Freeways PR-52 and PR-22 Boxplot

AASHTO recommends a right shoulder width of 3 meters up to 3.6 meters in high-speed facilities such as freeways, being 3 meters the preferred choice for designers. Figure 6.7 represents the histogram for the right shoulder width variable. The right shoulder width has a 75th percentile, a 25th percentile and a median of 3 meters. Figure 6.8 shows histograms that detail that 70% of the segments reported a right shoulder width of 3 meters. For this reason, a boxplot for this data was not possible because it would showed a flat line instead of a box. The histogram also shows that the maximum value is 3.4 meters and the minimum value is 2.4 meters, which represents 1 meter of difference between the values for the data set.

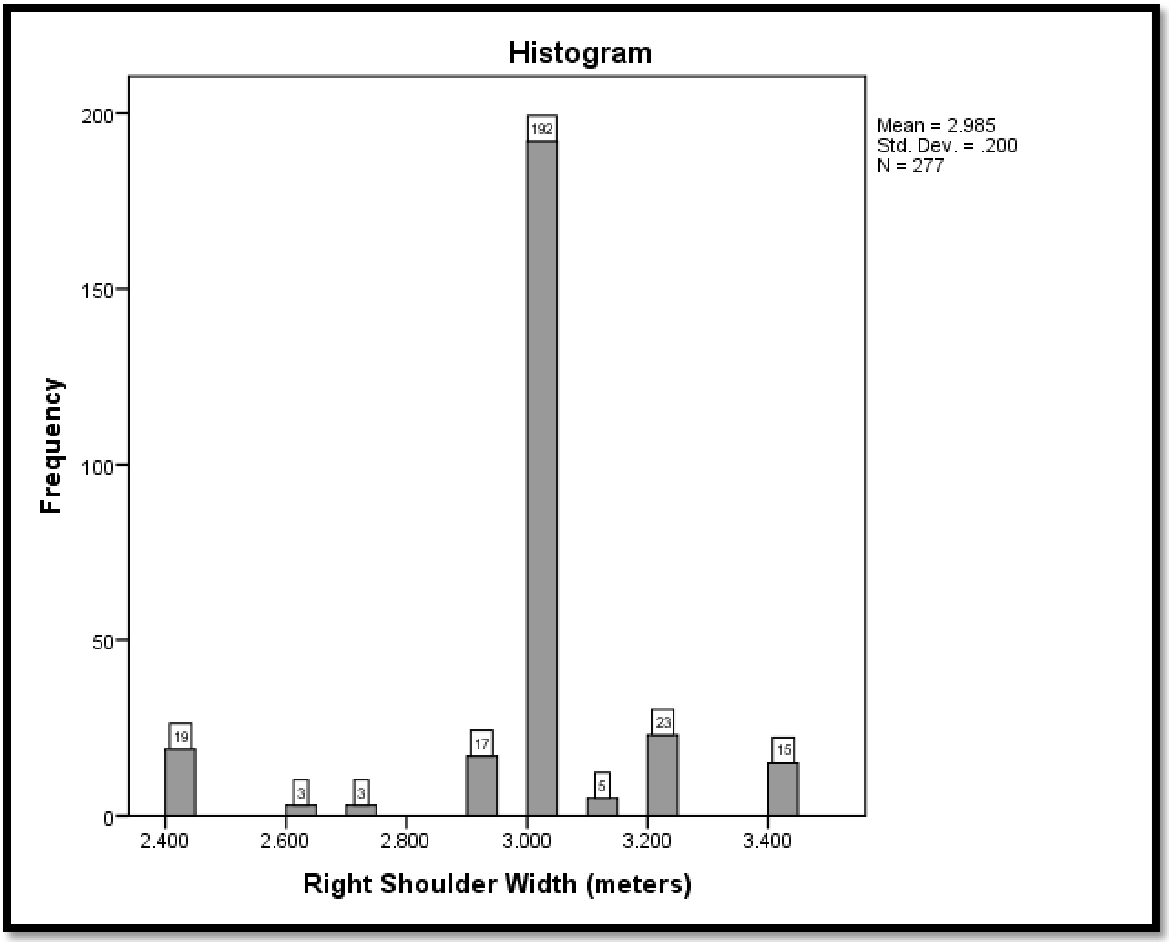


Figure 6.7 Histogram for the Right Shoulder Width Variable for Freeways PR-52 and PR-22

For left shoulder width, AASHTO recommends a width of 1.2 to 2.4 meters for four lane freeways. Figure 6.8 represents the histogram for the left shoulder width that shows that almost 60% of the segments had left shoulder width of 1.20 meters. The histogram also shows that the maximum value is 2.4 meters and the minimum value is 0.9 meters which represents 1.5 meter of difference between the values for the data set. The 75^{th} percentile was 1.3 meters and the 25^{th} percentile as well as the median reported a value of 1.2 meters.

AASHTO recommended values for left shoulder width varies from 1.2 to 2.4 meters, 85% of the segments of the reference group comply with these guidelines. The 15% that do not comply AASHTO guidelines is mainly because they have left shoulder width of less than 1.2 meters. Segments with left shoulder width of 1 meters or less were located on urban freeway segments. The majority of the segments that reported 1 meter or less of left shoulder width has a protective barrier on the median (39 out of 42). The effect on safety of the left shoulders that do not comply with the requirements should be included in the analysis and for this reason no outliers were identify for this variable.

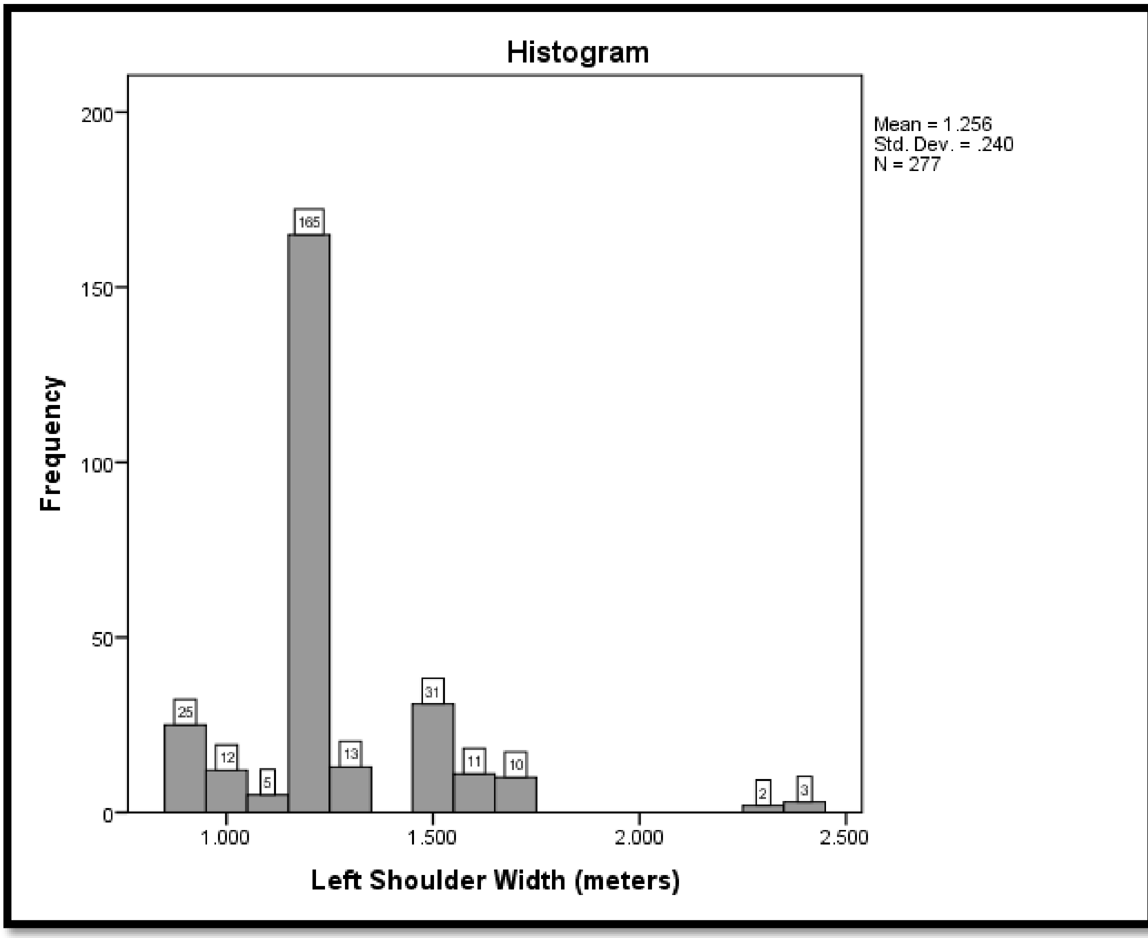


Figure 6.8 Histogram for the Left Shoulder Width Variable for Freeways PR-52 and PR-22

There are two quantitative variables related to pavement that are superelevation and IRI. Figure 6.9 shows the IRI boxplot. The 75th percentile for IRI was 2.6 m/km, the median was 2.4 m/km and the 25th percentile was 2 m/km. The minimum value of IRI was 1.7 m/km and the maximum value was 3.6 m/km.

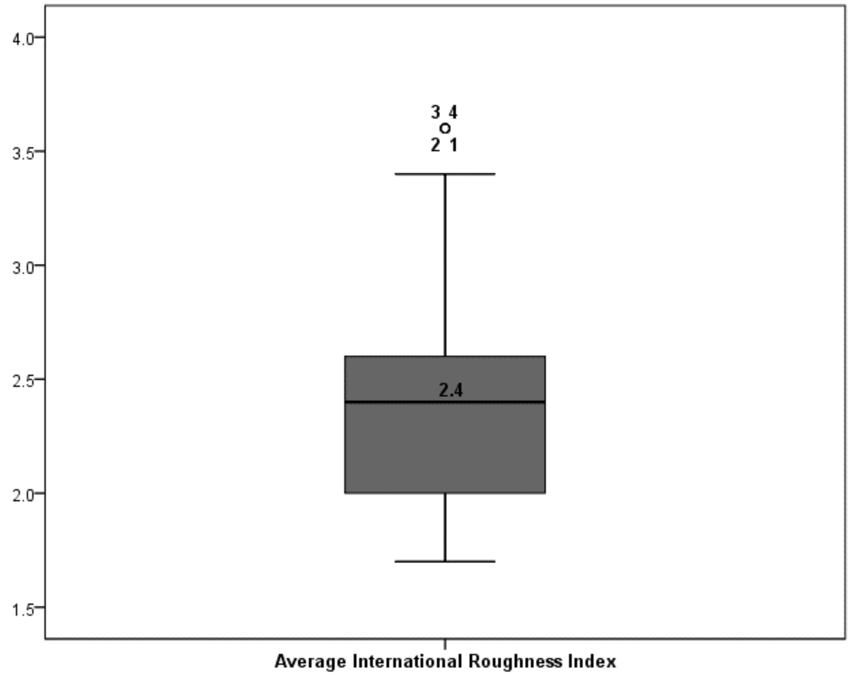


Figure 6.9 IRI (m/km) for Freeways PR-52 and PR-22 Boxplot

The FHWA defined categories for roughness condition based on IRI. For m/km the IRI's categories ranges from 0 (Excellent Condition) to more than 2.7 m/km (Very Poor) as shown in table 6.15. Figure 6.9 shows four segments with IRI values of more than 3.6 which classifies as segments with very poor IRI rating. The outliers marked with a circle, represents a mild outlier and for this reason, these segments will be included in the final dataset.

Table 6.15 FHWA IRI Categories

IRI Rating	in/m	m/km
Excellent	<60	<0.95
Good	61-95	0.96-1.5
Fair	96-120	1.51-1.9
Poor	121-170	1.91-2.7
Very Poor	>170	>2.7

Superelevation or roadway banking is another variable related to pavement. Figure 6.10 shows the boxplot for superelevation. AASHTO defines the maximum superelevation rates for freeway between 6 to 8%. The minimum value of superelevation was 0.52%, the maximum value was 7.16%, the median was 2.48%, the 25th percentile reported was 1.6% and the 75th percentile was 3.85%. The boxplot did not showed outliers for this variable.

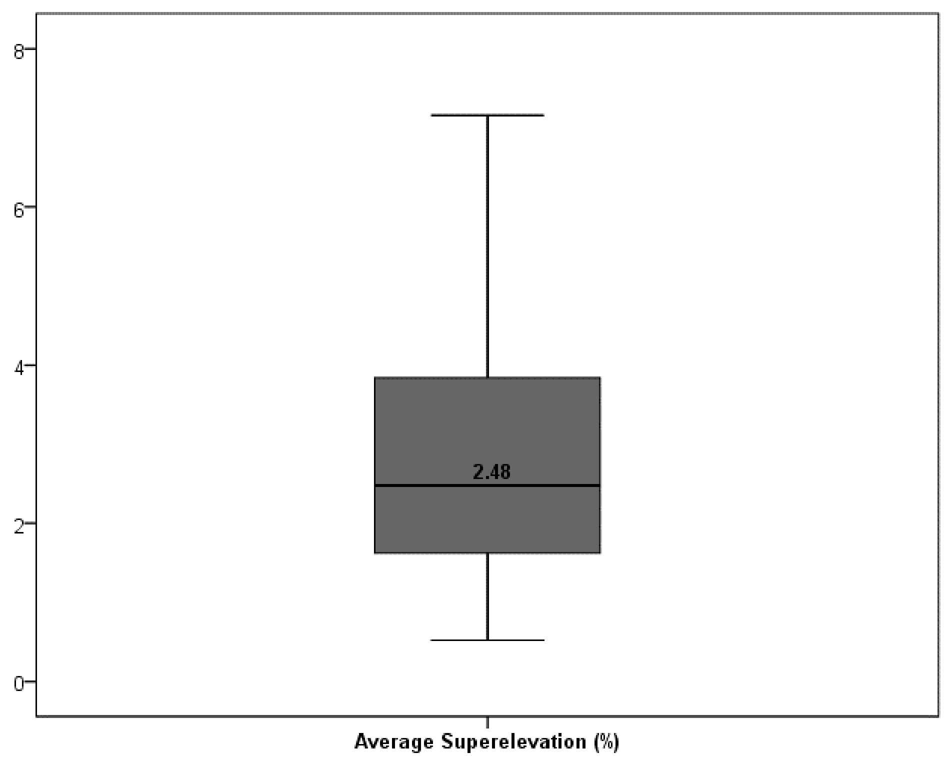


Figure 6.10 Superelevation for Freeways PR-52 and PR-22 Boxplot

There are several variables associated with curve sections within the reference group. Variables such as curve radius, degree of curvature, curve length, central curve angle and curvature change rate were evaluated. The outlier analysis for this variable was performed using only the values of the curve segments.

Figure 6.11 shows the boxplot for curve radius. The minimum value of curve radius was 308 meters, the maximum value was 3,423 meters, the median was 1,372 meters, the 25th percentile was 970 meters and the 75th percentile was 2,167.5 meters. The boxplot does not show outliers.

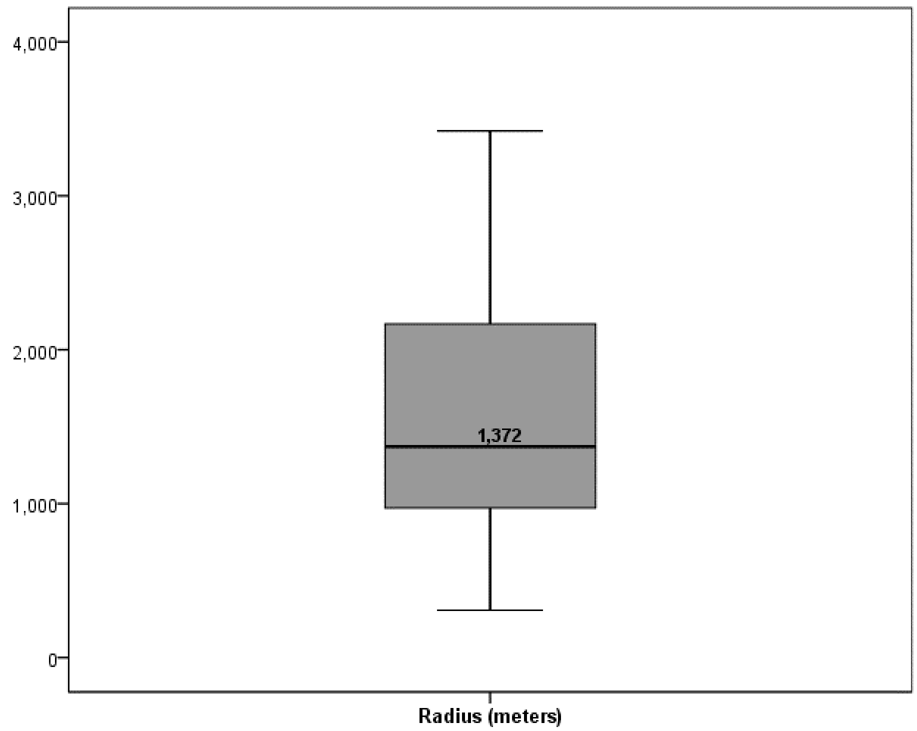


Figure 6.11 Curve Radius for Freeways PR-52 and PR-22 Boxplot

Another variable associated with curves is the degree of curvature, which is the measurement of the arc in the curve. Figure 6.12 shows the boxplot associated with the degree of curvature.

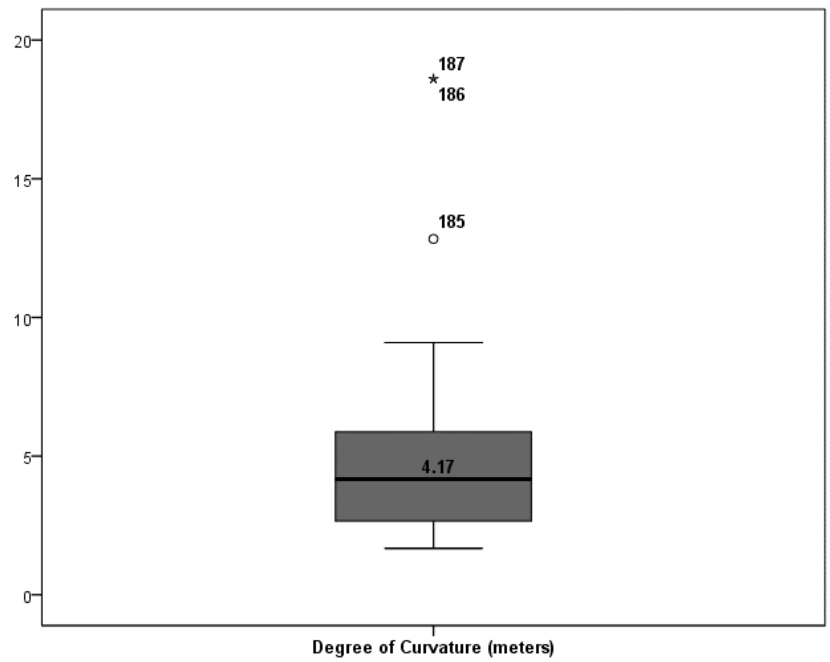


Figure 6.12 Degree of Curvature for Freeways PR-52 and PR-22 Boxplot

The minimum value of degree of curvature 1.67°, the maximum value was 18.6°, the median was 4.17°, the 25th percentile was 2.66° and the 75th percentile was 5.9°. The boxplot shows outliers in the segments 185, 186 and 187. The asterisk on the segments 186 and 187 represents that these outliers are extreme values and the circle in the segment 185 represents that this is a mild outlier. The extreme outliers in segments 186 and 187 should be eliminated from our final dataset but after calibrating the preliminary models the variables concerning freeway curves were not significant and for that reason, we decided to not eliminate any outliers related to freeway curve variables.

The boxplot for the curve length is presented in figure 6.13. The minimum value of curve length was 60 meters, the maximum value was 1,600 meters, the median was 500 meters, the 25th percentile was 320 meters and the 75th percentile was 900 meters. The boxplot did not reported outliers.

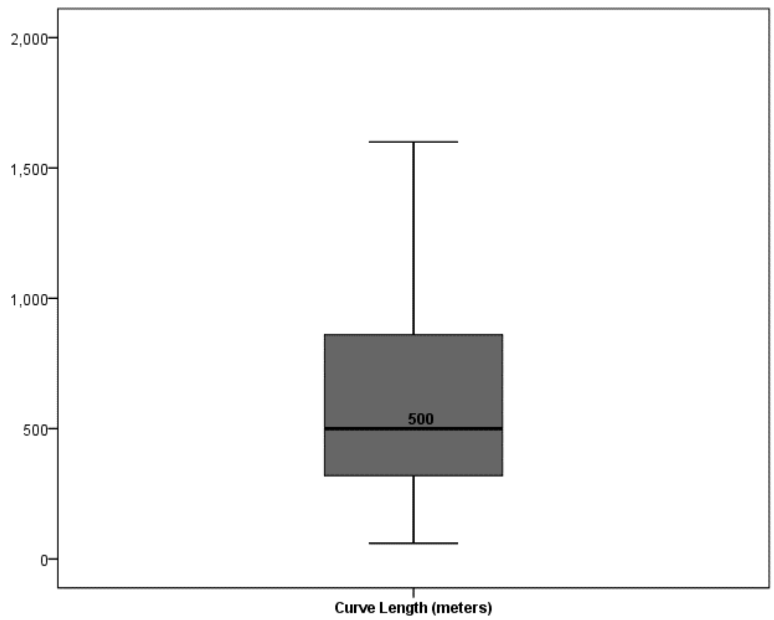


Figure 6.13 Curve Length for Freeways PR-52 and PR-22 Boxplot

Figure 6.14 presents the boxplot for central angle of the curve, which is measure in degrees. The minimum value of degree of curvature 1.4°, the maximum value was 97.5°, the median was 25.6°, the 25th percentile was 10.2° and the 75th percentile was 43.4°. The boxplot did not reported extreme outliers.

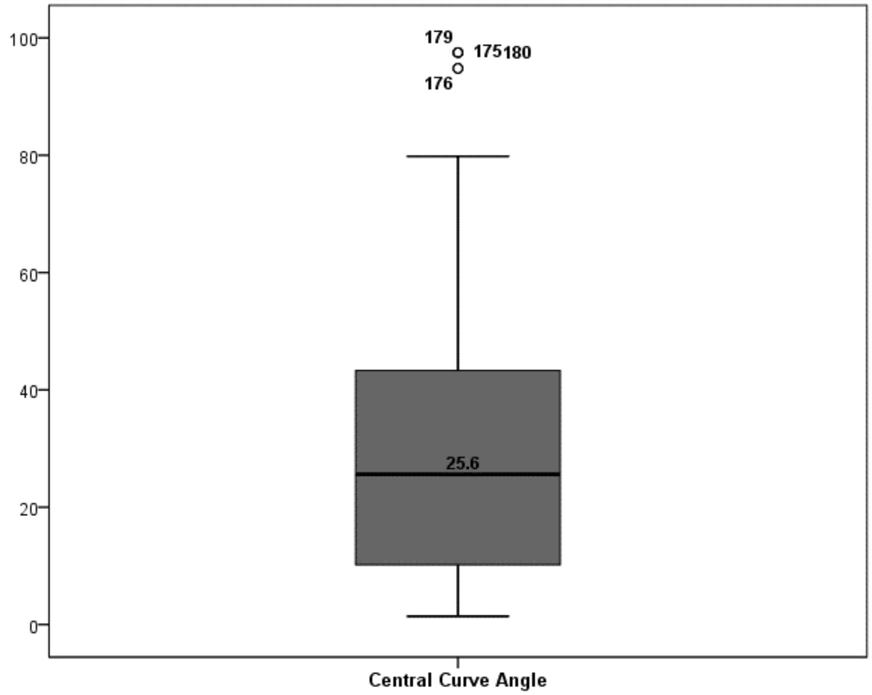


Figure 6.14 Central Curve Angle for Freeways PR-52 and PR-22 Boxplot

The final variable related to curve segments is the curvature change rate (CCR). Figure 6.15 shows the boxplot associated with CCR. The minimum value of CCR 0.017, the maximum value was 0.186, the median was 0.042, the 25th percentile was 0.026 and the 75th percentile was 0.059.

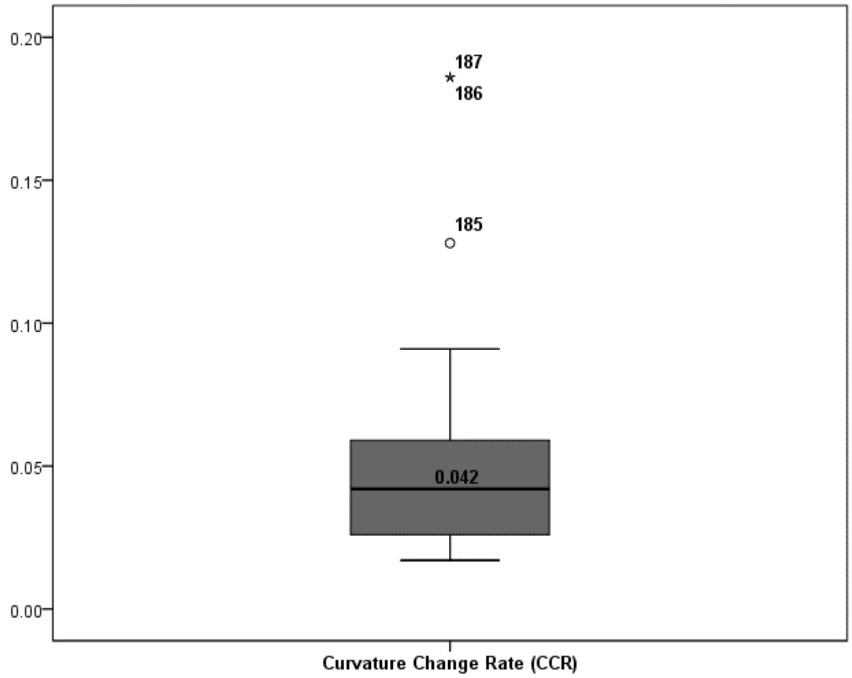


Figure 6.15 Curvature Change Rate for Freeways PR-52 and PR-22 Boxplot

The CCR boxplot shows outliers in the segments 185, 186 and 187. The asterisk on the segments 186 and 187 represents that these outliers are extreme values and the circle in the segment 185 represents that this is a mild outlier. The extreme outliers in segments 186 and 187 should be eliminated from our final dataset but after calibrating the preliminary models the variables concerning freeway curves were not significant and for that reason, we decided to not eliminate any outliers related to freeway curve variables.

The final variable evaluated was precipitation, which was measured in centimeters. Figure 6.16 presents the boxplot for average precipitation. The maximum value of precipitation reported was 210.9 centimeters, the minimum value was 100.8 centimeters and the median was 184.7 centimeters. In terms of percentiles, the 75th percentile was 192.5 centimeters and the 25th percentile was 106.5 centimeters. The boxplot did not showed any outliers for this variable.

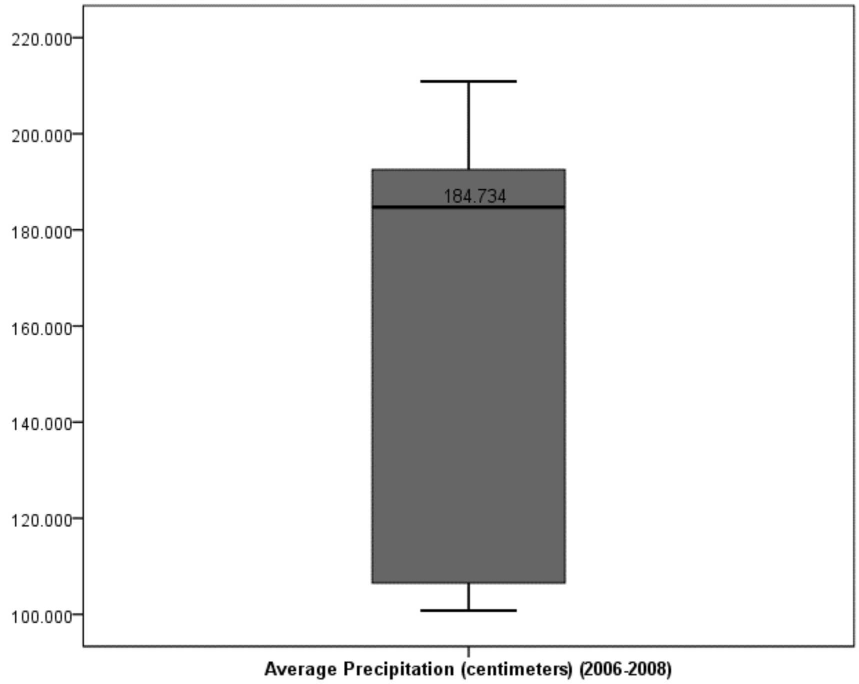


Figure 6.16 Average Precipitation for Freeways PR-52 and PR-22 Boxplot

Extreme outliers were detected on the variables degree of curvature and curvature change rate on segments 186 and 187. On preliminary calibration of the models this two variables were not significant with or without this segments included and a decision was made to not eliminate any curve related variables from analysis.

Summarizing, in this chapter the data preparation process was performed. After performing, the data merging process and homogeneous segmentation process a total of 775 homogeneous segments were identified for both freeways. The PR-52 freeway reported 395 segments and PR-22 freeway reported 380 segments. Then on the data cleansing process a total of 393 segments were eliminated either because they were missing values in the dataset or because they did not comply with the minimum segment length of 0.16 kilometers totalizing the segments to 382. From the 382 segments, a total of 277 segments comply with the requirements and criteria of the reference group. A total of ***277 segments*** will be use in the final development of SPF for total crashes and run off the road crashes.

7.0 DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

7.1 Introduction

This chapter will focus on the development of SPF's for total and run off the road crashes, in order to implement the EB method, for the evaluation of intermittent shoulder rumble strips on freeways in Puerto Rico. A total of ***277 segments*** that complies with the criteria of the reference group will be used for calibrating the models. Figure 7.1 shows the steps towards achieving the calibration process and the validation process. Due to a low count of segments identified on the previous chapter, a validation process was not possible.

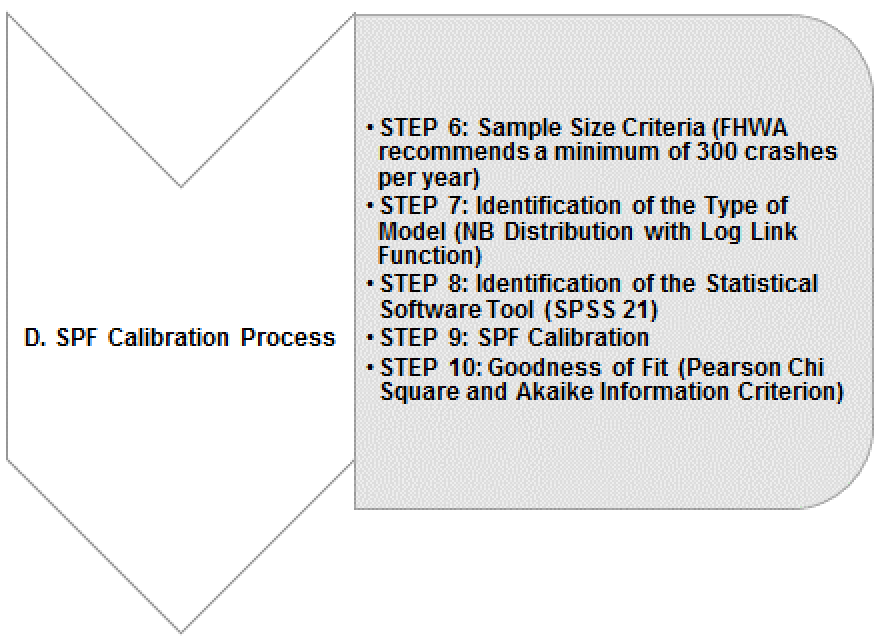


Figure 7.1 Development of SPF's - Final Steps

FHWA has specific guidelines for the development of SPF. Table 7.1 shows the guidelines for the calibration or development of SPF. FHWA indicates that for the development of SPF there should be a minimum sample of at least 300 crashes per year. It also recommends a minimum of 3 years of data for the calibration of SPFs.

The Reference Group totalizes 277 individual segments that quantified a longitude of 117 kilometers which is less than the minimum required. The SPF regarding total crashes for the Reference Group has an average of 940 crashes per year. The SPF regarding ROR crashes for the Reference Group has an average of 314 crashes per year. On both SPF's the minimum requirement of crashes per year are satisfied. In this particular study, a 3-year period data was used for the calibration of SPF for Total and ROR crashes.

Table 7.1 FHWA Guidelines for SPF's (FHWA, 2013)

Intended Use	Process	Sample needed	Staff hours needed - data collection and preparation (per SPF)
Project level	Calibrate SPF	30-50 sites; at least 100 crashes per year for total group[a]. At least 3 years of data are recommended.	150 to 350
Project level	Develop SPF	100-200 intersections or 100-200 miles; at least 300 crashes per year for total group[c]. At least 3 years of data are recommended.	450 to 1050

The NCHRP indicates on their recommended CMF protocols that the number of crashes is considered the sample unit in the development of a CMF. ***It also specifies that there is not an accepted method for determining the required sample size for the EB Method.*** (NCHRP, 2012) The crashes per year for this investigation succeed the minimum required provided as a guideline of the FHWA.

7.2 Reference Group Safety Performance Function Calibration

7.2.1 SPF for Total Crashes

The SPF is a mathematical equation that is use to estimate the prediction of crashes at a particular roadway segment or intersection. As mention on chapter 3, the models were calibrated based upon crash types using a Negative Binomial Distribution (NBD) which generates an additional parameter called the overdispersion parameter (Φ). The mathematical form of the model is given below:

$$E\,(\mu_i) = \exp\,(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots + \beta_n X_n) \qquad (7.1)$$

where the dependent variable $E(\mu_i)$ is the expected or predicted number of crashes and measured in crashes counts per year or per a period of time, the X's are the independent variables that includes exposure and road characteristics and the β_0, β_1, β_2, β_n are regression parameters.

The tool selected to calibrate the SPF' is the statistical software package called Statistical Package for the Social Sciences (SPSS) version 19. This software has a tool called "Generalized Linear Models" which can generate models in which the dependent variable is linearly connected to the factors and covariates with a specific link function. This tool can generate Negative Binomial with log link models as well as the overdispersion parameter. Figure 7.2 shows the Generalized Linear Models windows with the customization option for the distribution and link function for the type of model. It also has an option to estimate the value of the overdispersion parameter.

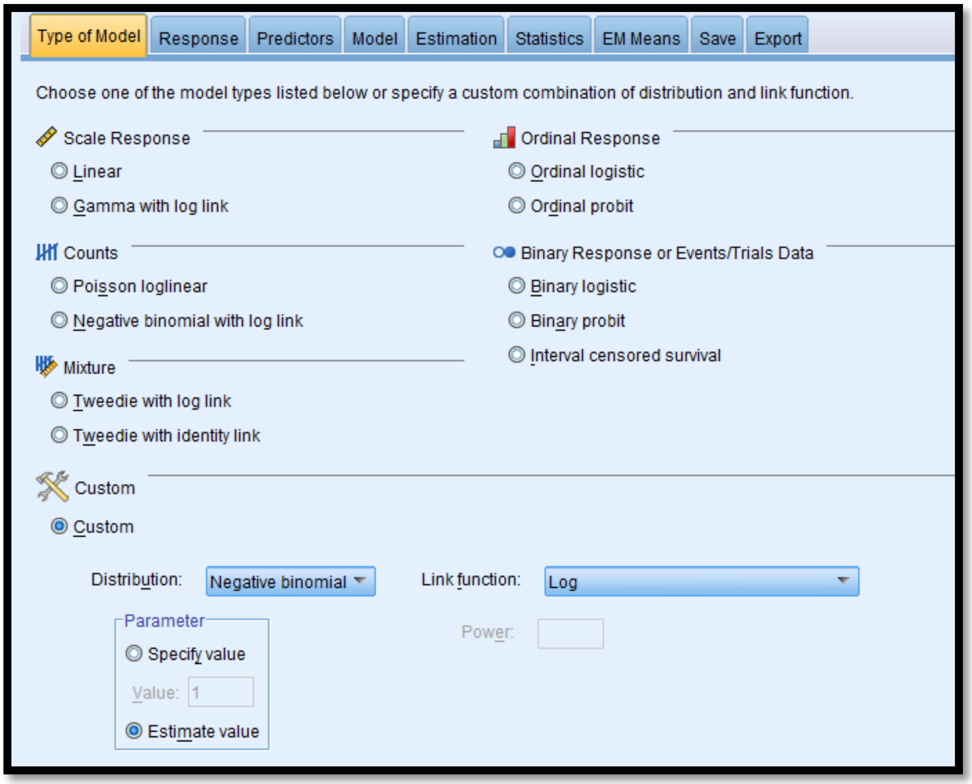


Figure 7.2 SPSS Generalized Linear Models Window (SPSS V21)

The dependent variable for this model is the total crashes for a period of three years (from year 2006 to 2008). This three year period is consider to be the "before period" in the observational study developed to measure the effectiveness of the intermittent shoulder rumble strips in freeways in Puerto Rico. In order to provide a model that estimates the average total crashes yearly, a variable that calculate the natural logarithm of the before period was created and was assigned as *an offset* of the model. The independent variables evaluated for the SPF associated to the reference group are summarized table 7.2. These variables are continuous and categorical variables.

Table 7.2 Evaluated SPF Variables for the Reference Group

Continuous Variables		Categorical Variables	
Description	**SPSS Variable Name**	**Description**	**SPSS Variable Name**
Segment Length (kms)	Length	Zone 0 for Rural and 1 for Urban	Zone
AADT /10k (veh/day)	AADT10k	Zone Categories 1.Rural Area (Less than 4,999 population) 2.Small Urban Area (5,000 to 49,999 population) 3.Small Urbanized Area (50,000 to 199,999 population) 4.Large Urbanized Area (More than 200,000 population)	ZoneCategories
IRI (m/km)	AverIRI	Pavement Type 4 for High Type Flexible, 5 for High Type Rigid and 6 for High Type Composite	PavType
Median Width (m)	Medianwidth	Median Type 2 for positive barrier (guardrail or concrete barrier) and 3 for unprotected median	MedianType
Right Shoulder Width (m)	Rshoulderwidth	Climate Category** 1 moist/wet climate (Precipitation > 104.14 cm) 2 dry climate (Precipitation < 104.14 cm)	ClimateCategory
Left Shoulder Width (m)	Lshouderwidth	Presence of Illumination O for no illumination system present and 1 for illumination system present	Illumination
Design Speed (km/hr)	DesignSpeed	Presence of Ramps 0 for no ramps and 1 for ramps presence	RampsPresence
Speed Limit (km/hr)	SpeedLimit	HSM Grade Category 1 for level terrain, 2 for moderate terrain and 3 for steep terrain	HSMGradeCategory
Average Single Unit Truck (%)	AveSingleTruck	Curvature Presence* 0 for no curves on segment and 1 for presence of curve in segment	CurvaturePres
Average Combination Trucks (%)	AveCombTruck	Bridge Presence 0 for no bridges presence on segment and 1 for bridge presence on segment	BridgePresence
Average Total Truck (%)	AveTotalTruck	Elevation 0 upward elevation and 1 downward elevation	Elevation
Average Directional Factor (%)	AveDirectFactor	*Freeway curvature related variables. **Climate category based upon publication by USDA. (Miller, 2009)	
Average Superelevation	AveSuperelev		
Absolute Radius (m)*	AbsRadius		
Degree of Curvature*	DegreeCurvM		
Curve Length (m)*	CurveLength		
Central Curve Angle*	CentralAngel		
Curvature Change Rate*	CurvChangeRate		
Average Precipitation (cm)	AvePreccm		

Calibration was conducted using the Generalized Linear Models tool in SPSS specifying the type of distributions as a Negative Binomial with a logarithm (Log) as the link function. It also specified the estimation of the value of the overdispersion parameter and an offset of natural logarithm for the before period which was 3 years. The SPF calibration for total crashes of the reference group was performed by using a ***total observation number of 277 reference group segments*** and a total of 30 independent variables were initially evaluated as shown in table 7.2. The dependent variable for this specific model is called the average total crashes for the period covering from 2006 to 2008, using data before the implementation of the treatment under evaluation.

SPSS predictor tab divides the variables as covariates or factors. The covariates are the scale or continuous variables and must be numeric. The factors are the categorical variables and they can be either numeric or string. The parameter estimation chosen was the Hybrid Method in which combines the Fisher scoring interactions and then switch to the Newton-Raphson method. Table 7.3 describes the parameters and goodness of fit statistics for the preliminary calibrated model for total crashes of the reference group.

Table 7.3 Parameters Estimates and Goodness of Fit Statistics of the Preliminary SPF for Total Crashes of the Reference Group

Parameter	Parameter Estimate, β	Std. Error	P-Value
Intercept	-0.043	0.1501	0.776
Climate Category=1 (Moist or Wet)	-0.661	0.1136	0.000
Climate Category=2 (Dry)	0^a	0^a	0^a
Ramp=0 (Ramp Not Presence)	-0.393	0.0869	0.000
Ramp=1 (Ramp Presence)	0^a	0^a	0^a
Length (km)	1.802	0.1612	0.000
AADT/10k	0.152	0.0147	0.000
Overdispersion Parameter	0.325	0.0387	
Goodness of Fit Statistics: **Deviance = 1.112** **Pearson Chi-Square = 1.072** **Akaike's Information Criterion (AIC)= 1,664.688**			

Note: 0^a SPSS set them zero because is a redundant parameter.

The estimated overdispersion parameter also known as the negative binomial parameter with a value of 0.325. Positive values of the negative binomial estimated parameter suggest that there is over-dispersion or that the variance is greater than the mean in this particular model. Only segment length, average AADT/10k, climate category and presence of ramps were found statistically significant with P-values < 0.00001.

The Deviance and Pearson Chi Square statistics indicates how well the model fits the data, values that are near one indicates that the model fits the data. This SPF for total crashes has Deviance (1.112) and Pearson Chi Square (1.072). Equation 7.2 and 7.3 are used to calculate the Deviance and Pearson Chi Square respectively. On both equations the $\hat{Y}_i$ represents the predicted value of Y_i. On Equation 7.3 the w_i represents the dispersion weight and V represents the variance.

$$\text{Deviance} = \sum_{i=1}^{n} 2\left(Yi \log\left(\frac{Yi}{\hat{Y}i}\right) - (Yi - \hat{Y}i)\right) \qquad (7.2)$$

$$\text{Pearson Chi Square} = \sum_{i=1}^{n} \frac{wi(Yi-\hat{Y}i)^2}{V(\hat{Y}i)} \qquad (7.3)$$

The Akaikes Information Criterion (AIC) evaluate the suitability of the model; a lower value of AIC specifies that is a better model. It is use for comparison purposed when performing more than one model with the same dataset. Equation 7.4 is used when calculating the AIC statistic.

AIC = -2 * Log Likehood + 2 * No. of Parameters (7.4)

In an attempt to detect unusual or influential data in this model, a model check process was performed. There are three ways to determine unusual or influential data by using outliers (observations with large residuals), leverage (observations with extreme values) and influence (observations that can change the estimate of the coefficients). The influence is a better way to identify unusual observations because it combines the leverage and the outliers of observations (IDRE, 2015).

SPSS 21 calculates the residuals, Cooks Distance, Leverage and the Standardized Deviance Residuals . Cooks Distance (D_i) is a measurement of influence. The higher the Cook's Distance the more influential the observation. The guideline to determine which observations are influential are shown on equation 7.5. In this equation, n represents the total observations or population and k represents the total independent variables of the model.

$$D_i \geq \frac{4}{(n-k-1)} \quad \text{or} \quad D_i \geq \frac{4}{(n)} \qquad (7.5)$$

The leverage (h_i) are observations with extreme values or the measurement of the distance between the independent variables from its mean. The guideline to determine which observations has high values of leverage is represented in equation 7.6.

$$h_i \geq \frac{2(k+1)}{(n)} \qquad (7.6)$$

The Standardize Deviance Residual (d_{si}) is use to check the model fit on GLM in terms of the measurement of deviance contributed from each observation. Equation 7.7 shows how to calculate the Standardize Deviance Residual for each observation, where, d_i represents the deviance for each observation and h_i represents the leverage for each observation. The Standardize Deviance Residuals can locate major outliers if there values are outside 3 and -3.

$$ds_i = \frac{di}{\sqrt{(1-hi)}} \qquad (7.7)$$

A model check process was performed by reviewing the Residuals, Cooks Distance, Leverage and Standardize Deviance Residuals larger than 3 or -3. Segments 191, 215, 246 and 260 were eliminated from the analysis and the model was recalibrated. The final model for total crashes is shown on table 7.4.

Table 7.4 Parameters Estimates and Goodness of Fit Statistics of the Final SPF for Total Crashes of the Reference Group

Parameter	Parameter Estimate, β	Std. Error	P-Value
Intercept	-0.183	0.1499	0.222
Climate Category=1 (Moist or Wet)	-0.644	0.1121	0.000
Climate Category=2 (Dry)	0[a]	0[a]	0[a]
Ramp=0 (Ramp Not Presence)	-0.357	0.0856	0.000
Ramp=1 (Ramp Presence)	0[a]	0[a]	0[a]
Length (km)	1.958	0.1774	0.000
AADT/10k	0.157	0.0143	0.000
Overdispersion Parameter	0.294	0.0373	
Goodness of Fit Statistics: **Deviance = 1.126** **Pearson Chi-Square = 1.099** **Akaike's Information Criterion (AIC)= 1,611.58**			

Note: 0[a] SPSS set them zero because is a redundant parameter.

Although the value of the Pearson Chi-Square and the Deviance slightly increases the value of the Akaike's Information Criterion (AIC) decreases by 53 points, indicating an improvement in the overall fitness of the model.

The SPF for total crashes of the Reference Group is defined on the equation 7.8. The intercept of the model has a p value greater than 0.05 and will not be included on the final model.

$$\mathbf{SPF_{Total\ Crashes} = exp\ (\ -0.183 + (-0.644 * (Climate{=}Moist/Wet)) + (-0.357 * (RampPresence{=}0)) + (1.958 * Length) + (0.157 * (AADT/10k))} \qquad \mathbf{(7.8)}$$

Where, *Climate=Moist or Wet* has values of 0 for dry climate and 1 if the climate is moist or wet in the segment and *RampPresence=0* has values of 0 if the segment has a freeway ramps and 1 if the segment do not have a freeway ramps. The continuous variables of the SPF are the length of the segment in kilometers and the AADT divided by 10,000 in vehicles per day.

A model check process was performed for the final model. Figure 7.3 shows a scatterplot of the Standardized Deviance Residuals versus Predicted value of Mean of Response. If the values of the standardized deviance residuals are between 2 and minus 2, it indicates that there are not major outliers compromising the fit of the model.

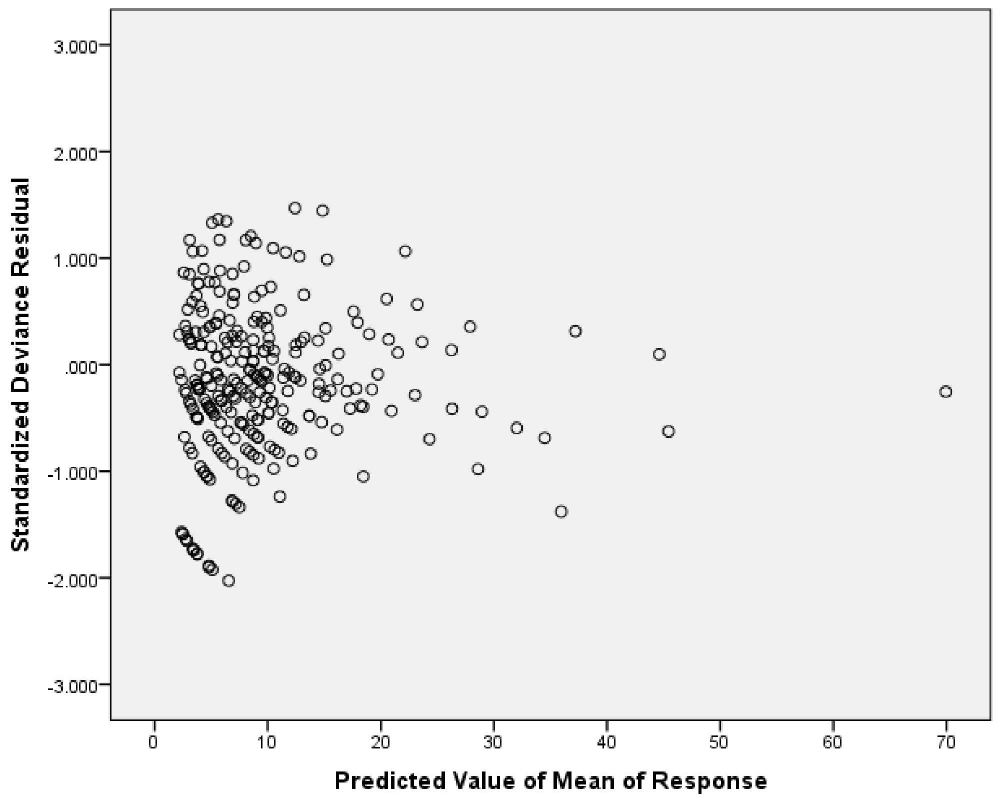


Figure 7.3 Standardized Deviance Residuals Scatterplot - SPF for Total Crashes

Finally, to prove the assumptions of the Negative Binomial Model three graphs were performed. The *first assumption* is that crash counts on every unit has a Poisson Distribution. Figure 7.4 is a histogram regarding the dependent variable use to fit the model. The pattern of the histogram shows that the crash counts approximates the Poisson Distribution shown on the top right corner of the figure.

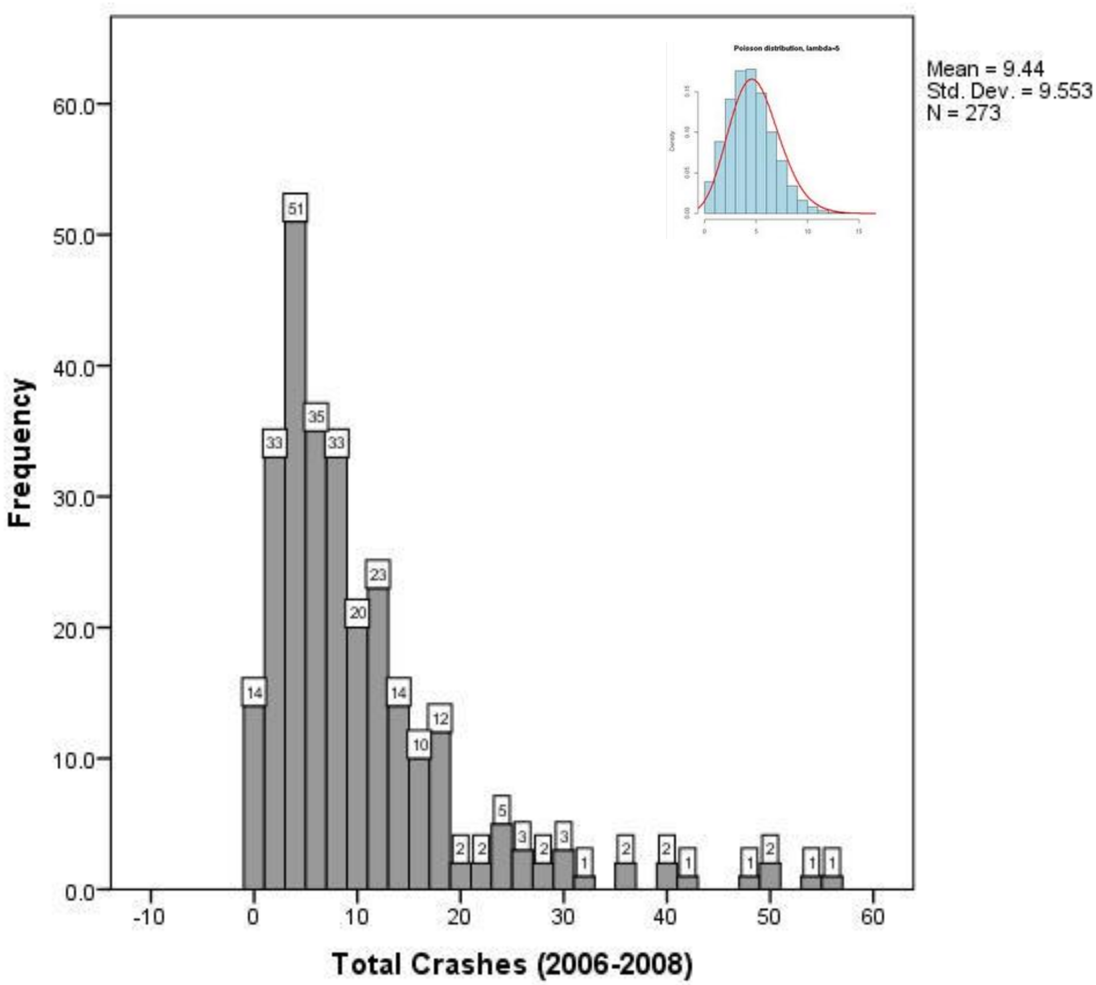


Figure 7.4 Total Crashes for the Before Period Histogram

The *second assumption* of this type of model is that the expected crashes per unit of which a population is comprised are different. To prove this assumption a scatterplot of the residuals versus the order of the observations was performed. Figure 7.5 shows the scatterplot of the residuals for the SPF for total crashes. The scatterplot shows that there is not a pattern in the residuals or that each observation are statistically independent.

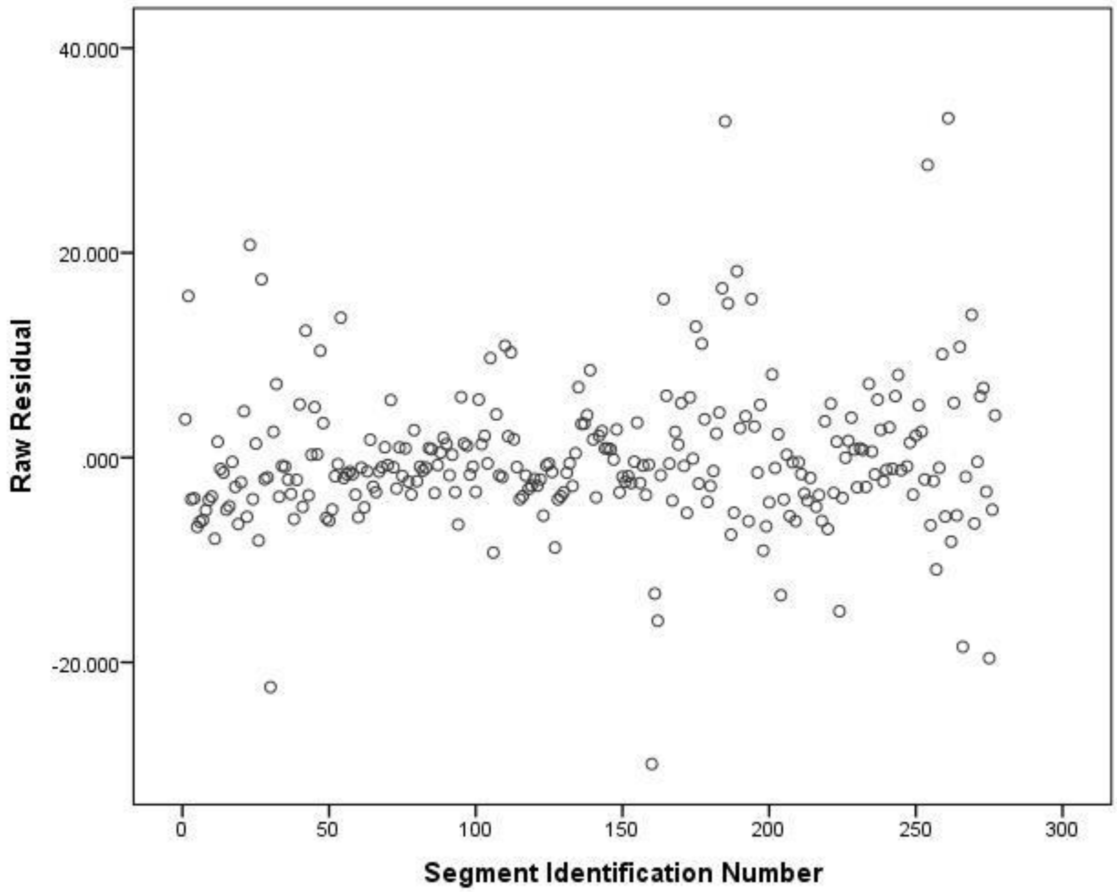


Figure 7.5 SPF for Total Crashes Residuals Scatterplot

The *third assumption* of NB Models is that the frequency of the expected crashes within a population can be well approximated to a gamma distribution (Hauer, 2015). Figure 7.6 shows a histogram of the expected total crashes. This assumption gives the NB Model flexibility because the gamma distribution has more than one form. This histograms shows that the expected crashes approximate a 3-parameter gamma distribution.

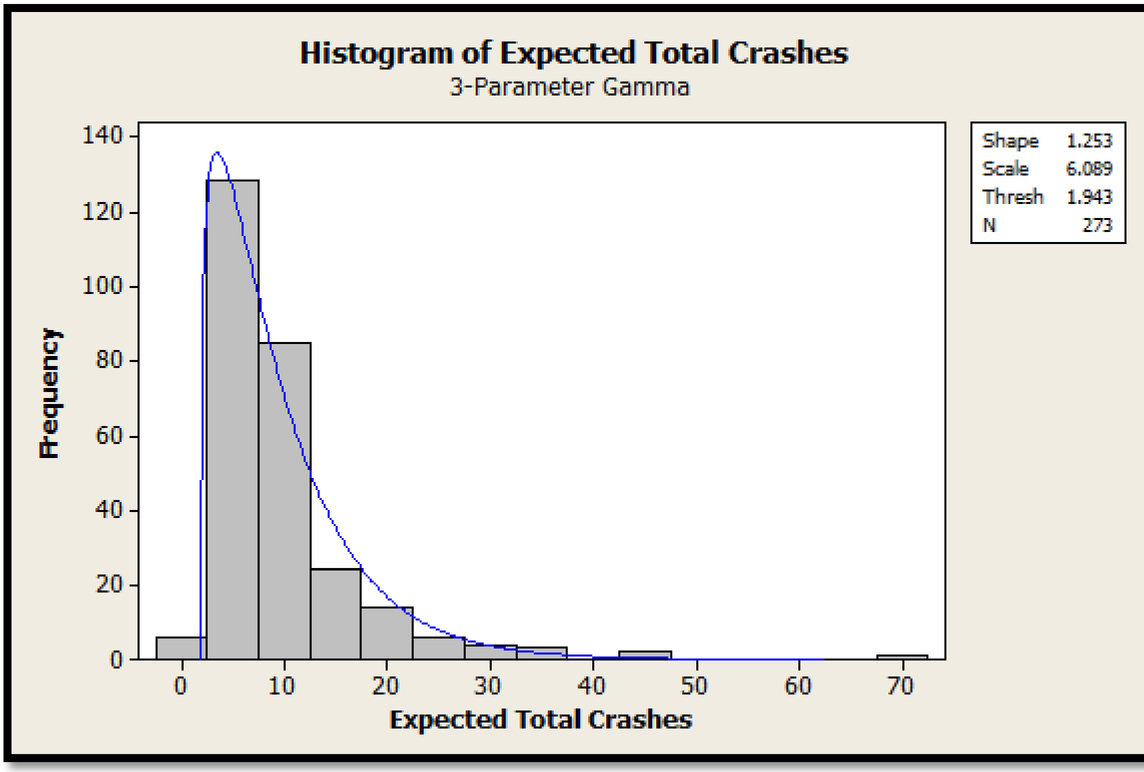


Figure 7.6 Expected Total Crashes Histogram

A sensitivity analysis was completed and describe in appendix C. The sensitivity analysis associated to the SPF for total crashes for the Reference Group indicated that an increase in segment length, AADT, presence of ramps and dry climate increase the prediction of total crashes. The variable segment length showed more sensitivity than AADT, Presence of Ramps and Climate.

In terms of freeway ramps, previous investigations suggest that ramps are the most common segment of crashes per mile driven on interstate freeways and highways. Speed is the contributing factor associated to crashes and the most common type of crash on ramps was ROR crashes. (Mc. Cartt, 2003) On this investigation presence of ramps was found statistically significant with P-values < 0.00001 on the calibrated SPF associated to both Total and ROR crashes.

Climate was found statistically significant with P-values < 0.00001. This variable suggest that in dry climate areas, were precipitation is less than 104.14 cm, there is a trend for the prediction of crashes to increase. Appendix B shows the average crash count for dry climate and moist or wet climates. The crash average for dry climate associated to the reference group was larger than on moist or wet climate.

The final SPF to estimate total crashes will be use in the chapter 8 when performing the EB method to evaluate the effectiveness of the intermittent shoulder rumble strip. The next section will address the development of a SPF for the same reference group regarding run off the road crashes.

7.2.1 SPF for Run off the Road Crashes

One relevant aspect in the evaluation of the effectiveness of shoulder rumble strips on freeways is the assessment in terms of the reduction in run off the road crashes. SPF related to ROR crashes were calibrated for the reference group. The same procedure followed on the SPF for total crashes was performed. The dependent variable for this model is the ROR crashes for the reference group. The PRHTA classifies ROR crashes as crashes involving vehicles that went off cliffs or roadside slopes, that crash with a fix object on the roadside such as illumination poles, barriers, trees, traffic signs, fences or other fixed objects. In the calibration process of the SPF for ROR crashes the same independent variables were used in addition to two new categorical variables concerning the dimensions of the width of both the right and left lane.

The first model SPF for ROR crashes of the reference group calibrated is shown in table 7.5. Only three independent variables were statistically significant. The overall model had a Pearson Chi-Square value that is close to one, indicating that the model is well fitted.

Table 7.5 Parameters Estimates and Goodness of Fit Statistics of the Preliminary SPF for ROR Crashes of the Reference Group

Parameter	Parameter Estimate, β	Std. Error	P-Value
Intercept	-0.893	0.1681	0.000
Ramp=0 (Ramp Not Presence)	-0.21	0.1071	0.05
Ramp=1 (Ramp Presence)	0[a]	0[a]	0[a]
AADT/10k	0.044	.0163	0.007
Length (km)	1.688	0.1755	0.000
Overdispersion Parameter	0.332	0.06	
Goodness of Fit Statistics **Deviance = 1.163** **Pearson Chi-Square = 1.076** **Akaike's Information Criterion (AIC)= 1209.061**			

In an attempt to detect unusual or influential data in this model, a check process was performed by using the estimated Cook's Distance, Leverage and the Residuals. The segments 175, 191 and 215 were eliminated because they had the highest Cooks Distance, Leverage and Residuals.

The estimates of the parameters and goodness of fit statistics for the recalibrated model are shown on table 7.6. The Pearson Chi-square and Deviance were slightly higher but the AIC is less than the first model calibrated, which indicates that it is a more suitable model for the dataset.

Table 7.6 Parameters Estimates for Final SPF of ROR Crashes

Parameter	Parameter Estimate, β	Std. Error	P-Value
Intercept	-0.919	0.1766	0.000
Ramp=0 (Ramp Not Presence)	-0.230	0.1065	0.031
Ramp=1 (Ramp Presence)	0[a]	0[a]	0[a]
AADT/10k	0.042	.0166	0.012
Length (km)	1.817	0.1981	0.000
Overdispersion Parameter	0.318	0.066	
Goodness of Fit Statistics **Deviance = 1.17** **Pearson Chi-Square = 1.09** **Akaike's Information Criterion (AIC)= 1181.995**			

The final SPF for ROR crashes of the reference group is shown in equation 7.9. The categorical variable “ramp=0” *indicates that a value of 0 is used when there is an ramp on the freeway segment and a value of 1 indicates that the segment does not have freeway ramps*. The overdispersion parameter for this particular model is 0.318. It is important to emphasis that this particular model can be use on roads or segments that have the same characteristics as the reference group shown on table 6.10.

$$\mathbf{SPF_{ROR\ crashes} = exp\ (-0.919 + (-0.23*(Ramp=0)) + (0.042*(AADT/10k)) + (1.817 * Length))} \quad \mathbf{(7.9)}$$

A model check process was performed for the final model. Figure 7.7 shows the Predicted Value of the Mean Response versus the Standardized Deviance Residuals for the SPF associated with ROR crashes. The values of the standardized deviance residuals are between 2 and minus 2 indicating there are not major outliers compromising the fit of the model. Each point on the scatterplot represents a freeway homogeneous segment.

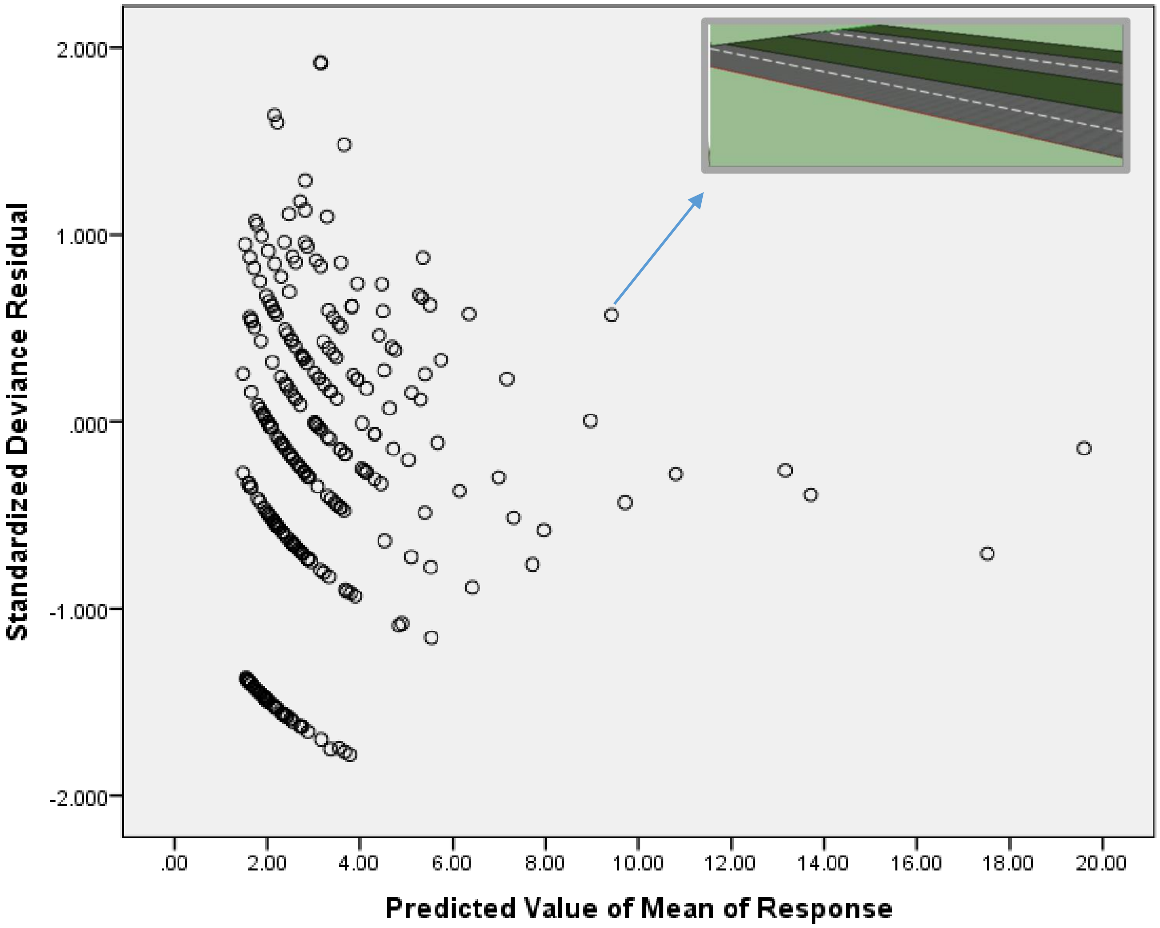


Figure 7.7 Standardized Deviance Residuals Scatterplot for the SPF for ROR Crashes

Finally, to prove the assumptions of the Negative Binomial Model three graphs were developed. The *first assumption* is that crash counts on every unit has a Poisson Distribution. Figure 7.8 is a histogram regarding the dependent variable use to fit the model. The pattern of the histogram shows that ROR count crashes approximates the Poisson Distribution.

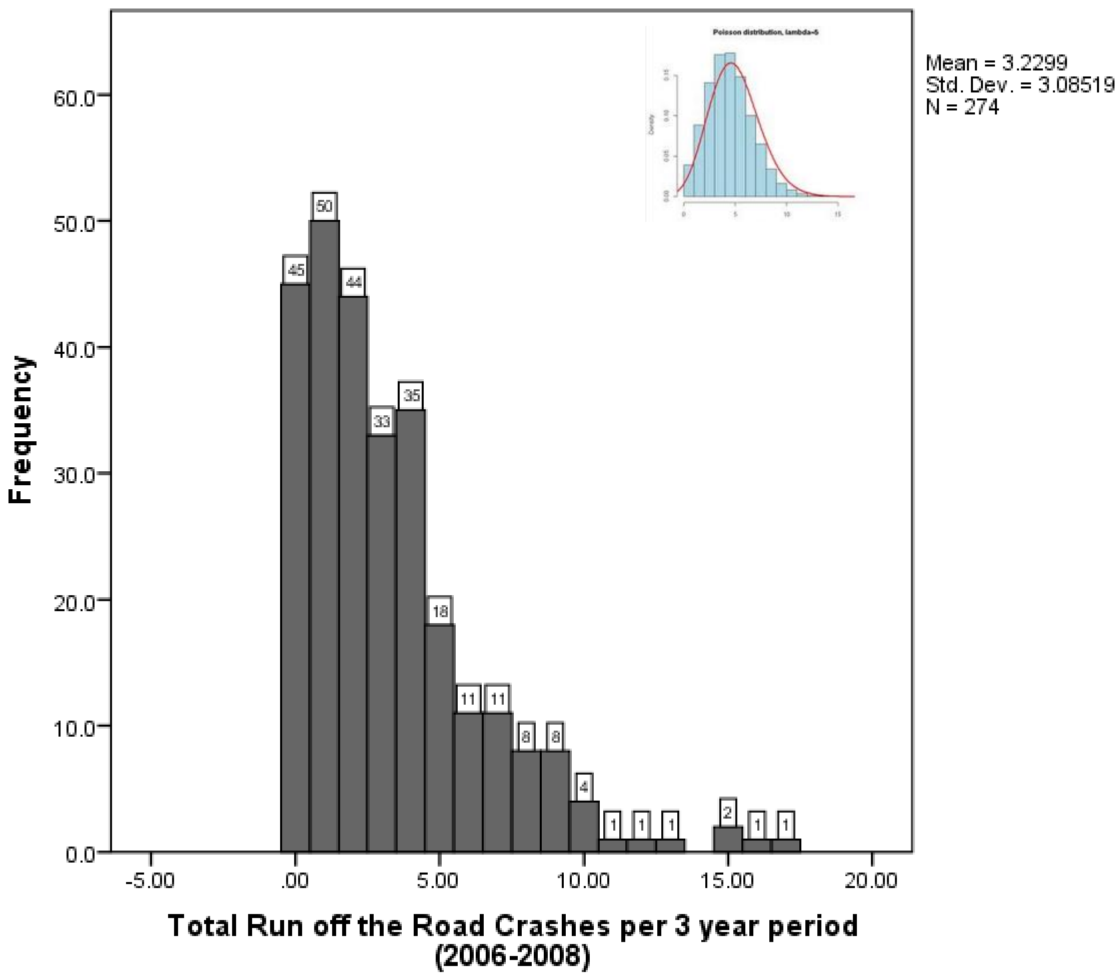


Figure 7.8 ROR Crashes for the Before Period Histogram

The *second assumption* of this type of model is that the expected crashes per unit of which a population is comprised are different. To prove this assumption a scatterplot of the residuals versus the order of the observations was performed. Figure 7.9 shows the scatterplot of the residuals for the SPF for ROR crashes. The scatterplot shows that there is not a pattern in the residuals and they act as independent observations.

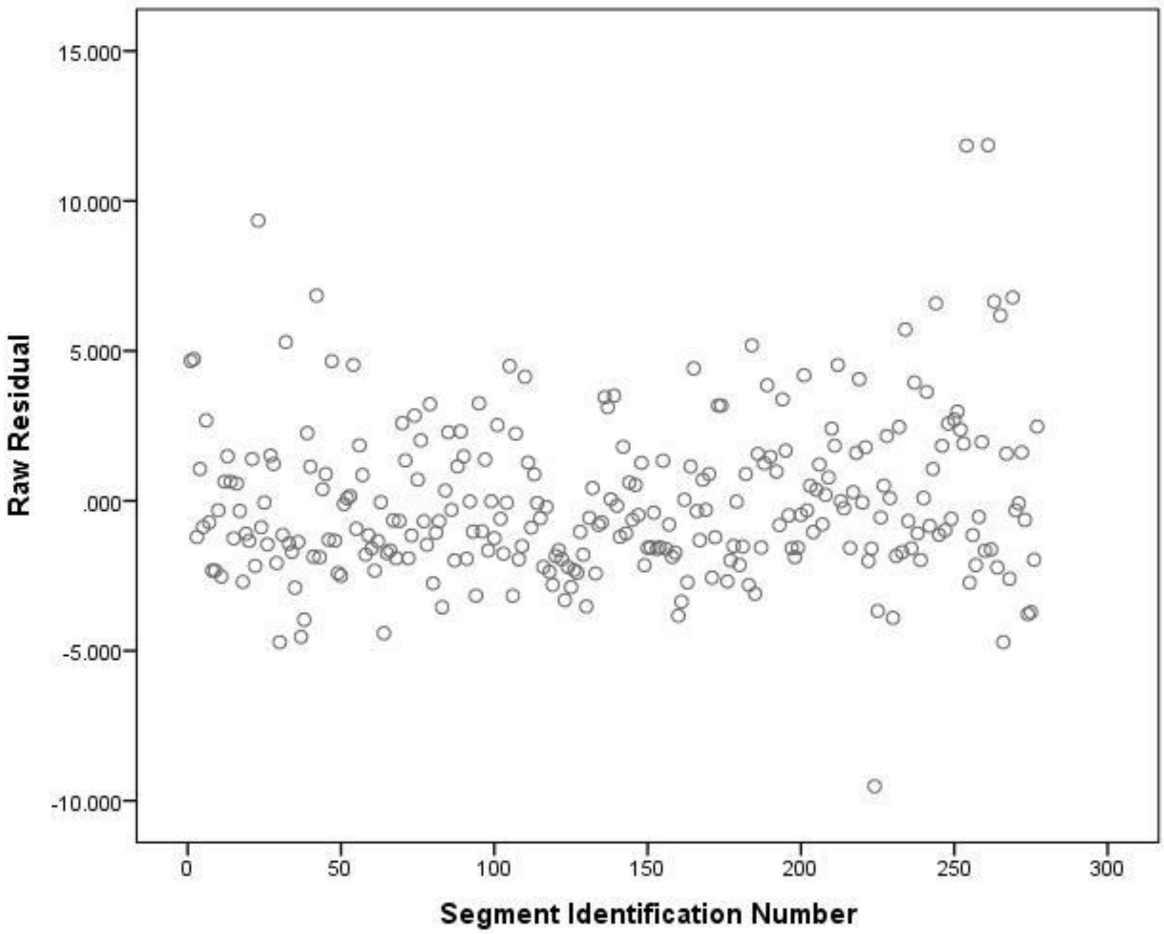


Figure 7.9 SPF for ROR Crashes Residuals Scatterplot

The *third and final assumption* of NB Models is that the frequency of the expected crashes within a population can be well approximated to a gamma distribution (Hauer, 2015). Figure 7.10 shows a histogram of the Expected ROR crashes. The histogram shows a that the expected crashes approximate a 3- parameter gamma distribution. Observations near the cero line represents that the residuals are smaller or that the error is smaller which indicates better approximation of the adjusted value of ROR crashes. Patterns that violates this assumption are if the observations decrease systematically or increases, curve or line patterns are also a violation of this assumption.

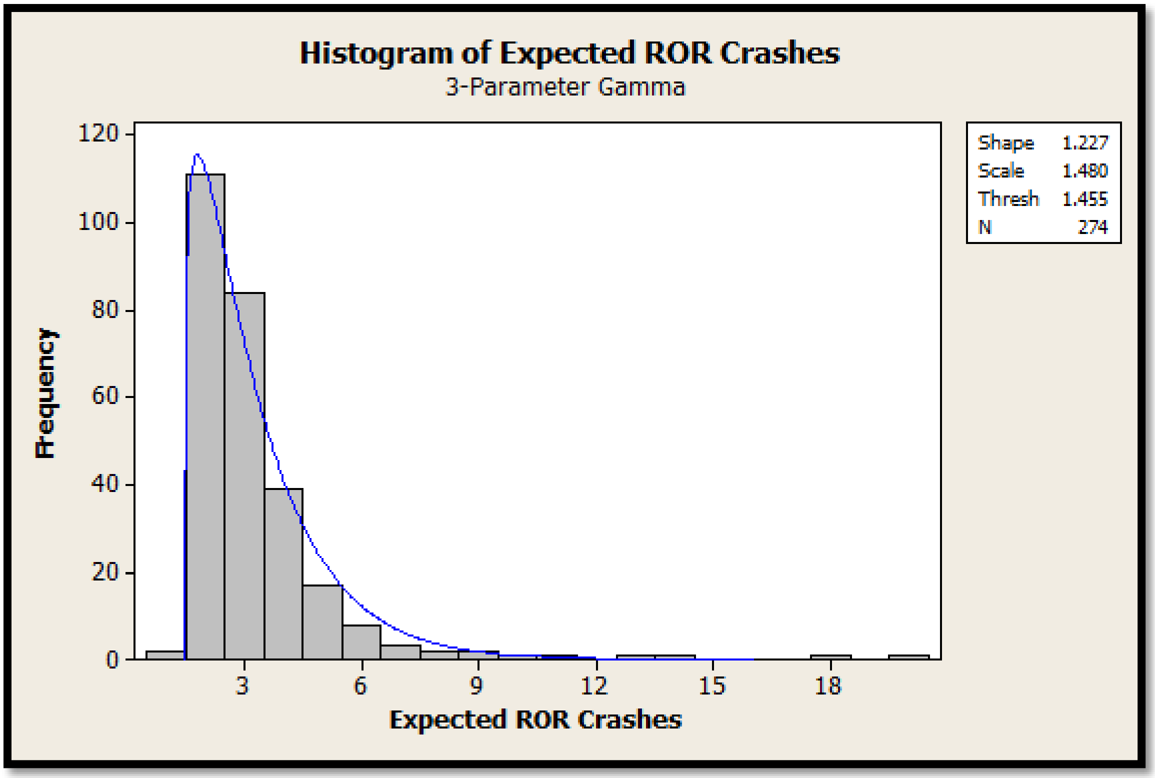


Figure 7.10 Expected ROR Crashes Histogram

The sensitivity analysis (appendix C) associated to the SPF for ROR crashes for the Reference Group indicated that an increase in segment length, AADT and presence of ramps increase the prediction of total crashes. The variable segment length showed more sensitivity than AADT and Presence of Ramps.

The next section will address the development of jurisdictional SPF for freeways in Puerto Rico. These models are not going to be use in the EB method for this investigation. This jurisdictional SPF is a great tool for a fast prediction of crashes in any freeway segment and can be use by practitioners and governmental entities in their quest to improve the highway safety of the island freeway network.

7.3 Safety Performance Function for Freeways in Puerto Rico

7.3.1 Jurisdictional Freeway SPF for Total Crashes

The FHWA recommends jurisdictional SPF for state transportation departments as a mean to be used as a tool for freeway network screenings. Jurisdictional SPF can be use by governmental entities to assist them identify high priority site locations for potential improvement purposes along the freeway. Many states in the United States are calibrating specific jurisdictional SPF to use in their State's network screening processes.

Jurisdictional SPF is used to estimate the average crashes along a particular segment based upon AADT and segment length. *A total of 382 homogeneous freeway segments that were less than 0.16 kilometers were used to calibrate this model*. The dependent variable for this model is the average crashes for freeway segments. Table 7.7 shows the parameter estimates and goodness of fit statistics for this preliminary Freeway SPF.

Table 7.7 Preliminary Parameters Estimates for Freeway SPF

Parameter	Parameter Estimate, β	Std. Error	P-Value
Intercept	-0.385	0.1165	0.001
AADT/10k (veh/day)	0.099	0.0102	0.000
Length (km)	1.683	0.1599	0.000
Overdispersion Parameter	0.485	0.0437	
Goodness of Fit Statistics **Deviance = 1.094** **Pearson Chi-Square = 1.266** **Akaike's Information Criterion (AIC)= 2,378.914**			

A model checking process for the identification of unusual observations was performed by using the estimated Cook's Distance. In this case the cut off horizontal line is four divided by the number of observations that totalizes 0.01047. Figure 7.11 shows a scatterplot of Cook's Distance for this jurisdictional freeway SPF. A total of 22 unusual observations were above the cut off horizontal line. A recalibration of the model without the unusual observations was performed and is shown in table 7.8.

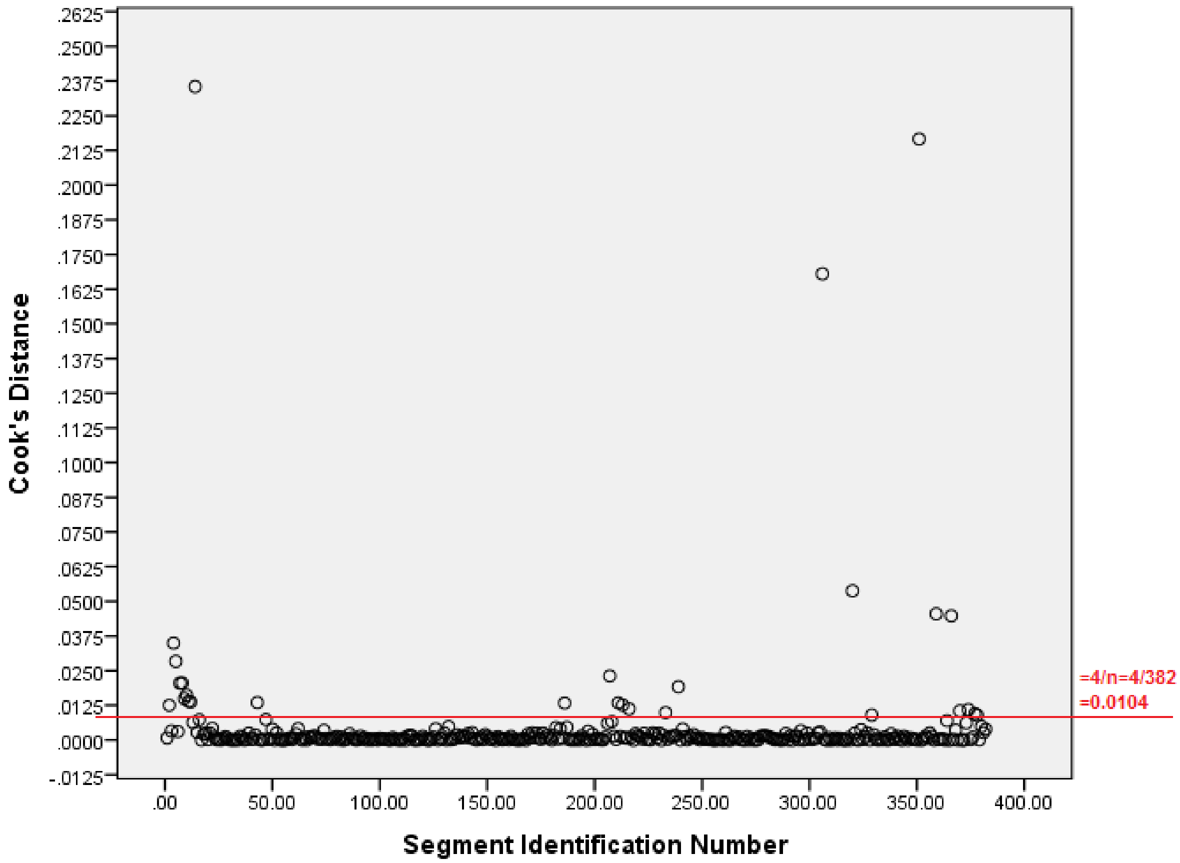


Figure 7.11 Cooks Distance Scatterplot for Jurisdictional SPF

Table 7.8 Parameters Estimates for Final Freeway Jurisdictional SPF

Parameter	Parameter Estimate, β	Std. Error	P-Value
Intercept	-0.655	0.1039	0.000
AADT/10k (veh/day)	0.115	0.0097	0.000
Length (km)	1.897	0.1479	0.000
Overdispersion Parameter	0.285	0.0334	
Goodness of Fit Statistics **Deviance = 1.138** **Pearson Chi-Square = 1.087** **Akaike's Information Criterion (AIC)= 2,082.7**			

The goodness of fit statistics between the preliminary model and the final model shows that the deviance and the Pearson Chi-Square decreasing in value and getting closer to one. The AIC shows and increase in 296 points indicating that this model is a more suitable data set for this particular model.

The final jurisdictional SPF to estimate total crashes for toll freeways in Puerto Rico is shown in equation 7.10. The overdispersion parameter for this particular model is 0.285.

$$\mathbf{SPF_{Total\ Crashes} = exp\ (-0.655 + (1.897 * Length) + (0.115 * (AADT/10k))} \quad \mathbf{(7.10)}$$

Where, the variable length is the segment length measured in kilometers and the variable AADT/10k is the AADT divided by a value of 10,000. This particular model has usage limits in terms of their maximum and minimum segment length. Guidelines for the use of this model are that estimates better when used in segments with a minimum length of 0.16 kilometers and maximum length of 1.6 kilometers.

A model check process was performed for the final model for total crashes on freeways segments. Figure 7.12 shows the Predicted Value of the Mean Response versus the Standardized Deviance Residuals associated with Jurisdictional Freeway SPF for total crashes. The values of the standardized deviance residuals are between 2 and minus 2 indicating there are not major outliers compromising the fit of the model.

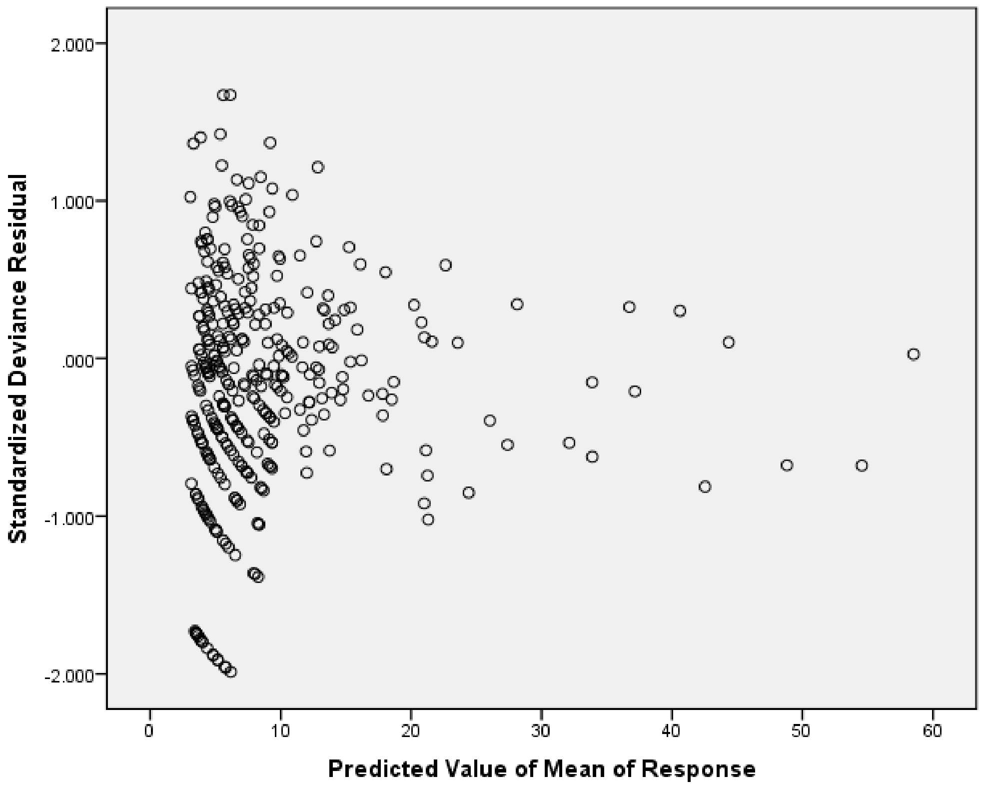


Figure 7.12 Standardized Deviance Residuals Scatterplot for Jurisdictional SPF

The three assumptions of the NB distribution model are proven using histograms and scatterplots. As mention before, the *first assumption* is that crash counts on every unit has a Poisson Distribution. Figure 7.13 is a histogram regarding the dependent variable use to fit the model. The pattern of the histogram shows that the average total crashes for freeway segments approximates the form of the Poisson Distribution.

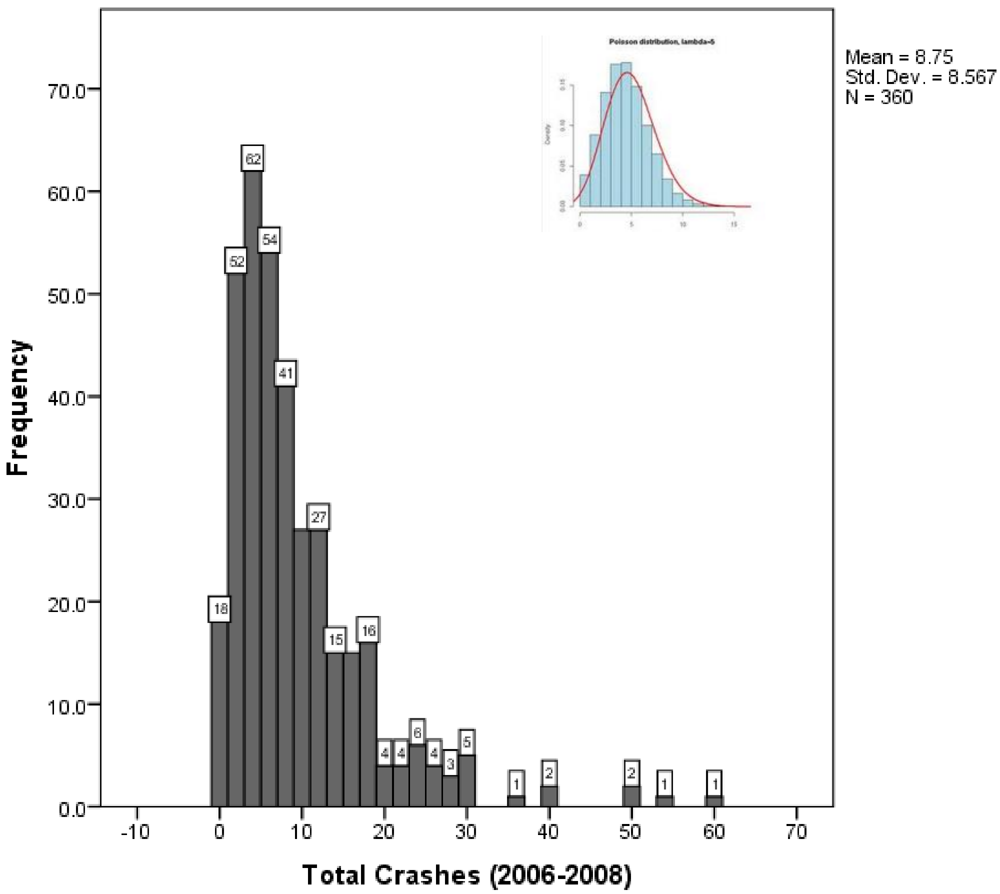


Figure 7.13 Total Crashes for Freeway Segments Histogram

The *second assumption* of this type of model is that the expected average crashes per unit of which a population is comprised are different. To prove this assumption a scatterplot of the residuals versus the order of the observations was performed. Figure 7.14 shows the scatterplot of the residuals of the freeway jurisdictional SPF. The scatterplot shows that there is not a pattern in the residuals and they act as independent observations.

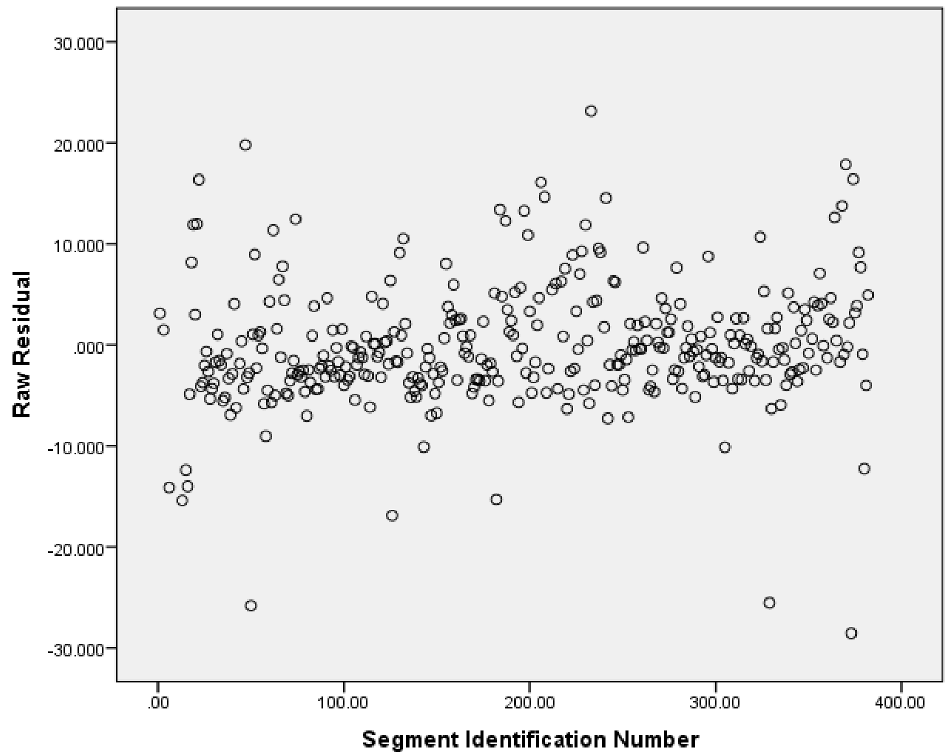


Figure 7.14 Freeway Jurisdictional SPF Residuals Scatterplot

The *third and final assumption* of NB Models is that the frequency of the expected crashes within a population can be well approximated to a gamma distribution (Hauer, 2015). Figure 7.15 shows a histogram of the Expected Crashes of the freeway jurisdictional SPF. The histogram shows that the expected crashes is well approximated to a 3- parameter gamma.

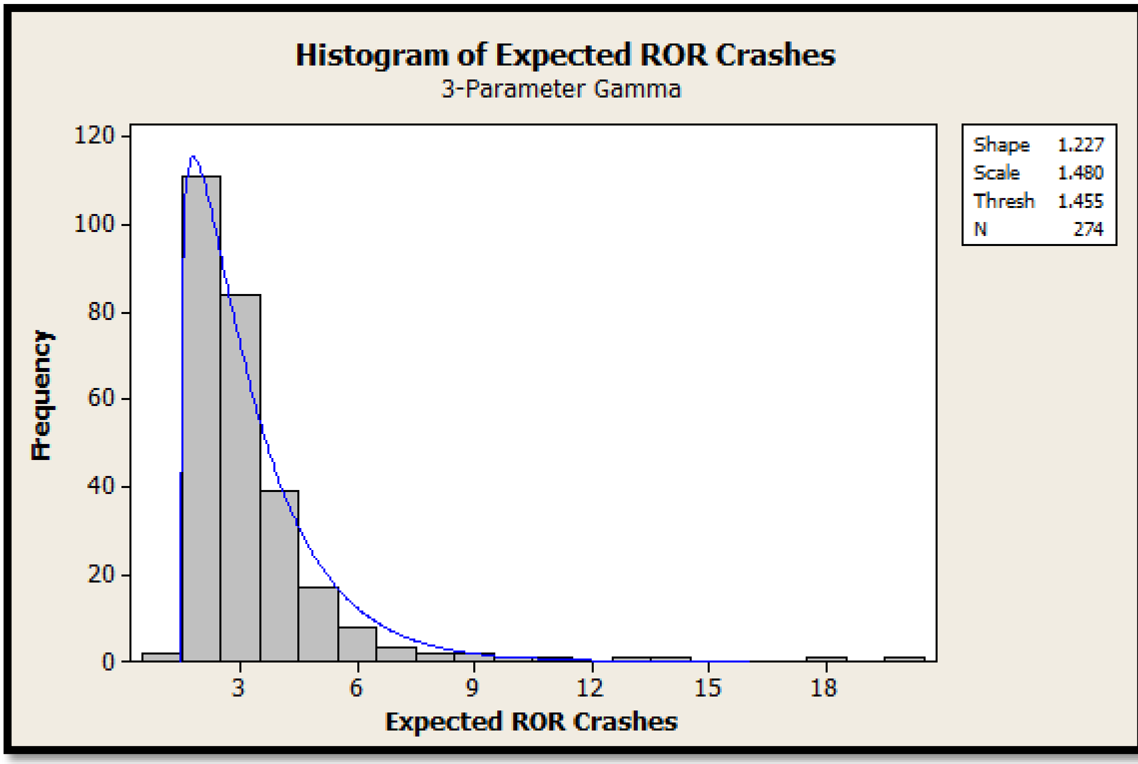


Figure 7.15 Freeway Jurisdictional SPF Residuals Histogram

The sensitivity analysis (appendix C) associated to the jurisdictional SPF for total crashes for the Reference Group indicated that an increase in segment length and AADT increase the prediction of total crashes. The variable segment length showed more sensitivity than AADT.

Finally, as a potential bias control several procedures where performed before the development of the SPF's. First, the crash sample size used for all the models exceeded the recommended amount of 300 crashes per year of the FHWA guidelines helping reduce potential bias associated with small sample size. Secondly, a collinearity test between all the dependent and independent variables for each SPF's associated to the reference group showed that the variables were not correlated (Appendix B).

Third, they weren't any changes in the crash reporting system of the PRHTA, for this particular investigation the crash rough data was provided on Microsoft Access for the study period which diminish the possibility of potential bias due to a change on crash reporting systems. Fourth, other relevant factors were included as variables such as weather effects and demographic effects, reducing potential bias associated with account other effects that can drastically change crash trends. The next chapter will address the EB methodology performed in order to obtain the effectiveness of the intermittent rumble strip on PR-52 Toll Freeway.

8.0 EFFECTIVENESS EVALUATION OF NON CONTINOUS SHOULDER RUMBLE STRIP

8.1 Introduction

During the year 2009, the PRDTPW performed a pilot project of installation of milled-in shoulder rumble strips, located on NHS PR-52 freeway. A regional crew performed this work. The rumble strips were installed only on the right shoulders from the South Caguas Toll Plaza (km 23.1) through the exit to the town of Salinas (km 66.3).

A total of 175 homogeneous segments were identified but only *84 segments will be included in the EB Method* after excluding the segments with missing variable values and segments that were less than 0.16 kilometers. The step #1 of the EB Method involves the calibration of a SPF with the data of the "before period". The EB Method will compare the estimated expected crashes if the treatment has not been implemented with the actual crashes that occurred on the after period. The next sections will include the EB Method for Total and ROR crashes for the study area.

8.2 Empirical Bayes Method for Total Crashes of the Study Area

The first step towards performing the EB Method is the calibration of the SPF. Chapter 3 describes step-by-step instructions for the development of the EB Method. Details of the calibration of the SPF for total crashes for the Reference Group are shown on section 7.2.1. The final SPF is shown on equation 8.1. The overdispersion parameter for this model was 0.294.

$$\mathbf{SPF_{Total\ Crashes} = exp\ (-0.183 + (-0.644 * (Climate{=}Moist/Wet)) + (-0.357 * (RampPresence{=}0)) + (1.958 * Length) + (0.157 * (AADT/10k))} \qquad \mathbf{(8.1)}$$

Where, *Climate=Moist or Wet* has values of 0 for dry climate and 1 if the climate is moist or wet in the segment and *RampPresence=0* has values of 0 if the segment has a freeway ramp and 1 if the segment do not have a freeway ramp. The continuous variables of the SPF are the length of the segment in kms and the AADT divided by 10,000 in vehicles per day.

The information regarding AADT, Ramps and Climate Category was updated with information from the after period from 2010 to 2012. For each segment, the total crashes and ROR crashes were allocated for the after period. Table 8.1 shows the updated information regarding the segments for the after period of the first 30 segments.

Table 8.1 Information of the "After Period" for the EB Method

ID	Start (km)	End (km)	Length (km)	Average AADT (Veh/Day)	Climate 1=Moist/Wet 0=Dry	Exit 1=No exit 0=Exit	AADT/10k	TC AFTER	ROR AFTER
1	23.1	23.26	0.16	62,900.0	1	0	6.290	3	2
2	23.36	23.58	0.22	62,900.0	1	0	6.290	8	2
3	23.58	23.96	0.38	62,900.0	1	1	6.290	11	1
4	24.16	24.52	0.36	62,900.0	1	1	6.290	10	3
5	24.58	25.12	0.54	62,900.0	1	1	6.290	12	5
6	25.12	25.4	0.28	62,900.0	1	1	6.290	8	4
7	25.4	25.7	0.3	62,900.0	1	1	6.290	6	3
8	26.02	26.74	0.72	62,900.0	1	1	6.290	18	8
9	26.74	27.12	0.38	62,900.0	1	1	6.290	10	3
10	27.12	27.34	0.22	62,900.0	1	1	6.290	5	0
11	27.36	27.54	0.18	62,900.0	1	1	6.290	3	1
12	27.58	28.24	0.66	62,900.0	1	1	6.290	12	4
13	28.32	28.78	0.46	62,900.0	1	1	6.290	19	3
14	28.84	29	0.16	62,900.0	1	1	6.290	5	1
15	29.08	29.42	0.34	62,900.0	1	1	6.290	8	2
16	29.66	30.16	0.5	62,900.0	1	1	6.290	13	2
17	30.3	30.74	0.44	81,333.3	1	1	8.133	3	0
18	31.04	31.46	0.42	81,333.3	1	1	8.133	5	2
19	31.46	31.64	0.18	81,333.3	1	0	8.133	3	1
20	31.82	32.22	0.4	81,333.3	1	0	8.133	12	6
21	32.22	32.48	0.26	61,133.3	1	0	6.113	8	3
22	32.48	32.64	0.16	61,133.3	1	0	6.113	2	2
23	32.64	32.8	0.16	61,133.3	1	0	6.113	0	0
24	33	33.38	0.38	61,133.3	1	1	6.113	3	2
25	33.38	33.8	0.42	61,133.3	1	1	6.113	1	0
26	33.8	34.52	0.72	61,133.3	1	1	6.113	4	1
27	34.52	34.74	0.22	61,133.3	1	1	6.113	2	1
28	34.74	36.08	1.34	61,133.3	1	1	6.113	33	16
29	39	39.22	0.22	48,900.0	1	0	4.890	7	4
30	39.22	39.62	0.4	48,900.0	1	0	4.890	5	4

Note: A total of 35.7% (30 out of 84) segments are represented on this table.

Table 8.2 represents the EB Method to measure the effectiveness of intermittent shoulder rumble strips on freeway PR-52. After estimating the average yearly crashes there are multiply by 3, representing the number of years of the analysis period. The column of estimated total crashes are highlighted on the table. The estimated crashes represent what would had happened is the treatment would not be implemented on the freeway.

The second step is the calculation of the adjusted overdispersion. The overdispersion parameter for this model was 0.294. Previous studies on EB Methodology indicates that an adjustment for each segment are based on the results of the calibrated SPF per segment. The equation 8.2 was used to adjust the overdispersion parameter β was assumed as 1 as early researches suggested. (Powers and Carson, 2004)

$$\Phi_i = \Phi * SPF^{\beta} \qquad (8.2)$$

The third step is the calculation of a relative weight (α) for each specific segment. Equation 8.3 was used to calculate the relative weight. The relative weight per each segment is denominated as (α_i), the predicted crashes are denominated as (μ_i) and the adjusted overdispersion parameter for each segment is denominated as (Φ_i). The calculated relative weight was 0.227 as shown on table 8.2.

$$\alpha_i = 1 / (1 + \mu_i / \Phi_i) \qquad (8.3)$$

The fourth step is the calculation of the total expected crashes per segment. Equation 8.4 was used to calculate the expected number of crashes per segment on the “after period” which is commonly denominated as (π_i), where the relative weight is denominated as (α_i), the predicted crashes using the SPF are denominated as (μ_i) and the actual count of crashes per year or per period of time is denominated as (λ_i).

$$\pi_i = (\alpha i) * (\mu_i) + (1-\alpha_i) *(\lambda_i) \qquad (8.4)$$

The fifth step is the calculation of the variance for each segment. Equation 8.5 was used to calculate the variance for each segment. After the calculation of the variance, the standard deviation was calculated by calculating the square root of the variance.

$$\sigma_i^2 = (1-\alpha_i) * \pi_i \qquad (8.5)$$

The last step was the calculation of the *Index of Effectiveness (θ)* and is a function containing all of the parameters that were earlier defined. The Index of Effectiveness for the total study area for total crashes was estimated as 0.98 and is highlighted in yellow on table 8.2.

$$\theta = (\lambda_i / \pi_i) / (1 + (\sigma_i^2 / \pi_i^2)) \qquad (8.6)$$

Table 8.2 Effectiveness Evaluation of PR-52 Shoulder Rumble Strips EB Method for Total Crashes

Φ	0.294	∑Actual Crashes, λi		∑Estimated Crashes E(μi)			∑Expected Crashes πi		∑Variance σ²	Total Index of Effectiveness θi
		534		580.5			545		420.830	0.98
ID	Segment Length, Li	Actual Crashes, λi	Estimated Yearly Crashes "SPF"	Estimated Crashes "SPF" E(μi)	Adjusted Overdispersion Φi	Relative Weight, αi	Expected Crashes, πi	Stdr Deviation (Sqrt(σ²))	Variance σ²	Index of Effectiveness, θi
1	0.16	3	1.61	4.818	1.417	0.227	3.4	1.6	2.638	0.717
2	0.22	8	1.81	5.419	1.593	0.227	7.4	2.4	5.729	0.977
3	0.38	11	1.73	5.187	1.525	0.227	9.7	2.7	7.480	1.052
4	0.36	10	1.66	4.988	1.466	0.227	8.9	2.6	6.848	1.038
5	0.54	12	2.37	7.096	2.086	0.227	10.9	2.9	8.412	1.029
6	0.28	8	1.42	4.265	1.254	0.227	7.2	2.4	5.527	1.010
7	0.3	6	1.48	4.435	1.304	0.227	5.6	2.1	4.362	0.935
8	0.72	18	3.36	10.094	2.968	0.227	16.2	3.5	12.522	1.060
9	0.38	10	1.73	5.187	1.525	0.227	8.9	2.6	6.883	1.033
10	0.22	5	1.26	3.792	1.115	0.227	4.7	1.9	3.652	0.909
11	0.18	3	1.17	3.506	1.031	0.227	3.1	1.6	2.407	0.772
12	0.66	12	2.99	8.975	2.639	0.227	11.3	3.0	8.742	0.993
13	0.46	19	2.02	6.067	1.784	0.227	16.1	3.5	12.412	1.129
14	0.16	5	1.12	3.372	0.991	0.227	4.6	1.9	3.578	0.925
15	0.34	8	1.60	4.796	1.410	0.227	7.3	2.4	5.620	0.994
16	0.5	13	2.19	6.561	1.929	0.227	11.5	3.0	8.916	1.056
17	0.44	3	2.60	7.792	2.291	0.227	4.1	1.8	3.160	0.617
18	0.42	5	2.50	7.493	2.203	0.227	5.6	2.1	4.302	0.789
19	0.18	3	2.23	6.692	1.968	0.227	3.8	1.7	2.967	0.651
20	0.4	12	3.43	10.296	3.027	0.227	11.6	3.0	8.974	0.969
21	0.26	8	1.90	5.700	1.676	0.227	7.5	2.4	5.779	0.970
22	0.16	2	1.56	4.686	1.378	0.227	2.6	1.4	2.017	0.591
23	0.16	0	1.56	4.686	1.378	0.227	1.1	0.9	0.823	0.000
24	0.38	3	1.68	5.045	1.483	0.227	3.5	1.6	2.677	0.708
25	0.42	1	1.82	5.456	1.604	0.227	2.0	1.2	1.555	0.359
26	0.72	4	3.27	9.817	2.886	0.227	5.3	2.0	4.113	0.656
27	0.22	2	1.23	3.688	1.084	0.227	2.4	1.4	1.842	0.634
28	1.34	33	11.02	33.053	9.718	0.227	33.0	5.1	25.512	0.977
29	0.22	7	1.45	4.350	1.279	0.227	6.4	2.2	4.944	0.976
30	0.4	5	2.06	6.188	1.819	0.227	5.3	2.0	4.073	0.827

Note: A total of 35.7% (30 out of 84) segments are represented on this table.

The final step is involving the calculation of the standard error of the EB Method for total crashes on the study area. Equation 8.7 and 8.8 were used to calculate the standard error, where, θ is the total effectiveness index, λ is sum of the actual crashes, π is the calculated expected crashes, σi^2 is the variance of the calculated expected crashes. A small standard error means greater certainty. The HSM defines the most reliable CMF's those that have standard errors of 0.1 or less and less reliable CMF's those that have standard errors between 0.2 and 0.3. ***The standard error 0.064 which means a reliable result.***

$$Var(\theta) = \theta_{total}^2 \{[\sum\lambda/\sum\lambda^2] + [\sum\sigma_i^2 / \sum\pi^2]\} / [1+ (\sum\sigma_i^2 / \sum\pi^2)]^2 \qquad (8.7)$$

$$\text{Standard Error} = SQRT(Var(\theta)) \qquad (8.8)$$

The purpose of performing the EB Method is to determine the effectiveness of the intermittent shoulder rumble strip. A reduction in crash occurrences indicates that the implementation of this treatment has been effective. The **percentage of reduction** of the occurrence of crashes from the before to the after period was calculated using Equation 8.9. ***The percent of reduction of total crashes regarding the study location after implementing the intermittent shoulder rumble strip was of approximately 2%.***

$$\text{Percent difference in crash} = \Delta = 100\,(1-\theta) \qquad (8.9)$$

The Crash Modification Factor (CMF) for intermittent shoulder rumble strips for total crashes is 0.98 or the same value as the total effectiveness index. CMF that are less than one indicates that an expected decrease in crashes on the future. The Crash Reduction Factor (CRF) associated with intermittent shoulder rumble strips for total crashes is the same as the percent of reduction of total crashes which was estimated as 2%.

8.3 Empirical Bayes Method for ROR Crashes of the Study Area

The pilot project of milled-in shoulder rumble strips on freeway PR-52 was installed to prevent ROR crashes or vehicles that leave the roadway. This section describes the EB method that estimates the reduction in ROR crashes on the study area.

Equation 8.10 is the calibrated SPF associated with ROR crashes. The variables *RampPresence=0* has values of 0 if the segment has a freeway ramp and 1 if the segment do not have a freeway ramp, length of the segment in kilometers and the AADT divided by 10,000 in vehicles per day. The overdispersion parameter for this model was 0.318.

$$SPF_{\text{ROR Crashes}} = \exp(-0.919 + (-0.23 * (Ramp=0)) + (0.042 * (AADT/10k)) + (1.817 * Length)) \quad (8.10)$$

Table 8.3 Effectiveness Evaluation of PR-52 Shoulder Rumble Strips EB Method for ROR Crashes

Φi	0.318	∑Actual Crashes, λi		∑Estimated Crashes E(μi)			∑Expected Crashes πi		∑Variance σ^2	Total Segment Index Θi
		217		257.12			226.68		171.99	0.95
ID	Segment Length, Li	Actual Crashes, λi	Estimated Yearly Crashes "SPF"	Estimated Crashes "SPF" E(μi)	Adjust Overdispersion Parameter	Relative Weight, αi	Expected Crashes, πi	Stdr Deviation (Sqrt(σ^2))	Variance, σ^2	Index of Effectiveness, Θi
1	0.16	2	0.69	2.084	0.663	0.241	2.0	1.2	1.533	0.720
2	0.22	2	0.77	2.325	0.739	0.241	2.1	1.3	1.577	0.705
3	0.38	1	0.82	2.470	0.785	0.241	1.4	1.0	1.028	0.473
4	0.36	3	0.79	2.382	0.757	0.241	2.9	1.5	2.163	0.831
5	0.54	5	1.10	3.303	1.051	0.241	4.6	1.9	3.483	0.935
6	0.28	4	0.69	2.060	0.655	0.241	3.5	1.6	2.680	0.932
7	0.3	3	0.71	2.136	0.679	0.241	2.8	1.5	2.118	0.845
8	0.72	8	1.53	4.582	1.457	0.241	7.2	2.3	5.444	1.008
9	0.38	3	0.82	2.470	0.785	0.241	2.9	1.5	2.179	0.826
10	0.22	0	0.62	1.847	0.587	0.241	0.4	0.6	0.338	0.000
11	0.18	1	0.57	1.717	0.546	0.241	1.2	0.9	0.890	0.518
12	0.66	4	1.37	4.108	1.306	0.241	4.0	1.7	3.055	0.836
13	0.46	3	0.95	2.857	0.908	0.241	3.0	1.5	2.250	0.806
14	0.16	1	0.55	1.656	0.527	0.241	1.2	0.9	0.879	0.522
15	0.34	2	0.77	2.297	0.730	0.241	2.1	1.3	1.572	0.707
16	0.5	2	1.02	3.072	0.977	0.241	2.3	1.3	1.714	0.663
17	0.44	0	0.99	2.976	0.946	0.241	0.7	0.7	0.545	0.000
18	0.42	2	0.96	2.870	0.913	0.241	2.2	1.3	1.677	0.674
19	0.18	1	0.78	2.336	0.743	0.241	1.3	1.0	1.003	0.481
20	0.4	6	1.16	3.483	1.108	0.241	5.4	2.0	4.092	0.975
21	0.26	3	0.83	2.481	0.789	0.241	2.9	1.5	2.181	0.826
22	0.16	2	0.69	2.069	0.658	0.241	2.0	1.2	1.530	0.721
23	0.16	0	0.69	2.069	0.658	0.241	0.5	0.6	0.379	0.000
24	0.38	2	0.82	2.452	0.780	0.241	2.1	1.3	1.600	0.697
25	0.42	0	0.88	2.637	0.838	0.241	0.6	0.7	0.483	0.000
26	0.72	1	1.52	4.548	1.446	0.241	1.9	1.2	1.408	0.382
27	0.22	1	0.61	1.833	0.583	0.241	1.2	1.0	0.911	0.510
28	1.34	16	4.68	14.029	4.461	0.241	15.5	3.4	11.779	0.983
29	0.22	4	0.73	2.192	0.697	0.241	3.6	1.6	2.704	0.925
30	0.4	4	1.01	3.040	0.967	0.241	3.8	1.7	2.859	0.884

Note: A total of 35.7% (30 out of 84) segments are represented on this table.

Table 8.3 presents the EB Method for ROR crashes on the study area for the first 30 segments. The estimated total index of effectiveness is 0.95 and is highlighted in yellow. The **calculated standard error of the EB Method for ROR Crashes on the study area was 0.0994**. An acceptable standard error should be less than 0.1 meaning this error shows a reliable result. ***The percent of reduction of ROR crashes regarding the study location after implementing the intermittent shoulder rumble strip was of approximately 5%.***

The Crash Modification Factor (CMF) for intermittent shoulder rumble strips for ROR crashes is 0.95 or the same value as the total effectiveness index. CMF that are less than one indicates that an expected decrease in crashes on the future. The Crash Reduction Factor (CRF) associated with intermittent shoulder rumble strips for ROR crashes is the same as the percent of reduction of total crashes which was estimated as 5%.

8.4 Additional Development of CMF's

Additional CMF's for intermittent shoulder rumble strips were generated by performing the EB Method on specific segments from the reference group. The estimated CMF for straight freeway segments was 0.95 with a standard error of 0.098. The estimated CMF for freeway segments on level terrain (less or equal than 3%) was 0.93 with a standard error of 0.094. All the standard errors for these additional CMF's were less than 0.1 indicating reliable results on the estimation.

Next chapter will address the conclusions and recommendations of this investigation. The last section will include a list of future researches that can be performed; many of those can be achieve by using the methodology described on this investigation.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions and Contributions to the State of the Art

9.1.1 General Conclusions

The objective of this research was the application of a methodology to evaluate the effectiveness of road safety measures associated with shoulder treatments implemented in Puerto Rico's freeway system. The pilot project associated to the implemented intermittent shoulder rumble strips prove to be effective. This investigation estimated that crashes associated to ROR reduce by 5% on the study area.

The first step in the evaluation of the effectiveness of the treatment was the development of SPF's for the reference group. Sample size and assumptions for the calibration of the SPF's were satisfied.

The evaluation of PRHTA historic freeway crash data from the study period showed that total crash counts on freeway PR-52 are higher than freeway PR-22. Crash trend analysis for the period covering between years 2006 to 2013 showed the crash trends for Total and ROR crashes on PR-52 are decreasing while on PR-22 are increasing. Crash rates for Total and ROR crashes are higher on freeway PR-52.

The characterization of ROR crashes for a 7 year period showed that 80% of the ROR crashes for both freeways involved a collision with a barrier. The majority of the ROR crashes occurred on straight segments, on day light and clear weather.

Summarizing, three contributions of the state of the art from this research investigation are the development of unique calibrated freeway crash prediction models for both the reference group for the study area and jurisdiction of the Commonwealth of Puerto Rico and the first generation of CMF's for intermittent shoulder rumble strip.

9.1.2 Development of SPF for Total and ROR Crashes

Previous research studies documented in the literature related to the evaluation of the effectiveness of SRS, calibrated SPF models with variables such as length, AADT, and Roadside Hazard Rating (RHR) as their independent variables. *This investigation revealed than other than length and AADT two other variables such as presence of* *freeway ramps and climate category (dry areas versus moist/wet areas) were statistically significant in the prediction of total crashes.*

The SPF associated with total crashes for the reference group, had statistically significant variables such as presence of ramps, climate (dry or moist /wet areas), segment length and AADT. The final model check process detected no major outliers that compromised the fit of the model. In this model, an increment in the values of Length and AADT shown an increment of the predicted total crashes. The presence of ramps also shown an increment in the predicted total crashes.

Otherwise, dry climate areas shown an increment in the predicted total crashes associated with the reference group, which by definition discards major metropolitan areas that have moist or wet climates. An analysis shown on appendix B shows that the mean total crash per segment for dry climates is higher than for moist and wet climates areas on the reference group.

The SPF associated with ROR crashes for the reference group, had statistically significant variables such as segment length, AADT and presence of freeway ramps. No major outliers were detected on the final model check process. In this model, an increment in the values of Length and AADT revealed an increment of the predicted total crashes. The presence of ramps also shown an increment in the predicted total crashes for this particular model.

9.1.3 Development of Jurisdictional SPF for Total Crashes

The last model calibrated was a jurisdictional SPF for average crashes on Puerto Rico's freeway network. This SPF was calibrated for state transportation departments as a mean to be used as a tool for freeway network screenings*. Length and AADT were statistically significant on this model. The overall model showed good model fit.*

9.1.4 EB Method for the Evaluation of Effectiveness of Intermittent SRS

EB Method in an observational before-and-after study proved to be an effective tool for treatment evaluation. It showed that for longitudinal intermittent shoulder rumble strips in the NHS PR-52 toll freeway there was a decrease on Total and ROR crashes by 2% and 5%, respectively*. The estimation of CMF for longitudinal intermittent shoulder rumble* *strips associated for total crashes was 0.98 and for ROR crashes was 0.95.* Both of the estimated CMF's had standard errors of less than 0.1 indicating reliable results based on AASHTO guidelines.

Additional estimation of CMF's for total crashes for intermittent shoulder rumble strips on specific freeway segments of the reference group showed a higher reduction on total crashes was achieved on straight and level terrains. The CMF for level segments was estimated as 0.93 and for straight segments as 0.95, meaning a reduction of 7% and 5%, respectively. These additional estimated CMF's had standard errors of less than 0.1 indicating reliable results based on AASHTO guidelines.

9.2 Study Limitations

Every research study represents a challenge for any investigator. In this particular study, there were several decisions made throughout the research project to provide a balance with the available data and the precision required in the development of the SPF and the CMF's. A summary of these decisions are listed below:

- A total of 5% of the crash data provided by PRDTPW Crash Analysis Office was not considered for the SPF model development because it did not offer the crash exact location.
- The error associated to the ARAN measurements were not contemplated as part of this investigation.
- Although the mission of the Strategic Highway Safety Plan is a reduction by 7% of fatalities on the year 2018 on our island road network, our investigation revealed a reduction of 5% of ROR crashes on PR-52 freeways associated to injuries and fatalities.
- The HPMS from the PRHTA Office of Highway System reported missing values for a total of 32 homogeneous segments out of 775 total homogeneous segments (equivalent to 4% of the segments). The PR-22 freeway reported missing values from the kilometers 0 to 0.8 and 7 to 10.2. The PR-52 freeway reported missing values from kilometer 36.1 to 38.8. Those segments were eliminated from the analysis.

- The PRDTPW did not have data regarding location of illumination systems and freeway ramps for freeways PR-52 and PR-22. This information was collected on site during the summer of the year 2014.
- PRDTPW databases indicated geographic region for segments of freeways. The precipitation in Puerto Rico is measured on 17 stations along the island. The allocation of precipitation for both freeways was performed by allocating and matching the measured precipitation for each specific region. There is no data regarding the measurement of annual precipitation by specific town on the island.
- This study used information provided by PRDTPW Crash Analysis Office, PRHTA Office of Highway System, PRHTA Office of Pavement Management and the National Climatic Data Center. The lack of a centralized transportation management system means collecting the data from different offices on the same governmental agency. As part of this investigation, a data merging process was performed to create a master database for the calibration of SPF's.
- This research consisted primarily of an observational study and the calibration of the SPF depended on historical data that was previously recorded by the PRDTPW and PRHTA. In this type of studies the omission of other significant explanatory variables is difficult to assess.
- HSM suggest a minimum homogeneous segment length of 0.16 kilometers. A total of 361 out of 775 homogeneous segments were eliminated from the calibration process in order to comply to this requirement. Both freeways have a total length of 192 kilometers. The 361 segments eliminated, only represents a total length of 26 kilometers which represents 13.5% of the total length for both freeways.
- The homogeneous segments are defined due to changes on freeway terrain varying from level, rolling, mountainous, presence of curves, freeway ramps, illumination systems and other freeway characteristics. The number of independent variables under consideration defines the quantity of

homogeneous segments, which means a larger number of variables representing a larger number of smaller segments.

- The freeway network in the Commonwealth of Puerto Rico has only two toll freeways with similar geometric and traffic characteristics. In the opinion of the researcher there were enough segments to generate the SPF models; additional segments would be required for a full validation process.

9.3 Recommendations

Recommendations are summarized in terms of short (within the next 6 month), medium-term (6 month to 1 year) and long-term (more than a year) are listed below.

9.3.1 Short-Term

One of the priorities of the Puerto Rico Strategic Highway Safety Plan was to improve the Traffic Records, Crash and Information Systems within the agencies. It is pertinent to mention, that some improvement had been made towards Puerto Rico Crash Analysis issues. PRTSC developed the CARE Desktop Software that includes information regarding crash records in Puerto Rico including fatal crashes, crashes that involved injuries and crashes that involved property damage. This unique tool can performed simple filters, histograms, crosstabs, graphs and hotspots analysis.

Short-term recommendation is the inclusion of the Crash Prediction Models such as the jurisdictional freeway SPF calibrated during this investigation on CARE Desktop Software for the exclusive use of highway safety officials to better quantify performance measures needed to obtain funding for future highway related projects.

9.3.2 Medium-Term

A medium-term recommendation is the submission of the CMF's generated on this investigation to the Crash Modification Factor Clearinghouse for further evaluation. Also the PRHTA can use the generated CMF's and CRF's, as a performance measure for intermittent shoulder rumble strip as a countermeasure implemented on Puerto Rico freeways.

9.3.3 Long-Term

On this investigation, during the data cleaning process of the crash dataset a large quantity of inaccurate or incomplete records were eliminated for the final dataset. Approximately, 5% of the crash records were eliminated because they lacked the exact location of the crash or had errors related to the exact kilometer location. A long-term improvement should be to provide tablets or mobile devices to police officers that include an application with an updated standardized police crash report as well as the ability to incorporate photos or videos from the crash scene. These tablets or mobile devices should have a Global Positioning System (GPS) application to describe the exact location of the crashes. These applications can reduce the time police officers take to fill the crash report, increase the precision of the locations of the crashes and can send real time data immediately to government officials.

Another recommendation is to motivate future researchers in the development and the calibration of other jurisdictional SPF for various road classifications that should be included on CARE Desktop Software.

9.4 Future Research

Future research in the area of shoulder rumble strips for freeway application shall considered geometric configuration, climate, topography, traffic mix and updated crash data. Potential research studies around this area includes:

- Study the effect of freeway ramps that tends to increase the prediction of Total and ROR crashes on toll freeways. This type of analysis would involve an evaluation of each individual ramp or interchange along both freeways but it was not contemplated as part of this investigation.
- Investigation related the effects on safety associated with fog on mountainous terrains on toll freeway PR-52.
- Calibration of jurisdictional SPF’s for other road classifications on the island.
- Development of other CMF’s associated with shoulder treatments on other freeway segments.
- Defects of premature deterioration of SRS due to accelerated traffic associated with shoulder usage during construction work zones.

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APPENDIX A: Glossary of Pertinent Technical Terms Associated with Highway Safety

Annual Average Daily Traffic: Average daily traffic on a roadway or highway including all the days of the week during a period of one year. (vpd)

Crash Modification Factor: Index that quantifies the expected change in crash frequency if a specific treatment is implemented.

Crash Reduction Factor: Percentage of the crash reduction or rise expected after implementing a treatment.

Crash Rates: Includes the combination of crash frequency and vehicle exposure (traffic volumes). It is expressed as crashes per 100 million vehicle – miles of travel

International Roughness Index (IRI): It is measured on longitudinal road profiles and is denominated as the roughness index with units in/mi or m/km.

Moving Ahead for Progress in the 21st Century (MAP-21) was a law signed by President Obama on July 6, 2012. It provides funding for transportation programs based upon performance measures.

Overdispersion Parameter: An estimated parameter that results from a statistical model that indicates how widely the crash counts are distributed around the estimated mean. (AASHTO, 2010)

Rumble Strips: Is a road safety treatment that produce a vibration or sound that alert drivers if they are leaving the travel way.

Safety Performance Function: An equation that used to predict the expected number of crashes per year on a specific location as a function of exposure data such as annual average daily traffic and other roadway characteristics.

APPENDIX B: SPSS Outputs

SPSS Output: SPF for Total Crashes

Model Information

Dependent Variable	Total crashes (2006-2008)
Probability Distribution	Negative binomial (MLE)
Link Function	Log
Offset Variable	Log_Year

Case Processing Summary

	N	Percent
Included	273	100.0%
Excluded	0	0.0%
Total	273	100.0%

Categorical Variable Information

			N	Percent
Factor	Ramp Presence (Including Diverge and Merge Influence Areas)	Not an Ramp on the Segment	177	64.8%
		Ramp on Segment	96	35.2%
		Total	273	100.0%
	Climate Category	Moist	227	83.2%
		Dry	46	16.8%
		Total	273	100.0%

Continuous Variable Information

		N	Minimum	Maximum	Mean	Std. Deviation
Dependent Variable	Total crashes (2006-2008)	273	0	55	9.44	9.553
Covariate	Segment Length (km)	273	.160	1.520	.40777	.234379
	Average Annual Daily Traffic divided by 10k (2006-2008) (veh/day)	273	2.583	16.083	6.92993	3.038154
Offset	Log_Year	273	1.10	1.10	1.0986	.00000

Goodness of Fit[a]

	Value	df	Value/df
Deviance	300.717	267	1.126
Scaled Deviance	300.717	267	
Pearson Chi-Square	293.422	267	1.099
Scaled Pearson Chi-Square	293.422	267	
Log Likelihood[b]	-799.794		
Akaike's Information Criterion (AIC)	1611.588		
Finite Sample Corrected AIC (AICC)	1611.903		
Bayesian Information Criterion (BIC)	1633.245		
Consistent AIC (CAIC)	1639.245		

Dependent Variable: Total crashes (2006-2008)

Model: (Intercept), RampPresence, ClimateCategory, Length, AADT10k, offset = Log_Year[a]

a. Information criteria are in small-is-better form.

b. The full log likelihood function is displayed and used in computing information criteria.

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
189.386	4	.000

Dependent Variable: Total crashes (2006-2008)

Model: (Intercept), RampPresence, ClimateCategory, Length, AADT10k, offset = Log_Year[a]

a. Compares the fitted model against the intercept-only model.

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	-.183	.1499	-.477	.111	1.489	1	.222
[RampPresence=0]	-.357	.0856	-.525	-.189	17.403	1	.000
[RampPresence=1]	0[a]	.	.	.	.	.	.
[ClimateCategory=1]	-.644	.1121	-.864	-.424	33.014	1	.000
[ClimateCategory=2]	0[a]	.	.	.	.	.	.
Length	1.958	.1774	1.610	2.306	121.846	1	.000
AADT10k	.157	.0143	.129	.185	120.681	1	.000
(Scale)	1[b]						
(Negative binomial)	.294	.0373	.229	.377			

Dependent Variable: Total crashes (2006-2008)

Model: (Intercept), RampPresence, ClimateCategory, Length, AADT10k, offset = Log_Year

a. Set to zero because this parameter is redundant.

b. Fixed at the displayed value.

SPSS Output: SPF for ROR Crashes

Model Information

Dependent Variable	Total Run off the Road Crashes per 3 year period (2006-2008)
Probability Distribution	Negative binomial (MLE)
Link Function	Log
Offset Variable	Log_Year

Case Processing Summary

	N	Percent
Included	274	100.0%
Excluded	0	0.0%
Total	274	100.0%

Categorical Variable Information

			N	Percent
Factor	Ramp Presence (Including Diverge and Merge Influence Areas)	Not an Ramp on the Segment	177	64.6%
		Ramp on Segment	97	35.4%
		Total	274	100.0%

Continuous Variable Information

		N	Min	Max	Mean	Std. Deviation
Dependent Variable	Total Run off the Road Crashes per 3 year period (2006-2008)	274	.00	17.00	3.2299	3.08519
Covariate	Segment Length (km)	274	.160	1.540	.41168	.243276
	Average Annual Daily Traffic divided by 10k (2006-2008) (veh/day)	274	2.583	16.083	6.89590	3.026735
Offset	Log_Year	274	1.09861	1.09861	1.098612	.00000000

Goodness of Fit[a]

	Value	df	Value/df
Deviance	314.596	269	1.170
Scaled Deviance	314.596	269	
Pearson Chi-Square	293.971	269	1.093
Scaled Pearson Chi-Square	293.971	269	
Log Likelihood[b]	-585.997		
Akaike's Information Criterion (AIC)	1181.995		
Finite Sample Corrected AIC (AICC)	1182.218		
Bayesian Information Criterion (BIC)	1200.060		
Consistent AIC (CAIC)	1205.060		

Dependent Variable: Total Run off the Road Crashes per 3 year period (2006-2008)

Model: (Intercept), RampPresence, Length, AADT10k, offset = Log_Year[a]

a. Information criteria are in small-is-better form.

b. The full log likelihood function is displayed and used in computing information criteria.

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
80.797	3	.000

Dependent Variable: Total Run off the Road Crashes per 3 year period (2006-2008)

Model: (Intercept), RampPresence, Length, AADT10k, offset = Log_Year[a]

a. Compares the fitted model against the intercept-only model.

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	-.919	.1766	-1.265	-.573	27.070	1	.000
[RampPresence=0]	-.230	.1065	-.439	-.021	4.668	1	.031
[RampPresence=1]	0[a]	.	.	.	.	.	.
Length	1.817	.1981	1.428	2.205	84.120	1	.000
AADT10k	.042	.0166	.009	.074	6.254	1	.012
(Scale)	1[b]						
(Negative binomial)	.318	.0606	.219	.462			

Dependent Variable: Total Run off the Road Crashes per 3 year period (2006-2008)

Model: (Intercept), RampPresence, Length, AADT10k, offset = Log_Year

a. Set to zero because this parameter is redundant.

b. Fixed at the displayed value.

SPSS Output: SPF for Jurisdictional Total Crashes

Model Information

Dependent Variable	Total crashes (2006-2008)
Probability Distribution	Negative binomial (MLE)
Link Function	Log
Offset Variable	log_year

Case Processing Summary

	N	Percent
Included	360	100.0%
Excluded	0	0.0%
Total	360	100.0%

Continuous Variable Information

		N	Minimum	Maximum	Mean	Std. Deviation
Dependent Variable	Total crashes (2006-2008)	360	0	60	8.75	8.567
	Segment Length (km)	360	.160	1.540	.40406	.239205
Covariate	Average Annual Daily Traffic divided by 10,000	360	2.58	25.82	6.7143	3.51374
Offset	log_year	360	1.098600	1.098600	1.09860000	.000000000

Goodness of Fit[a]

	Value	df	Value/df
Deviance	405.105	356	1.138
Scaled Deviance	405.105	356	
Pearson Chi-Square	386.825	356	1.087
Scaled Pearson Chi-Square	386.825	356	
Log Likelihood[b]	-1037.349		
Akaike's Information Criterion (AIC)	2082.698		
Finite Sample Corrected AIC (AICC)	2082.810		
Bayesian Information Criterion (BIC)	2098.242		
Consistent AIC (CAIC)	2102.242		

Dependent Variable: Total crashes (2006-2008)

Model: (Intercept), Length, AverAADT10k, offset = log_year[a]

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
228.195	2	.000

Dependent Variable: Total crashes (2006-2008)

Model: (Intercept), Length, AverAADT10k, offset = log_year[a]

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	-.655	.1039	-.858	-.451	39.679	1	.000
Length	1.897	.1479	1.607	2.187	164.507	1	.000
AverAADT10k	.115	.0097	.096	.134	142.502	1	.000
(Scale)	1[a]						
(Negative binomial)	.285	.0334	.227	.359			

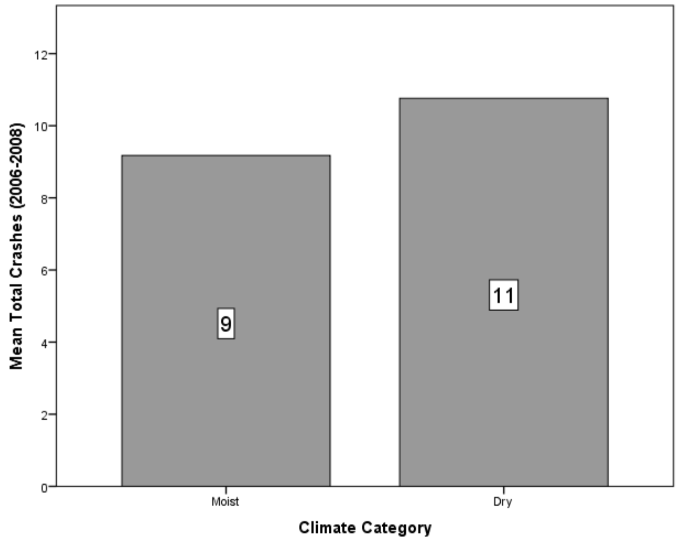
Dependent Variable: Total crashes (2006-2008)

Model: (Intercept), Length, AverAADT10k, offset = log_year

a. Fixed at the displayed value.

SPSS Output: Variable Climate (Moist/Wet vs. Dry Areas)

The SPF for total crashes of the Reference Group had climate category as a statistically significant variable. Dry climate zones had higher mean total crashes than moist/wet zones as shown on the following SPSS histogram.



SPSS Output: Descriptive Statistics and Correlation of the Statistically Significant Variables for the Reference Group

Descriptive Statistics for the 19 Continuous Explanatory Variables of the Reference Group

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Segment Lenght (km)	277	.160	2.200	.42534	.280409
Average Annual Daily Traffic (2006-2008) (veh/day)	277	25833.300	160833.300	69175.44765	30381.815847
Number of Lanes	277	4.000	6.000	4.48375	.857991
Average International Roughness Index	277	1.70	3.60	2.4242	.47169
Median Width (meters)	277	2.800	27.500	17.10361	6.108072
Right Shoulder Width (meters)	277	2.400	3.400	2.98520	.200265
Left Shoulder Width (meters)	277	.900	2.400	1.25560	.239594
Design Speed (km/h)	277	105.000	110.000	109.78339	1.019739
Speed Limit (km/h)	277	90.000	105.000	102.61733	5.492893
Average Single Unit Trucks (%) (2006-2008)	277	3.000	7.300	4.79711	1.263073
Average Combination Trucks (%) (2006-2008)	277	1.000	4.700	2.56354	1.123468
Average Total Truck (%) (2006-2008)	277	4.000	12.000	7.30794	2.300601
Radius (meters)	277	-99999.000	99999.000	1418.82852	65934.376903
Degree of Curvature (meters)	277	.000	18.600	2.60383	2.944946
Curve Length (meters)	277	.000	1600.000	360.36101	435.169315
Central Curve Angle	277	.000	97.500	17.29278	23.596273
Average Precipitation (centimeters) (2006-2008)	277	100.787	210.896	163.35711	39.534006
Average Directional Factor (2006-2008)	277	51.700	63.300	58.66787	2.593068
Average Superelevation (%)	277	.520	7.160	2.82738	1.473022
Valid N (listwise)	277				

Correlation for all the variables associated to the SPF for Total Crashes of the Reference Group

Correlations

		Segment Lenght (km)	Average Annual Daily Traffic divided by 10k (2006-2008) (veh/day)	Ramp Presence (Including Diverge and Merge Influence Areas)	Climate Category	Total Crashes (2006-2008)
Segment Length (km)	Pearson Correlation	1	-.123*	-.189**	.102	.430**
	Sig. (2-tailed)		.043	.002	.092	.000
	N	273	273	273	273	273
Average Annual Daily Traffic divided by 10k (2006-2008) (veh/day)	Pearson Correlation	-.123*	1	.178**	-.346**	.405**
	Sig. (2-tailed)	.043		.003	.000	.000
	N	273	273	273	273	273
Ramp Presence (Including Diverge and Merge Influence Areas)	Pearson Correlation	-.189**	.178**	1	-.024	.137*
	Sig. (2-tailed)	.002	.003		.692	.023
	N	273	273	273	273	273
Climate Category	Pearson Correlation	.102	-.346**	-.024	1	.062
	Sig. (2-tailed)	.092	.000	.692		.306
	N	273	273	273	273	273
Total Crashes (2006-2008)	Pearson Correlation	.430**	.405**	.137*	.062	1
	Sig. (2-tailed)	.000	.000	.023	.306	
	N	273	273	273	273	273

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

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation for all the variables associated to the SPF for ROR Crashes of the Reference Group

Correlations

		Segment Length (km)	Average Annual Daily Traffic divided by 10k (2006-2008) (veh/day)	Ramp Presence (Including Diverge and Merge Influence Areas)	Total Run off the Road Crashes per 3 year period (2006-2008)
Segment Lenght (km)	Pearson Correlation	1	-.147*	-.178**	.538**
	Sig. (2-tailed)		.015	.003	.000
	N	274	274	274	274
Average Annual Daily Traffic divided by 10k (2006-2008) (veh/day)	Pearson Correlation	-.147*	1	.178**	.065
	Sig. (2-tailed)	.015		.003	.281
	N	274	274	274	274
Ramp Presence (Including Diverge and Merge Influence Areas)	Pearson Correlation	-.178**	.178**	1	.009
	Sig. (2-tailed)	.003	.003		.880
	N	274	274	274	274
Total Run off the Road Crashes per 3 year period (2006-2008)	Pearson Correlation	.538**	.065	.009	1
	Sig. (2-tailed)	.000	.281	.880	
	N	274	274	274	274

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

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation for all the variables associated to the Jurisdictional SPF

Correlations

		Segment Lenght (km)	Average Annual Daily Traffic divided by 10,000	Total Crashes (2006-2008)
Segment Lenght (km)	Pearson Correlation	1	-.126*	.480**
	Sig. (2-tailed)		.014	.000
	N	382	382	382
Average Annual Daily Traffic divided by 10,000	Pearson Correlation	-.126*	1	.299**
	Sig. (2-tailed)	.014		.000
	N	382	382	382
Total Crashes (2006-2008)	Pearson Correlation	.480**	.299**	1
	Sig. (2-tailed)	.000	.000	
	N	382	382	382

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

**. Correlation is significant at the 0.01 level (2-tailed).

APPENDIX C: Sensitivity Analysis of Safety Performance Functions

SENSITIVITY ANALYSIS OF THE IMPACT OF SEGMENT LENGTH, AADT, RAMPS AND CLIMATE ON PREDICTED TOTAL CRASHES ON FREEWAYS FOR THE REFERENCE GROUP

The sensitivity analysis associated to the SPF for total crashes for the Reference Group indicated that an increase in segment length, AADT, presence of ramps and dry climate increase the prediction of total crashes. The variable segment length showed more sensitivity than AADT, Presence of Ramps and Climate.

AADT =70,000 vpd
Ramps = Yes
Climate = Dry

Segment Length, km	Predicted Total Crashes per Year
0.5	6.653
0.75	10.854
1	17.708
1.25	28.890
1.5	47.134

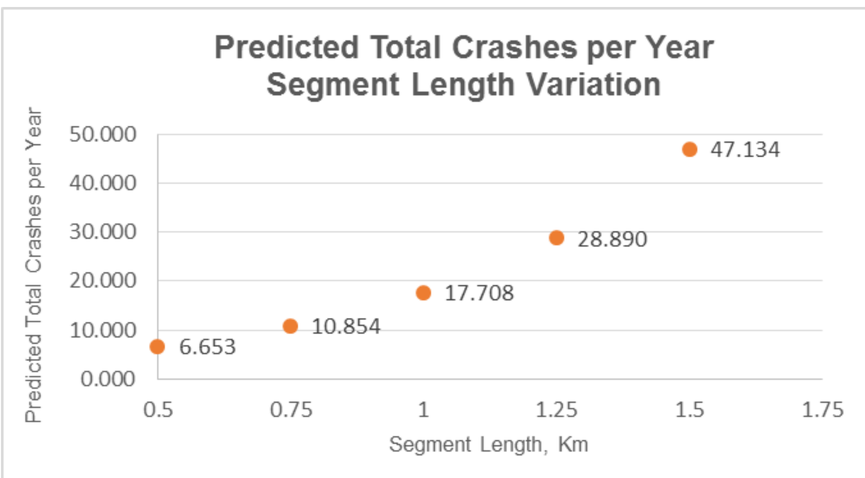
Segment Length = 0.5 kms
Ramp = Yes
Climate = Dry

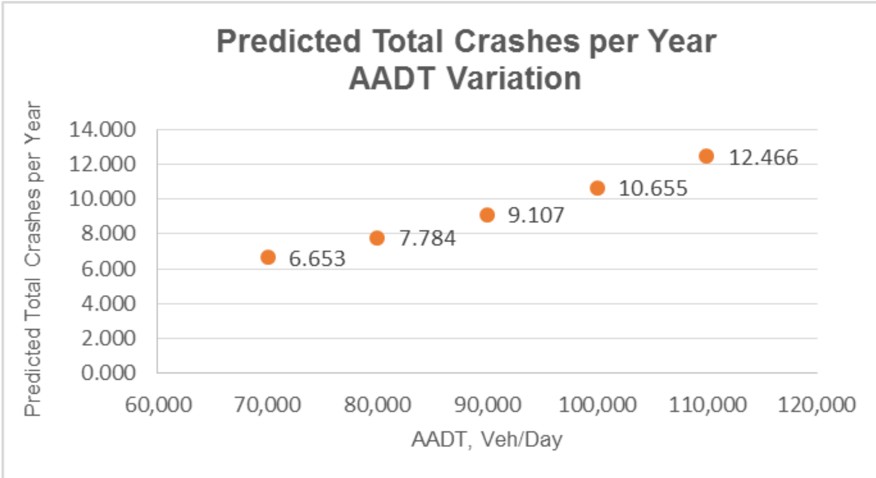
AADT, Veh/Day	Predicted Total Crashes per Year
70,000	6.653
80,000	7.784
90,000	9.107
100,000	10.655
110,000	12.466

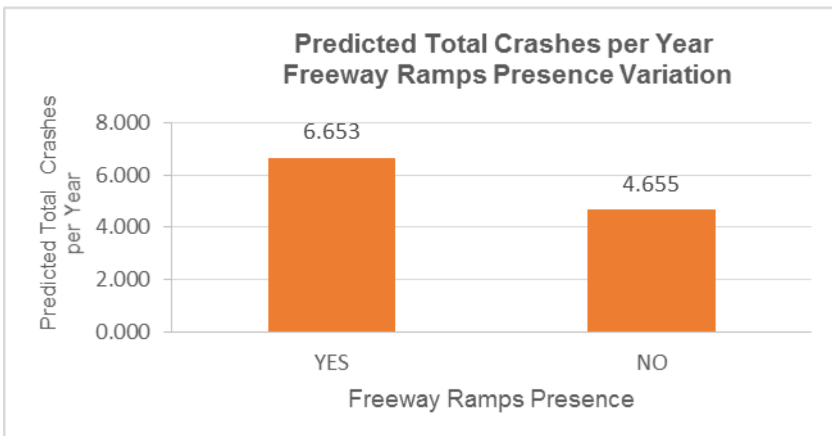
Segment Length=0.5 kms
AADT=70,000 vpd

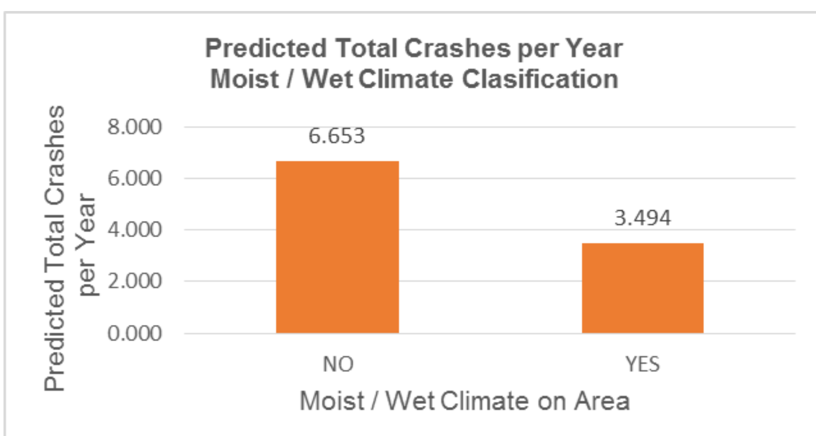
Ramps Present	Predicted Total Crashes per Year
YES	6.653
NO	4.655

Moist/Wet Climate	Predicted Total Crashes per Year
NO	6.653
YES	3.494




Predicted Total Crashes per Year
AADT Variation
Predicted Total Crashes per Year
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
6.653
7.784
9.107
10.655
12.466
60,000
70,000
80,000
90,000
100,000
110,000
120,000
AADT, Veh/Day


Predicted Total Crashes per Year
Freeway Ramps Presence Variation
Predicted Total Crashes per Year
8.000
6.000
4.000
2.000
0.000
6.653
4.655
YES
NO
Freeway Ramps Presence


Predicted Total Crashes per Year
Moist / Wet Climate Clasification
Predicted Total Crashes per Year
8.000
6.000
4.000
2.000
0.000
6.653
3.494
NO
YES
Moist / Wet Climate on Area

SENSITIVITY ANALYSIS OF THE IMPACT OF SEGMENT LENGTH, AADT AND RAMPS ON PREDICTED ROR CRASHES ON FREEWAYS FOR THE REFERENCE GROUP

The sensitivity analysis associated to the SPF for ROR crashes for the Reference Group indicated that an increase in segment length, AADT and presence of ramps increase the prediction of total crashes. The variable segment length showed more sensitivity than AADT and Presence of Ramps.

AADT=70,000 vpd
Ramp

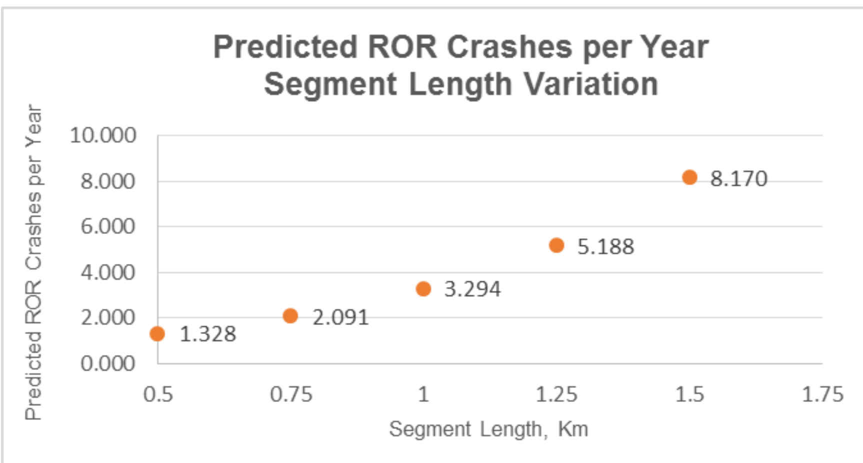
Segment Length, km	Predicted ROR Crashes per Year
0.5	1.328
0.75	2.091
1	3.294
1.25	5.188
1.5	8.170

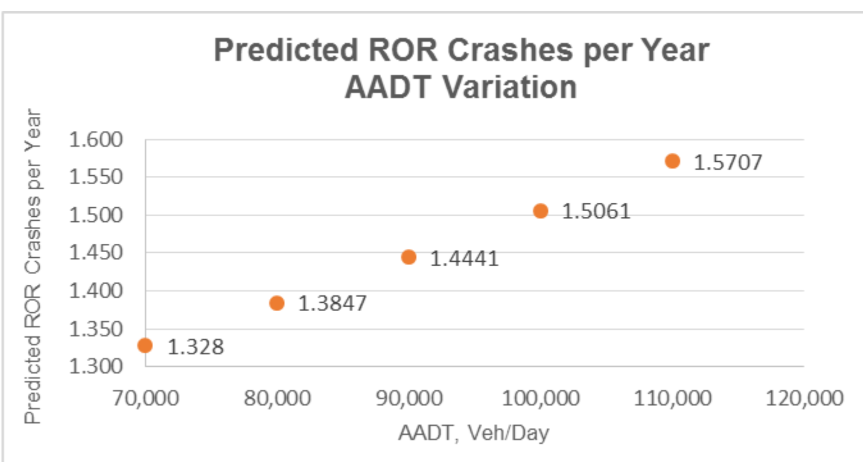
Segment Length= 0.5 kms
Ramp

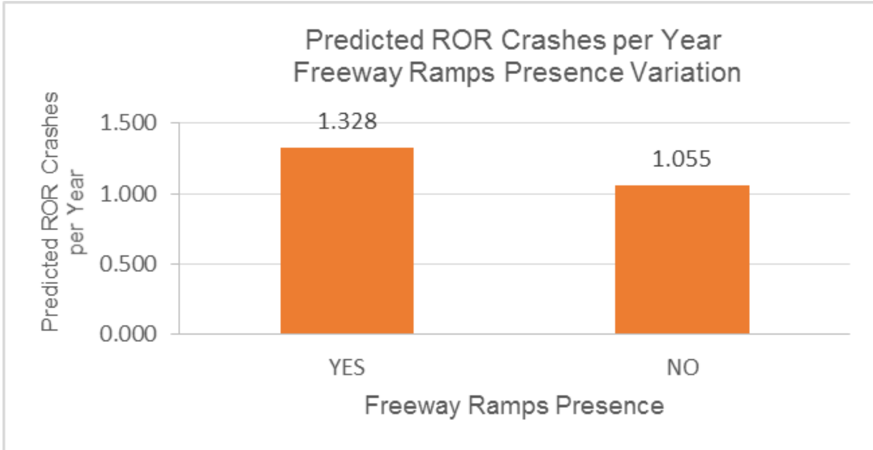
AADT, Veh/Day	Predicted ROR Crashes per Year
70,000	1.328
80,000	1.3847
90,000	1.4441
100,000	1.5061
110,000	1.5707

Seg.Length=0.5kms
AADT=70,000 vpd

Ramps	Predicted ROR Crashes per Year
YES	1.328
NO	1.055







SENSITIVITY ANALYSIS OF THE IMPACT OF SEGMENT LENGTH AND AADT ON PREDICTED TOTAL CRASHES ON FREEWAYS (JURISDICTIONAL SPF)

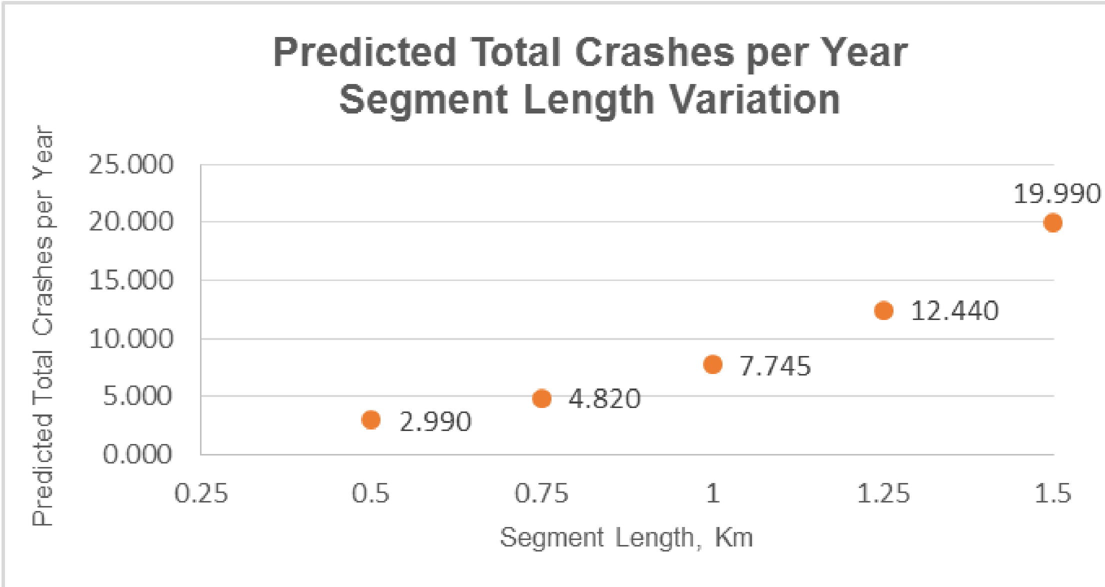
The sensitivity analysis associated to the jurisdictional SPF for total crashes for the Reference Group indicated that an increase in segment length and AADT increase the prediction of total crashes. The variable segment length showed more sensitivity than AADT.

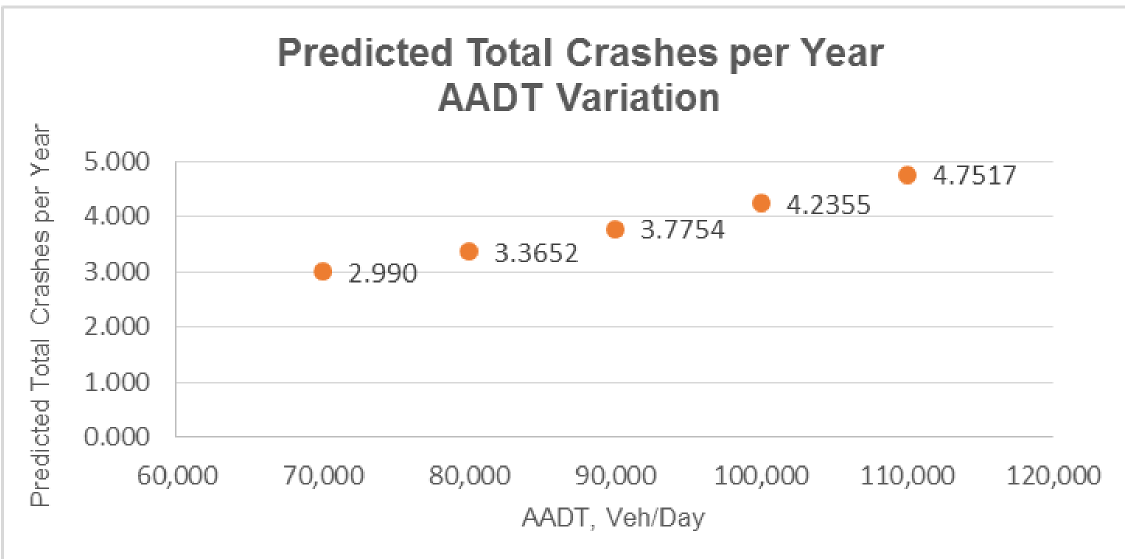
Volume = 70,000 vpd

Segment Length, km	Predicted Total Crashes per Year
0.5	2.990
0.75	4.820
1	7.745
1.25	12.440
1.5	19.990

Segment Length = 0.5 kms

AADT, Veh/Day	Predicted Total Crashes per Year
70,000	2.990
80,000	3.3652
90,000	3.7754
100,000	4.2355
110,000	4.7517


Predicted Total Crashes per Year
Segment Length Variation
Predicted Total Crashes per Year
25.000
20.000
15.000
10.000
5.000
0.000
19.990
12.440
7.745
4.820
2.990
0.25
0.5
0.75
1
1.25
1.5
Segment Length, Km


Predicted Total Crashes per Year
AADT Variation
Predicted Total Crashes per Year
5.000
4.000
3.000
2.000
1.000
0.000
4.7517
4.2355
3.7754
3.3652
2.990
60,000
70,000
80,000
90,000
100,000
110,000
120,000
AADT, Veh/Day