A Study of the Effects of Pavement Widening, Rumble Strips, and Rumble Stripes on Rural Highways in Alabama

by

Luana Clara de Sena Monteiro Ozelim

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Approved by

Rod E. Turochy, Chair, Associate Professor of Civil Engineering
Ash Abebe, Associate Professor of Mathematics and Statistics
Jeffrey J. LaMondia, Assistant Professor of Civil Engineering
Huaguo Zhou, Associate Professor of Civil Engineering

Abstract

Run-off-road (ROR) crashes are usually severe and account for a significant amount of highway fatalities. It is estimated that more than 50% of the fatal crashes in the United States and in Alabama are ROR crashes. Rural roads are the main reason of concern; approximately 62% of fatal crashes in Alabama occur on rural roads. The frequent occurrence of run-off-road (ROR) crashes and the corresponding high severity of them, especially on rural roads, led to several states starting new practices or update existing policies as a tentative to improve safety. Some common countermeasures include paved shoulders, shoulder rumble strips, and shoulder rumble stripes. This study developed a survey regarding state agencies' policies, studies of treatment effectiveness, and dimensions of paved shoulders, shoulder rumble strips, and shoulder rumble stripes in the United States. Of all states in the country, 20 completed the survey. Dates of the most recent policies vary significantly from one location to the other, as well as dimensions. Only a few states developed safety effectiveness studies, but data was not sufficient, as crash data after treatment implementation were not available, or the methods were not the most recommended for these evaluations. This study recommends that, after states have enough "after" crash data, statistical methods, especially the ones suggested by the *Highway Safety Manual* (HSM), should be applied to verify if treatments are effective and appropriate to reduce crashes at each state. The Alabama Department of Transportation (ALDOT) implemented a policy in 2006 to widen pavements and install milled-in rumble strips or stripes when rural two-lane highways with less than 28 ft of pavement width are resurfaced. In practice, this policy was also extended to four-lane divided rural roads. This study considered data from 101 resurfacing

projects in Alabama that had 2 to 4 ft of full-depth paved shoulders added, and in some cases, rumble strips or rumble stripes were scored into the pavement within the shoulder. This study to address the effectiveness of the treatments implemented in Alabama after ALDOT policy considered an EPDO analysis to express changes in crash severity, an application of the Empirical Bayes method to quantify changes in crash frequency, and a benefit-cost analysis. For two-lane roads, the EPDO analysis showed a reduction of EPDO scores of 3.78% for the combined effect of paved shoulders and shoulder rumble strips, 3.51% for the combined effect of paved shoulders and shoulder rumble stripes, and 10.67% for paved shoulder only. For four-lane roads, there was a reduction of EPDO scores of 11.10% for the combined effect of paved shoulders and shoulder rumble strips and a reduction of 4.01% for paved shoulder only. The EB analysis was initially performed using the HSM safety performance function. For two-lane rural roads, the analysis resulted in CMFs of 0.79, 0.82, and 0.72 for the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and paved shoulder only respectively. For four-lane roads, CMF for the combined effect of paved shoulder and shoulder rumble strips was 0.84, but for paved-shoulder only it was not significant and reliable. The EB analysis was also performed applying state-specifics SPFs, but results were not consistent with typical research findings or the literature. Benefit-cost ratios on two-lane roads were 4.57, 3.61, and 5.76 for the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and paved shoulder only respectively. On four-lane roads, B/C ratio was 4.56 for the combined effect of paved shoulder and shoulder rumble strips and 2.03 for the paved shoulder-only treatment. This study applied Poisson, zero-inflated Poisson (ZIP), negative binomial (NB), and zero-inflated negative binomial (ZINB) distributions to estimate run-off-road crash frequency on 72 control segments of two-lane rural roads and 32 control segments of four-lane divided rural roads in Alabama, during the period from 2001 to 2010. After evaluating all distributions and comparing the value of the Vuong's test statistic, AIC, and BIC the ZINB was the best to model crash data for both two and four-lane rural roads.

Acknowledgements

Several people has doubts concerning which profession they should follow. When I was a kid, I always thought I would become a teacher. I remember I had a blackboard at home, and I used to make all my friends attend my “lectures”, take tests and work on homework. Yes, I used to do that for fun, and grading their tests was so much more interesting than sports or playing with dolls. When it was time to decide what career I wanted to follow, I knew I wanted to build roads; therefore, I decided to be a Civil Engineer. Since the first year of College, I started to be engaged on research related to transportation: I found my passion. Since Civil Engineering was a broad degree, I decided to learn more about transportation and applied for graduate school. After graduating with a master’s degree, something was still missing. I guess that kid’s passion for learning and teaching people came back, and I applied for the doctorate degree with focus in transportation. Now, it has been 10 and a half years since I’ve started College, and I look back and everything was worth it. I am ready to finally start working in the practical transportation field and make contributions to the world. This journey has not always been smooth, but it was definitely possible due to all the people that helped me in different ways.

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TABLE OF CONTENTS

List of Tables

List of Figures

List of Abbreviations

AADT	Annual average daily traffic
AIC	Akaike information criterion
ALDOT	Alabama Department of Transportation
BIC	Bayesian information criterion
Caltrans	California Department of Transportation
CARE	Critical Analysis Reporting Environment
CMF	Crash modification factor
CMF	Calibration factor
EB	Empirical Bayes
EPDO	Equivalent property damage only
FHWA	Federal Highway Administration
HMA	Hot mix asphalt
HSM	Highway Safety Manual
KLD	Kullback–Leibler divergence
NB	Negative binomial
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NYSTA	New York State Thruway Authority

ROR	Run-off-road
RTM	Regression-to-mean
SPF	Safety performance function
SVROR	Single vehicle run-off-road
SVROR FI	Single vehicle run-off-road fatal and injury
TRRL	British Transport and Road Research Laboratory
ZI	Zero-inflated
ZINB	Zero-inflated negative binomial
ZIP	Zero-inflated Poisson

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Crashes are rare events, as they represent only a very small proportion of the total number of events that occur on the transportation system, and their incidence is a function of a set of events influenced by several factors. Factors that influence crashes are partly deterministic, which can be controlled, and partly stochastic, which are random and unpredictable. (AASHTO, 2010).

Roadway departure crashes are frequently severe and account for the majority of highway fatalities in the United States. At a national level, an average of 34,156 fatal crashes occurs every year; 17,991 of these crashes are fatal roadway departure crashes, which represents 52 percent of the fatal crashes in the United States. (FHWA, 2013). At a state level, roadway departures are also high severity crashes. These crashes account for approximately 458 fatalities every year in Alabama. They constitute only 25% of all reported crashes, but 42% of incapacitating injuries and 53% of reported fatalities. This type of crash causes more than half of the state's fatalities and almost half of the most severe crashes. (ALDOT, 2012).

Urban roadways in Alabama experience 73% of all highway crashes, but only 38% of fatal crashes; in other words, most of the crashes occur in urban areas, but crash severities are below average. On the other hand, rural areas account for 27% of all highway crashes, but 62% of fatal crashes. Therefore, rural crashes are generally not as frequent as urban crashes, but are more severe. (ALDOT, 2012).

1.2 MOTIVATION OF THE STUDY

In an effort to address this particularly frequent and severe crash type, the Alabama Department of Transportation (ALDOT) implemented a policy in February 2006 to widen pavements and install milled-in rumble strips when rural two-lane highways with less than 28 ft of pavement width are resurfaced. On the vast majority of these roadways, little or no hardsurfaced shoulder had previously existed. The policy determined that upon resurfacing, shoulders were to be strengthened, 2 ft of full-depth pavement added on each side of the roadway, and in some cases, rumble strips or stripes were scored into the pavement within the 2 ft shoulder. The practice of pavement widening, or shoulder wedging, to provide an additional recovery area for errant vehicles leaving the travel lane but prior to leaving the pavement surface is becoming increasingly common in many states. Although this had previously been done in isolated cases in Alabama, this new policy represents a major effort to reduce roadway departure crashes on rural roadways over the next several years.

Due to the level of investment associated with this policy, and its intended safety benefits, a study to quantify the potential benefits is worthy of consideration, and its findings could possibly be used to further support this initiative. The Empirical Bayes (EB) method, as outlined in the *Highway Safety Manual*, the equivalent property damage only (EPDO) analysis, and the benefit-cost analysis are proposed to address safety effectiveness of the countermeasures implemented in Alabama. Zero-inflated models are also applied to crash data modeling of control sites in Alabama and compared to the traditional distributions used to develop safety performance functions. The distribution that best fits the data is recommended to estimate ROR crashes in Alabama on future studies.

1.3 OBJECTIVES

The objectives of this study are as follows:

- Document the state of the practice and results of prior research;
- Estimate reduction in run-off-road (ROR) crashes, by severity, based on the data, applying both EB and EPDO methods
- Develop crash modification factors for the following five treatments:
    - Paving 2 to 4 ft of unpaved shoulders on two-lane rural roads;
    - Combined effect of paving 2 to 4 ft of unpaved shoulder and adding rumble strips on two-lane rural roads;
    - Combined effect of paving 2 to 4 ft of unpaved shoulder and adding rumble stripes on two-lane rural roads;
    - Paving 2 to 4 ft of unpaved shoulders on four-lane divided rural roads;
    - Combined effect of paving 2 to 4 ft of unpaved shoulder and adding rumble strips on four-lane divided rural roads;
- Quantify the benefits and costs of the ALDOT policy;
- Estimate run-off-road (ROR) crash frequency on two-lane and multilane rural roads in Alabama, applying several statistical distributions to crash data. As a result, two safety performance functions will be recommended, for two-lane and for multilane roads, modeled according to the best distribution;
- Make recommendations for future application.

1.4 SCOPE

This study documents the state of the practice and results of prior research related to the implementation of pavement widening, shoulder rumble strips and shoulder rumble stripes as an effort to reduce run-off-road (ROR) crashes on rural highways in the United States. A survey was distributed to the department of transportation of each state in the country to summarize how the countermeasures to reduce roadway departure crashes were applied, as well as which safety effectiveness measures were obtained after the implementation of the treatments.

Given ALDOT's policy of 2006 regarding the implementation of countermeasures as an effort to reduce ROR crashes in the state, a dataset including 101 projects in Alabama was analyzed to estimate the safety effectiveness of the treatments. All sites included segments on two and four-lane rural roads with shoulder width varying from 2 to 4 ft. Among the two-lane segments, the analysis considered 40 sites where paved shoulder and shoulder rumble strips were implemented, 12 sites with paved shoulder and shoulder rumble stripes, and 31 sites with only paved shoulder applied. The four-lane segments included 9 sites where paved shoulder and shoulder rumble strips were implemented, and 9 sites with only paved shoulder applied. The reduction in run-off-road crashes was first estimated using the Empirical Bayes (EB) method as outlined in the *Highway Safety Manual* (HSM). The EB analysis applied both HSM safety performance functions (SPF) and state-specific SPFs developed for Alabama conditions (Mehta and Lou, 2014). Crash modification factors (CMF) were developed for each treatment after the EB analysis was concluded. Following this analysis, the equivalent property damage only (EPDO) method was applied to provide an overview of ROR crash reduction, by severity, after the implementation of countermeasures in Alabama.

A benefit-cost analysis was performed to quantify the benefits and costs of the ALDOT policy. Estimated average costs of crashes, by severity, were based on a National Highway Traffic Safety Administration (NHTSA) report. (Blincoe et al., 2014).

Finally, an estimation of run-off-road crash frequency on two-lane and four-lane rural roads was performed. This analysis applied Poisson, negative binomial, and zero-inflated models to 10 years of crash data on 72 two-lane road segments and 32 four-lane road segments in Alabama. As a result, two safety performance functions were recommended, for two-lane and for four-lane roads.

Conclusions and recommendations are made at the end of this dissertation, with suggestions for the implementation of the countermeasures to reduce ROR crashes, as well as recommendations for future research that could improve the findings of this study.

1.5 ORGANIZATION OF DISSERTATION

Chapter 2 documents literature review relevant to this study. The importance of analyzing crashes by severity and the crash severity scale (KABCO) adopted in this study are described. Also, methods on how to implement and evaluate safety effectiveness of countermeasures to avoid crashes are presented. Details on the Empirical Bayes method of evaluating safety effectiveness, as outlined in the *Highway Safety Manual*, are provided. The use of zero-inflated distributions to represent crash data is also discussed in Chapter 2. Finally, an overview of previous studies that evaluated the safety effects of paved shoulders, shoulder rumble strips and shoulder rumble stripes as countermeasures to avoid crashes is summarized.

This study documents the state of the practice of the implementation of paved shoulders, shoulder rumble strips, and shoulder rumble stripes on rural roads in the United States. Also, the estimated safety effectiveness of countermeasures applied in Alabama as a result of a policy from 2006 is performed using both EB and EPDO methods, and a benefit-cost analysis quantifies this safety effectiveness. Finally, several statistical distributions are applied to crash data from control sites in Alabama to model two state-specific safety performance functions. Chapter 3 presents the methods to accomplish these goals, and Chapter 4 shows the corresponding results. Chapter 5 organizes all results and relevant conclusions from the analyses conducted in this study. Recommendations for practice and future studies are also suggested in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A run-off-road collision (ROR), also known as roadway departure event, is a single-vehicle crash that occurs when a vehicle leaves the travel lane and invades the shoulder and strikes one or more objects, such as bridge walls, poles, embankments, guardrails, parked vehicles, and trees. (Neuman et al., 2003).

Factors significantly associated with the occurrence of ROR crashes include driver inattention, driver fatigue status, roadway surface conditions, driver alcohol presence, driver's familiarity with the roadway, driver's pre-existing physical or mental health conditions, driver's gender, driver's work-related stress or pressure, and if the driver was in a hurry. (Liu and Ye, 2011).

One way to reduce the chance that a vehicle will leave the roadway is through changes in roadway design, such as increasing curve radius of horizontal curves, installing shoulder rumble strips and stripes, enhancing pavement markings at appropriate locations, and applying skid-resistant pavements. Also, if it is possible to minimize the likelihood of the vehicle crashing into an object or overturning after the vehicle leaves the roadway, fatalities and injuries resulting from a ROR crash can be reduced. Examples of measures that can be applied in these cases are the design of safer slopes and ditches to prevent rollovers, removal or relocation of objects in hazardous locations, and delineation of roadside objects. Safety measures can also be adopted to reduce the severity of the ROR crashes, which can be done by improving the design of roadside hardware, such as bridge rails, and by enhancing the design and application of barrier and attenuation systems, for example. (Neuman et al., 2003).

2.2 CRASH SEVERITY SCALE (KABCO)

Crash severity can be divided into categories according to the KABCO scale, which provides five levels of injury severity. (AASHTO, 2010). The KABCO scale is used in the *Highway Safety Manual* (HSM), and is applied to this research. The five KABCO crash severity levels are defined as:

- K (fatal injury): results in death;
- A (incapacitating injury): any injury, other than a fatal injury, that prevents the injured person from walking, driving, or normally continuing the activities the person was capable of performing before the injury occurred;
- B (non-incapacitating evident injury): any injury, other than a fatal injury or an incapacitating injury, that is evident to observers at the scene of the crash in which the injury occurred;
- C (possible injury): any injury reported or claimed that is not a fatal injury, incapacitating injury, or non-incapacitating evident injury and includes claim of injuries not evident;
- O (no injury/property damage only – PDO).

2.3 EVALUATION OF THE SAFETY EFFECTIVENESS OF COUNTERMEASURES

The safety of an entity (a road section, an intersection, a driver, a bus fleet, etc.) is “the number of crashes (crashes), or crash consequences, by kind and severity, expected to occur on the entity during a specified period" (Hauer, 1997). Since what is "expected" cannot be known, safety can only be estimated. (Hauer et al., 2002). When evaluating the safety effectiveness of a treatment applied to a specific site of the roadway, it has to be considered how safety was in the period "before" the treatment was implemented, and how it changed in the "after" period, has the treatment been implemented.

2.3.1 Crash data modeling and regression-to-the-mean (RTM) bias

Crashes can be modeled as random events; therefore, crash frequencies naturally fluctuate over time at a given site. This randomness indicates that short-term crash frequencies alone are not a reliable estimator of long-term crash frequency. The short-term average crash frequency may vary significantly from the long-term average crash frequency, and this effect is magnified at study locations with low crash frequencies. (AASHTO, 2010). Figure 2.1 shows the randomness of observed crash frequency and the limitation of estimating crash frequency based on short-term observations.

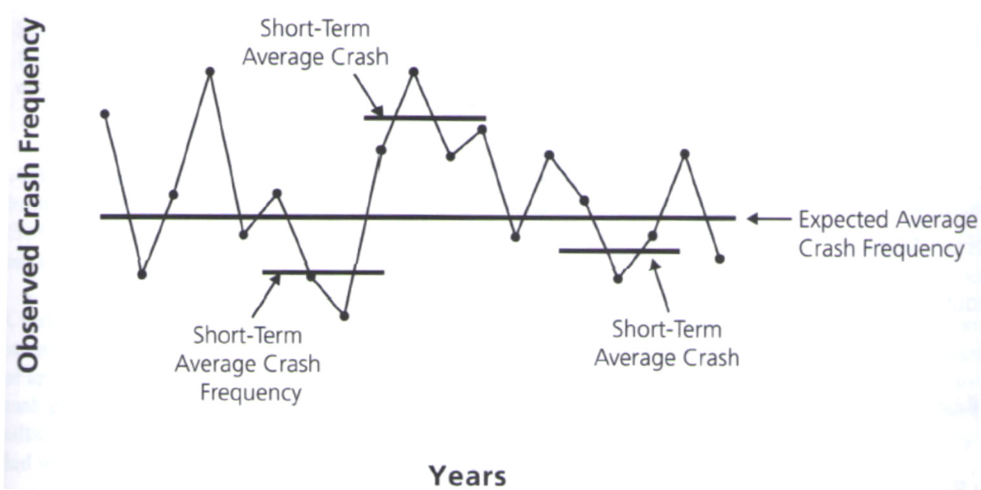

FIGURE 2.1 Variation in short-term observed crash frequency

SOURCE: AASHTO, 2010

The crash fluctuation over time makes it difficult to determine whether changes in the observed crash frequency are due to changes in site conditions or are due to natural fluctuations. When a period with high crash frequency is observed, it is statistically probable that the following period will have low crash frequency. This tendency is known as regression-to-the-mean (RTM) and is also valid for low crash frequency periods having a high probability of being followed by a high crash frequency period. Not accounting for the effects of RTM introduces the potential for "RTM bias". (AASHTO, 2010). Figure 2.2 shows the effect of RTM and RTM bias in evaluation of treatment effectiveness. As an example, consider that the observed crash frequency before the implementation of a treatment is represented by "year 0" in Figure 2.2. After 3 years, the number of crashes after treatment was implemented is the observed crashes indicated by "year 3". The evaluation of safety effectiveness is based on the reduction in the crash frequency between "year 0" and "year 3". The perceived effectiveness of treatment is higher than the actual reduction due to treatment, as the effectiveness should be related to the expected average crash frequency if treatment was not implemented.

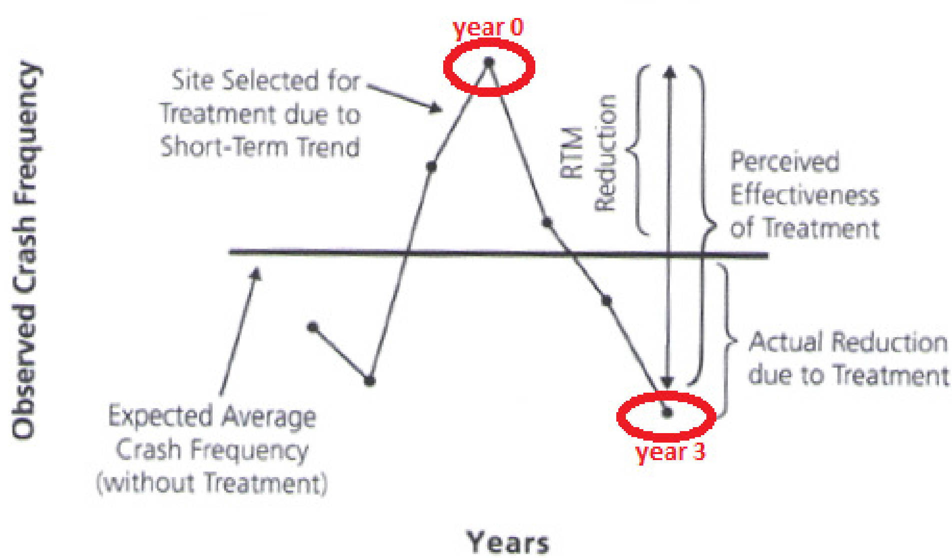

FIGURE 2.2 Regression-to-the-mean (RTM) and RTM bias

SOURCE: AASHTO, 2010

2.3.2 Methods to evaluate safety effectiveness

The method used to evaluate the safety effectiveness of a treatment should ideally address the random characteristics of crashes and also avoid RTM bias. The HSM discusses three crash estimation methods (AASHTO, 2010):

a) Crash rates

Crash rate is the number of crashes that occur at a given site during a certain time period in relation to a measure of exposure, usually “per million vehicle miles of travel” for a roadway segment.

b) Indirect or surrogate safety measures for identifying high crash locations

These measures provide a surrogate methodology when crash frequencies are not available because the roadway or facility is not yet in service or has only been in service for a short time.

c) Statistical analysis techniques:

These techniques incorporate observed crash data to improve the reliability of crash estimation models. Statistical models using regression techniques have been developed to address some limitations of other methods. Several statistical methods exist for combining estimates of crashes from a statistical model with the estimate using observed crash frequency at a site or facility; some examples are the Empirical Bayes method (EB), the Hierarchical Bayes method, and the Full Bayes method.

2.3.3 Evolution of the statistical methods for safety effectiveness evaluation

Experimental studies are designed to answer a question or to infer cause and effect, as experiments can be controlled. However, in an observational study it is not possible to isolate the effects of a treatment to answer a research question while keeping everything else constant. The effects influencing crash occurrence cannot be controlled in a laboratory experiment; therefore, crash data analysis can only be performed through observational studies. Several methods can predict the safety effects of a treatment considered in an observational study; the most commonly seen in the literature are the before-after study, the comparison group, and the Empirical Bayes (EB) methods. These methods attempt to predict what the expected number of crashes would have been in the "after" period had the treatment not been implemented, and compare this prediction with what safety in the "after" period was, with the treatment in place. (Hauer, 1997).

The simplest method of evaluating the safety effectiveness of a treatment is the "naïve" before-after study. It compares the count of "before" period crashes to the count of "after" period crashes. This method considers that the count of "before" period crashes can be used to predict what would have been the expected count of "after" period crashes had the treatment not been implemented. This approach focuses on the implementation of a treatment being the only factor that caused change in the crash frequency during the "before" and "after" periods, it does not consider any other changes that may have affected the safety of the analyzed site of study. As a result, some factors can be mentioned to make the naive assumption questionable. (Hauer, 1997).

Hauer (1997) lists some factors that may affect differences in crash frequency over time, which shows the limitations of applying the "naïve" before-after analysis to crash studies. In addition to the implementation of a treatment, several factors may change over time at a specific roadway segment, such as traffic, weather, road user behavior, and vehicle fleet. Therefore, it is not a safe assumption to attribute the change in number of crashes from “before” to “after” periods exclusively to the effect of treatment implementation. Also, various other treatments other than the considered treatment may be implemented during the “before” and “after” periods, so crash frequencies also reflect their effects. The probability of crashes being reported can also vary over time, being a factor influencing crash frequency differences between the “before” and “after” periods.

The comparison group method identifies a group of sites that remained untreated, and that are similar to the treated sites. The treated sites are the “treatment group”, and the untreated sites are the “comparison group”. The premise of the method is that the change from “before” to “after” in the safety of the comparison group indicates how safety on the treatment group would have changed had the treatment not been applied. Therefore, comparison group method assumes that the factors that affect safety have changed from the “before” to the “after” period in the same manner on both the treatment and the comparison group, and that this change influences the safety of both groups in the same way. The idea of this method is similar to that of randomized experiments with control groups. The main limitation of this method is that different factors may have acted on the two different groups; for example, one group may have experienced snow storms or have hosted a big event that generated significantly higher traffic during a certain period, while the other group did not experience those. (Hauer, 1997).

The most accurate methods to predict safety effectiveness of a treatment should increase the precision of estimates when there are no long-term data available, and provide no regression-to-the mean bias. (Hauer, 1997). The Empirical Bayes (EB) method addresses two problems of safety estimation that are not considered in other methods such as the “naïve” and the comparison group: it increases the precision of estimates when only short-time periods of crash history data are available, and it corrects for the regression-to-mean bias. (Hauer, 2002). The EB method also accounts for external causal factors that change with time, such as weather, crash reporting practices, and driving habits. (Khan et al., 2014).

2.4 THE HIGHWAY SAFETY MANUAL PREDICTIVE METHOD

The *Highway Safety Manual* (HSM) uses statistical methods for crash estimation and safety evaluation. The HSM predictive method estimates the expected average crash frequency of a site, facility or roadway network for a given time period, geometric design and traffic control features, and annual average daily traffic (AADT) volumes, by total crashes, crash severity, or collision type. (AASHTO, 2010).

The expected average crash frequency, $N_{expected}$, is estimated using a predictive model estimate of crash frequency, $N_{predicted}$ and observed crash frequency, $N_{observed}$. There are two main elements of the HSM predictive method. The first element is a predictive model estimate of the average crash frequency for a specific site type, which is done using a statistical model developed from data for a number of similar sites. The model is adjusted to account for specific site conditions and local conditions. The second element is the use of a method, known as Empirical Bayes (EB), to combine the estimation from the statistical model with observed crash frequency at the specific site. A weighting factor is applied to the two estimates to reflect the model's statistical reliability. (AASHTO, 2010). The main concepts of the predictive method used in the HSM are: safety performance functions (SPFs), crash modification factors (CMFs), calibration factor (C), and Empirical Bayes method (EB method). (AASHTO, 2010).

2.4.1 Estimating average crash frequency with the Highway Safety Manual

Safety Performance Functions (SPFs) are regression equations that estimate the average crash frequency for a specific site type as a function of variables such as traffic (AADT), and segment length. Base conditions are specified for each SPF and may include conditions such as lane width, and presence or absence of lighting. The SPFs in the HSM have been developed for three facility types: rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials. (AASHTO, 2010). A supplement that addresses freeways and ramps was released in 2014.

Safety performance functions in the HSM are developed through statistical multiple regression techniques using observed crash data collected over a number of years at sites with similar characteristics and covering a wide range of AADTs. The regression parameters of the SPFs are determined by assuming that crash frequencies follow a negative binomial distribution. (AASHTO, 2010). Historically, it was a common approach to consider that the number of crashes at a site follows a Poisson distribution, but research found that the crash counts used in the calibration of SPFs are usually more widely dispersed than what would be consistent with the Poisson assumption. (Hauer, 2002).

Therefore, nowadays it is common to assume that the number of crashes follow a negative binomial distribution. The negative binomial distribution is an extension of the Poisson distribution, and is better suited than the Poisson distribution to modeling of crash data. The Poisson distribution would be appropriate if the mean and the variance of the data were equal; for crash data, however, the variance typically exceeds the mean. Data for which the variance exceeds the mean are said to be overdispersed, and the negative binomial distribution is very well-suited to modeling overdispersed data. The degree of overdispersion in a negative binomial model is represented by the overdispersion parameter, which is estimated along with the coefficients of the regression equation. The larger the overdispersion parameter, the more the crash data vary as compared to a Poisson distribution with the same mean. (AASHTO, 2010).

In the *Highway Safety Manual*, for a two-lane rural road, the base conditions for a safety performance function are:

- 12 ft lane width;
- 6 ft shoulder width;
- Paved shoulder;
- Roadside hazard rating (RHR) of 3;
- Driveway density (DD) of 5 driveways per mile;
- No horizontal curvature;
- No vertical curvature;
- No centerline rumble strips;
- No passing lanes;
- No two-way left-turn lanes;
- No lighting;
- No automated speed enforcement;
- 0% grade.

For a multilane divided rural road, the base conditions are:

- 12 ft lane width;
- 8 ft right shoulder width;
- 30 ft median width;
- No lighting;

- No automated speed enforcement.

Safety performance functions are developed based on control sites, which means that they are applied to estimate crash frequency at a site has the treatment not been implemented. In this study, the base conditions are: no shoulder, no rumble strips and stripes, and varying lane widths for each site. The absence of shoulder and the different lane widths were corrected applying crash modification factors to the HSM safety performance functions. No detailed data were available for the analyzed sites considering the remaining base conditions listed in the HSM, but this was not a significant issue as they remain constant among all segments. This process is more detailed in the Methodology chapter.

2.4.2 Crash modification factors (CMF)

Crash modification factors represent the relative change in crash frequency due to a change in one specific condition, when all other conditions and site characteristics remain constant. A CMF is the ratio of the crash frequency of a site under two different conditions and may serve as an estimate of the effect of a particular geometric design or traffic control feature or the effectiveness of a particular treatment or condition. Equation 2.1 shows the calculation of a CMF. (AASHTO, 2010).

$$CMF = \frac{Expected\ average\ crash\ frequency\ with\ site\ condition\ b}{Expected\ average\ crash\ frequency\ with\ site\ condition\ a} \qquad \text{(Equation 2.1)}$$

Where:

Condition a = how the site would be if treatment was not implemented;

Condition b = how the site is after treatment was implemented.

CMFs are multiplied by the crash frequency predicted by the SPF to account for the differences between site conditions and specified base conditions. CMFs can be found in Volume 3 of the *Highway Safety Manual*, in Part D. They can be represented by discrete values, equations, or graphs. They are organized by chapters, from 13 to 17, that show CMFs for roadway segments, intersections, interchanges, special facilities and geometric situations, and road networks, respectively. As an example, when using a SPF for two-lane rural roads, the base condition for shoulder width is 6 ft; if the analyzed roadway segment has 2 ft shoulder width, then the SPF should be multiplied by: (for details, refer to AASHTO, 2010).

- A CMF of 1.07, if AADT < 400 veh/day;
- A CMF of [1.07 + 1.43 x 10^{-4}(AADT – 400)], if AADT is between 400 and 2000 veh/day;
- Or by a CMF of 1.30, if AADT > 2000 veh/day.

The HSM has CMFs for shoulder widths in relation to the base condition of the SPFs for both two-lane (6 ft shoulder width) and multilane rural roads (8 ft shoulder width), but these SPFs do not consider base condition as the absence of shoulder. In addition, they are not specific to run-off-the road crashes, but instead represent all crash types. Also, HSM has CMF for shoulder rumble strips on multilane rural highways, but this topic is limited in the manual, as CMFs do not consider rumble strips and stripes separately and they do not specify on which shoulder width the rumble strips are applied. Also, there are no CMFs for rumble strips or stripes on two-lane rural roads.

Crash modification factors can also be found online in the *Crash Modification Factors Clearinghouse*. The website is funded by the U.S. Department of Transportation Federal Highway Administration (FHWA) and maintained by the University of North Carolina Highway

Safety Research Center. For example, the CMF for implementing shoulder widening in conjunction with shoulder rumble strip installation on freeways is 0.87. (FHWA, 2014).

There are several studies in the *Crash Modification Clearinghouse* that are related to paved shoulder and shoulder rumble strips. Hanley et al. (2000) studied the implementation of shoulder widening in conjunction with shoulder rumble strip installation, but only on freeways. Pitale et al. (2009) evaluated the effect of paving shoulders and also the combined effect of paving shoulders and adding rumble strips, but the study was not specific to rural roads or run-off-the-road crashes, and did not specify shoulder widths. Torbic et al. (2009) analyzed the effect of adding rumble strips or rumble stripes to two-lane rural roads with shoulder width less than 5 ft, but did not specify if shoulders were 1, 2, 3, 4, or 5ft, for example, and there was no CMF for the combined effect of paving shoulder and adding rumble strips or rumble stripes.

The present study is important as it will make it possible to develop CMFs for the Alabama condition, which is different than the cases found in the literature, as shoulder widths are as narrow as 2 ft. CMFs developed will include:

- CMF for paving 2 to 4ft of unpaved shoulders on two-lane rural roads;
- CMF for paving 2 to 4ft of unpaved shoulders on multilane rural roads;
- CMF for combined effect of paving 2 to 4ft of unpaved shoulder and adding rumble strips on two-lane rural roads;
- CMF for combined effect of paving 2 to 4ft of unpaved shoulder and adding rumble strips on multilane roads;
- and CMF for combined effect of paving 2 to 4ft of unpaved shoulder and adding rumble stripes on two-lane rural roads.

2.4.3 Calibration factor (C)

The SPFs in the HSM must be calibrated to local conditions. A calibration factor is multiplied by the crash frequency predicted by the SPF to account for differences between the jurisdiction and time period for which the predictive models were developed and the jurisdiction and time period to which they are applied by HSM users. (AASHTO, 2010).

2.4.4 Predicting average crash frequency with the Highway Safety Manual

Crash Modification Factors (CMFs) and calibration factors (C) are used to correct the HSM safety performance function to the analyzed roadway segments specific conditions that differ from base conditions. If lane widths and shoulder widths of a specific roadway segment in a two-lane rural road are different from 12ft and 6ft, for example, two CMFs are applied, according to Tables 2.1 and 2.2.

TABLE 2.1 CMFs for two-lane rural roads: lane widths

Lane Width	AADT (veh/day)		
	< 400	400 to 2000	>2000
9 ft or less	1.05	$1.05 + 2.81 \times 10^{-4}$ (AADT - 400)	1.50
10 ft	1.02	$1.02 + 1.75 \times 10^{-4}$ (AADT - 400)	1.30
11 ft	1.01	$1.01 + 2.5 \times 10^{-5}$ (AADT - 400)	1.05
12 ft or more	1.00	1.00	1.00

SOURCE: AASHTO, 2010

TABLE 2.2 CMFs for two-lane rural roads: shoulder widths

Shoulder Width	AADT (veh/day)		
	< 400	400 to 2000	>2000
0 ft	1.10	$1.10 + 2.5 \times 10^{-4}$ (AADT - 400)	1.50
2 ft	1.07	$1.07 + 1.43 \times 10^{-4}$ (AADT - 400)	1.30
4 ft	1.02	$1.02 + 8.125 \times 10^{-5}$ (AADT - 400)	1.15
6 ft	1.00	1.00	1.00
8 ft or more	0.98	$0.98 - 6.875 \times 10^{-5}$ (AADT - 400)	0.87

SOURCE: AASHTO, 2010

The same procedure is valid for multilane rural roads. Table 2.3 has the CMFs for lane width on multilane divided roads, and Table 2.4 has the CMFs for right shoulder width on multilane divided roads.

TABLE 2.3 CMFs for multilane divided roads: lane widths

Lane Width	AADT (veh/day)		
	< 400	400 to 2000	>2000
9 ft or less	1.03	$1.03 + 1.38 \times 10^{-4}$ (AADT - 400)	1.25
10 ft	1.01	$1.01 + 8.75 \times 10^{-5}$ (AADT - 400)	1.15
11 ft	1.01	$1.01 + 1.25 \times 10^{-5}$ (AADT - 400)	1.03
12 ft or more	1.00	1.00	1.00

SOURCE: AASHTO, 2010

TABLE 2.4 CMFs for multilane divided roads: shoulder widths

Shoulder Width	Setting (road type)	Traffic volume	Crash type (severity)	CMF	Std. Error
8 ft to 6 ft conversion	Rural (multilane highways)	Unspecified	Unspecified	1.04	N/A
8 ft to 4 ft conversion				1.09	N/A
8 ft to 2 ft conversion				1.13	N/A
8 ft to 0 ft conversion				1.18	N/A

SOURCE: AASHTO, 2010

2.4.5 The Empirical-Bayes (EB) method in the HSM

The EB method in the *Highway Safety Manual* uses a safety performance function (SPF) and weights the observed crash frequency with the SPF-predicted average crash frequency to obtain an expected crash frequency. The method requires at least 10 to 20 sites at which the treatment of interest has been implemented, 3 to 5 years of crash and traffic volume data for the period before treatment implementation, 3 to 5 years of crash and traffic volume data for the period after treatment implementation, and a SPF for treatment site types. The method can be summarized in 14 steps, as it can be seen below. (AASHTO, 2010). The computational procedure for the Empirical Bayes method will be detailed in the Methodology chapter.

I. *PART 1 – EB estimation of the expected crash frequency in the "before" period*
   a. Step 1: calculate the predicted crash frequency for each site during each year of the "before" period, using a SPF for the specific site type;
   b. Step 2: calculate the predicted crash frequency for each site summed over the entire "before" period.

II. *PART 2 – EB estimation of the expected crash frequency in the "after" period*
   a. Step 3: calculate the predicted crash frequency for each site during each year of the "after" period, using a SPF for the specific site type;
   b. Step 4: calculate an adjustment factor to account for differences between "before" and "after" periods;
   c. Step 5: calculate the expected crash frequency for each site over the entire "after" period in the absence of treatment.

III. *PART 3 – Estimation of treated effectiveness* *a.* Step 6: calculate an estimate of the safety effectiveness at each site in terms of an odds ratio;

b. Step 7: calculate an estimate of the safety effectiveness at each site as a percentage crash change;

c. Step 8: calculate the overall effectiveness of the treatment for all sites combined in terms of an odds ratio;

d. Step 9: perform an adjustment to obtain an unbiased estimate of the treatment effectiveness in terms of an odds ratio;

e. Step 10: calculate the overall unbiased safety effectiveness as a percentage change in crash frequency across all sites.

IV. *PART 4 – Estimation of the precision of the treated effectiveness*

a. Step 11: calculate the variances of the unbiased estimated safety effectiveness as an odds ratio;

b. Step 12: calculate the standard error of the odds ratio from step 11;

c. Step 13: calculate the standard error of the unbiased safety effectiveness calculated in step 10;

d. Step 14: assess the statistical significance of the estimated safety effectiveness.

2.5 STATE SPECIFIC SAFETY PERFORMANCE FUNCTIONS AND CALIBRATION FACTORS

In 2013, the University of Alabama performed a study that used data from the Critical Analysis Reporting Environment (CARE) maintained by the Center for Advanced Public Safety at the University of Alabama. CARE receives the roadway inventory data from Alabama

Department of Transportation and the crash data from the Alabama Department of Public Safety. The data set consisted of a total of 1,126 miles of roads of Alabama, including two-lane two-way rural roads and four-lane divided highways, from 2006 to 2009. The study developed state specific SPFs and calibration factors for Alabama. (Mehta and Lou, 2014).

The study estimated a Poisson-Gamma regression model, a special type of Negative Binomial model. A Poisson-Gamma regression assumes the Poisson mean λi takes the form shown in Equations 2.2 and 2.3.

$$\lambda_i = exp(\beta_{i0} + \sum_j x_{ij}\beta_{ij} + \varepsilon) \quad \text{(Equation 2.2)}$$

$$\lambda_i = exp(\beta_{i0} + \sum_j x_{ij}\beta_{ij})exp(\varepsilon) \quad \text{(Equation 2.3)}$$

Where:

x_{ij} = the j^{th} explanatory variable for the mean of crash counts at site *i*;

β_{ij} = coefficients to be estimated;

β_{i0} = constant to capture other unknown or unobserved factors;

ε = random term following Gamma distribution with a mean of one and a variance of $1/\alpha$, being α the overdispersion parameter.

Therefore, an SPF that has negative binomial distribution with mean μi and variance μi + $\alpha\mu_i^2$, can be represented mathematically by Equation 2.4.

$$\widehat{\mu_i} = exp(\beta_{i0} + \sum_j x_{ij}\beta_{ij}) \quad \text{(Equation 2.4)}$$

The study by Mehta and Lou developed four SPFs for Alabama, with different model forms. The first model kept the form of HSM base SPF due to its simplicity and minimal requirements on data availability. The developed model can be observed for two-lane rural roads in Equation 2.5, with overdispersion parameter of 1.09, and for four-lane divided rural roads in Equation 2.6, with overdispersion parameter of 2.854.

$$\widehat{\mu_{i,2l}} = exp(-7.135)AADT_i^{0.916}SL_i \qquad \text{(Equation 2.5)}$$

$$\widehat{\mu_{i,4l}} = exp(-7.706)AADT_i^{0.974}SL_i \qquad \text{(Equation 2.6)}$$

Where:

$\widehat{\mu_i}$ = estimated average crash frequency for site *i*;

$AADT_i$ = annual average daily traffic for site *i*;

SL_i = segment length of site *i*.

The second model was based on a SPF developed in the United Kingdom for two-lane rural roads. (Mountain et al., 1996). The model can be seen in Equation 2.7 for two-lane rural roads, with an overdispersion parameter of 1.0189, and in Equation 2.8for four-lane divided rural roads, with an overdispersion parameter of 2.085.

$$\widehat{\mu_{i,2l}} = exp(-6.295)AADT_i^{0.786}SL_i^{0.747}exp\left(\frac{bn_i}{SL_i}\right) \qquad \text{(Equation 2.7)}$$

$$\widehat{\mu_{i,4l}} = exp(-6.166)AADT_i^{0.748}SL_i^{0.356}exp\left(\frac{bn_i}{SL_i}\right) \qquad \text{(Equation 2.8)}$$

Where:

n_i= number of minor junctions within site i. As roadway segments were considered homogeneous, the developed model considered n_i equal to zero, and the parameter "b" was not estimated in the study.

The third model of the Mehta and Lou study took the form developed by a study from the Washington State Transportation Institute (Milton and Mannering, 1996). The developed model can be observed for two-lane rural roads in Equation 2.9, with an overdispersion parameter of 0.9814, and for four-lane divided rural roads in Equation 2.10, with an overdispersion parameter of 2.077.

$$\widehat{\mu_{i,2l}} = exp(-7.971 + 0.0388DY_i + 0.775lnAADT_i + 0.694lnSL_i + 0.0552LW_i + 0.1641S_i) \quad \text{(Equation 2.9)}$$

$$\widehat{\mu_{i,4l}} = exp(-7.784 + 0.081DY_i + 0.759lnAADT_i + 0.354lnSL_i + 0.099LW_i + 0.049S_i) \quad \text{(Equation 2.10)}$$

Where:

DY_i = dummy variable to account for effects of the year on the intercept;

LW_i = lane width for site i;

S_i = speed limit of site i.

The last model developed for Alabama conditions was based on a study by Council and Stewart based on data from North Carolina, Washington, Minnesota, and California (Council and Stewart, 1999). The model can be seen in Equation 2.11 for two-lane rural roads, with an overdispersion parameter of 1.0593, and in Equation 2.12 for four-lane divided rural roads, with an overdispersion parameter of 2.844.

$$\widehat{\mu_{i,2l}} = exp(-7.020 - 0.0961SW_i + 0.0507LW_i) + AADT_i^{0.9279}SL_i \qquad \text{(Equation 2.11)}$$

$$\widehat{\mu_{i,4l}} = exp(-8.022 + 0.0520SW_i - 0.0528LW_i) + AADT_i^{0.991}SL_i \qquad \text{(Equation 2.12)}$$

Where:

SW_i = shoulder width for site i.

The Mehta and Lou study developed calibration factors for Alabama using two different approaches. The first approach considered the calibration factor estimated a special case of SPF development. When a base SPF is adjusted by a calibration factor C, the new regression model can be seen as it is shown in Equations 2.13 to 2.15.

$$\widehat{\mu_i} = exp\left(\beta_{i0} + \sum_j x_{ij}\beta_{ij}\right)C \qquad \text{(Equation 2.13)}$$

$$\widehat{\mu_i} = exp\left(\beta_{i0} + \sum_j x_{ij}\beta_{ij} + \ln(C)\right) \qquad \text{(Equation 2.14)}$$

$$\widehat{\mu_i} = exp(\ln(C) + \ln(Base\ SPF\ for\ site\ i)) \qquad \text{(Equation 2.15)}$$

The estimation of the intercept *ln(C)* gives the value for the calibration factor *C*. This approach leaded to a calibration factor of 1.522 for two-lane two-way rural roads and 1.863 for four-lane divided highways. (Mehta and Lou, 2014).

The second approach was the HSM recommended method. The HSM-recommended method for estimating the calibration factor is very straightforward. After the expected crash frequencies are calculated from the HSM base SPFs (predicted number of crashes for site i), the calibration factor is simply computed using Equation 2.16. The HSM-recommended approach leaded to a calibration factor of 1.392 for two-lane two-way rural roads and 1.103 for four-lane divided highways. (Mehta and Lou, 2014).

$$C_r = \frac{\sum_i Observed\ number\ of\ crashes\ for\ site\ i}{\sum_i Predicted\ number\ of\ crashes\ for\ site\ i} \quad \text{(Equation 2.16)}$$

2.6 EQUIVALENT PROPERTY DAMAGE ONLY (EPDO) ANALYSIS

The equivalent property damage only (EPDO) method is an extension of the “naïve” before-after analysis but it is focused on changes in crash severity rather than frequency. Each crash is weighted based on its severity and the equivalent property damage only crash cost. According to a National Highway Traffic Safety Administration (NHTSA) report, an average incapacitating injury is 22 times more costly than the average PDO crash. Therefore, the EPDO score for one incapacitating injury crash is 22, while the score for one PDO crash is 1. (Blincoe et al., 2014).

Data needed for the EPDO analysis are crash frequency by severity and location and crash weighting factors by severity. This method has limitations, as it does not account for RTM bias, it may overemphasize locations with a small number of severe crashes, and it does not account for traffic volume. (Herbel et al., 2010).

2.7 ZERO-INFLATED MODELS

There is a wide variety of models applied to crash data analysis. A crash is, in theory, the result of a Bernoulli trial; each time a vehicle enters an intersection, a highway segment, or any other type of entity on a given transportation network, it will either crash or not crash. The occurrence of a crash is defined as a "success" while failure to crash is a "failure". The appropriate probability model that accounts for a series of Bernoulli trials is the binomial distribution. For typical motor vehicle crashes where the event has a very low probability of occurrence and a large number of trials exist, the binomial distribution is approximated by a Poisson distribution. (Lord et al., 2005).

Poisson distribution models consider that variance and mean must be approximately equal. However, this restriction is a problem when data are overdispersed, with variance exceeding the mean of crash counts, or underdispersed, with mean greater than the variance. Other problems that may result in a poor estimation of crash frequency are time-varying explanatory variables, temporal and spatial correlation, low sample-mean and small sample size, under-reporting of crashes, omitted variables in the model, endogenous variables, among others. (Lord and Mannering, 2010).

Crash data are usually overdispersed, which makes the negative binomial (NB) distribution more appropriate as it accounts for the overdispersion. However, estimation applying NB models can be misleading due to the large number of zero-crash observations. (Shankar et al., 1997). A dual-state system can be a good fit for crash data modeling, as it handles zero crash occurrences separated from the occurrences of one or more crashes. The modeling of the zero count state, having no crashes observed in some time period, considers that the absence of crashes may be the cumulative effect of whether a crash is ever to occur and the roadway is safe, or may be the possibility of zero crashes resulting from the underlying count distribution and the roadway is unsafe but, by chance, no accidents were observed in the observation period. Dual-state systems are estimated using zero-inflated models. (Carson and Mannering, 2001).

2.7.1 Previous studies applying zero-inflated models

Poisson and negative binomial distribution models have been historically applied to crash data modeling. However, due to the limitations of these models in considering the presence of "excess" zeros in crash data, zero-inflated models have been recently considered. Zero-inflated models assume a dual-state data-generating process where entities such as intersections, road segments, and pedestrian crossings, exist in one of two states: safe and unsafe. (Lord et al., 2005).

The concept of a zero-inflated distribution originated from the work of Rider (1961) and Cohen (1963). Zero-inflated regression models are characterized by a dual-state process, where the observed count can either be located in a perfect state or in an imperfect state with a mean μ. This type of model is suitable for data generated from two fundamentally different states.

A study was developed to evaluate the relationship between truck crashes and geometric design of road sections using Poisson, zero-inflated Poisson, and negative binomial distribution models. (Miaou, 1994). Data included crashes of large trucks (gross vehicle weight of 10,000 lb or over) on rural Interstate highways with section lengths varying from 0.01 to 7.77 miles. The study was performed in Utah with data from 1985 to 1989, including 8,263 homogeneous road sections, which represented 14,731 miles of roadway. Among the models, the negative binomial was the best for estimating the frequency of road sections with zero accidents; the zero-inflated Poisson was the best for estimating the frequency of road sections with 1, 2 and 3 accidents and when data had excess zeros; Poisson without the zero-inflated Poisson state was the best for estimating the frequency of road sections with 4 or more accidents.

Shankar et al. (1997) evaluated how to distinguish sections of a roadway that are safe from those that are unsafe but happen to have zero accidents during the period of observation applying zero-inflated Poisson (ZIP) and zero-inflated negative binomial (ZINB) models. Data of major functional classes by geographic location were analyzed: principal and minor arterial highways from Western Washington, and collector arterials from Eastern Washington. Data were available from January 1992 to December 1993. As a result, for principal-arterials the best model was NB; for minor-arterials, ZINB was better; for collector-arterials, ZIP was better.

The effect of ice warning signs on accident frequencies and severities was evaluated applying NB, ZINB, and ZIP models in Washington State using data from January 1993 to December 1995. Three separate frequency models were estimated to better account for differences attributable to roadway functional classes of interstate, principal arterial, and minor arterial. For interstates, ZINB was the best; for other principal arterials and minor arterials, NB was the best. (Carson and Mannering, 2001).

Lee and Mannering (2002) studied the impact of roadside features on the frequency and severity of run-off-road crashes to quantify the effect of countermeasures to prevent this crash type. Data from a 96.6 km (60 mi) section of highway in Washington State was evaluated. The study used the Vuong (1989) test to determine which was the most suitable model to apply to the data. For urban section run-off-roadway crash frequency, the negative binomial regression model was found to be the most appropriate count model; for rural section run-off-roadway accident frequency, the zero-inflated negative binomial regression model was determined to be the most appropriate model.

A study to model crashes involving pedestrians and motorized traffic in Washington State was performed by Shankar et al. (2003). The study included empirical models based on the negative binomial distribution and mixing distributions, such as the zero-inflated Poisson distribution. The zero-inflated models were a tentative to address modeling issues related to the presence of excess zeros as well as unobserved heterogeneity in pedestrian crash distributions. Results showed that ZIP was a promising methodology for providing explanatory insights into the causality behind pedestrian-traffic crashes.

Lord et al. (2005) emphasizes that zero-inflated models have been justified based on their superior statistical fit, usually centered on the Vuong statistics (Vuong, 1989). However, zero-inflated models provide good statistical fit but do not characterize the underlying crash process well, they do not consider several conditions that may lead to excess zeros in crash data, such as: spatial or time scales are too small; there is under-or mis-reporting of crashes; some sites may be characterized by low exposure and high risk; and important variables may be omitted.

Lord et al. (2007) noted that it is preferable to begin to develop models that consider the fundamental process of a crash and avoid striving for best fit models in isolation. However, when the main objective is to find the best-fitted model to estimate crash data, the zero-inflated models may be appropriate, since they offer improved statistical fit compared to Poisson or negative binomial models.

A study conducted in Malaysia fitted the frequency of head-on crashes by comparing seven count-data models: Poisson, negative binomial, random-effect negative binomial, hurdle Poisson, hurdle negative binomial, zero-inflated Poisson, and zero-inflated negative binomial models. The analysis included data from 448 segments of five federal roads in Malaysia with crash data from 2004 to 2010. The Vuong test was applied to compare zero-inflated models and hurdle models with single count models. Also, the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) were used to compare models. The comparison results showed that the random-effect negative binomial was preferred over the other models. (Hosseinpour et al., 2014).

2.7.2 Zero-inflated models applied to SPF development in Alabama

The *Highway Safety Manual* provides general safety performance functions for several types of roads. The manual suggests that calibration factors should be applied to account for differences between road conditions in each state or, if data are available, state-specific SPFs should be developed. (AASHTO, 2010). The development of state-specific SPFs is, in most cases, limited. Data availability has been restrictive in terms of providing information on cause and effect of crashes and which models could be developed to generate these conclusions. The availability of data that includes detailed driving information such as acceleration, braking and steering information, and driver response to stimuli, and crash data from vehicle "black-boxes" are considerable promising for the future development of the field. (Lord and Mannering, 2010).

There is a broad range of potential independent variables that can influence crash frequency, as well as several statistical methods to model number of crashes. There are also different points of view among safety researchers on applying zero-inflated (ZI) methods to crash frequency modeling. ZI models assume that some zeros in the data are from the road segment being "safe" but others from other sources. Some researchers argue that there are no inherently safe road segments (Lord et al., 2007); however, this is an assumption that can be made when data from finite segments over finite time are modeled. In the data analyzed in this study, zero count segments exist, as well as non-zero count segments.

From a statistical approach, inference is limited by observations and model assumptions. Every method has its limitations due to assumptions made; however, an important goal of applying a specific method to model data is to maximize the goodness of fit of the model given the data by estimating the model parameters that make the model best fit the data.

Researchers argue that random effect models that can capture spatial clustering effects over small areas should be applied to overcome issues with ZI models limitations (Lord et al., 2007); however, this is only effective if the segments with zero counts are spatially clustered in small regions, which is not the case for the data considered in this study.

In summary, zero-inflated models can be used to perform a discriminant analysis and to determine if the variables are good discriminators of "safe" and "unsafe". The definition of a perfectly "safe" segment of road is not valid and a long-term mean equal to zero does not apply. However, zero-inflated models can account for other factors, such as unreported crashes, that may be responsible for zero crash occurrence at an "unsafe" segment. Therefore, the assumption of applying a zero-inflated model in this study is based on the attempt to establish a difference between sites that are safer and the sites that are not as safe, but happened to have zero crashes recorded during the period of time considered in the study. This is an observational study and, as mentioned before, no causation can be inferred, only correlation. Therefore, the goal of this analysis is not to explain the reason why one site would have a long-term mean equal to zero while an adjacent site, with similar attributes, would have mean above zero.

This study has the objective of developing state-specific SPFs for Alabama comparing several commonly used distribution models in the literature. Limitations exist when applying zero-inflated models to data modeling; however, if the data has excess zeros, ZI models will provide a better representation than the traditional single-state models such as Poisson and negative binomial. Several other models can be evaluated in posterior research, and due to the limitations of this study, future analyses are recommended when more data are available, especially when cause an effect of crashes can be analyzed.

2.8 PAVED SHOULDERS APPLIED AS COUNTERMEASURES TO REDUCE CRASHES

Among all roadway elements, shoulder is one of the most extensively studied. Its safety effectiveness on safety has been the focus of several research projects.

One of the first studies related to paved shoulders and safety was published in 1974. Rural two-lane highways were analyzed and 3 to 4 ft sections of paved shoulders were compared to 3 to 4 ft sections with grass or unstabilized shoulders. The study found that paved shoulders with construction costs less than $14,000/mile, for both sides, could be economically justified on total crash reduction for two-lane rural primary highways with AADT greater than 2,000 vehicles per day. (Heimbach et al., 1974).

A study was conducted in Texas to analyze the effects of paved shoulders on three types of rural highways: two-lane roadways without paved shoulders, two-lane roadways with full-width paved shoulders, and four-lane undivided roadways without paved shoulders. Approximately 30 roadways of each type were analyzed and almost 1,250 km of highway involving 16,000 crashes were included in the research. The highest crash rates were found for two-lane highways without paved shoulders. Two-lane highways with paved shoulders presented the lowest crash rates until the traffic volume reached 7,500 vehicles per day, when four-lane highways were safer. The conclusion of this study was that full-width paved shoulders are effective to reduce crash rates on rural highways. (Turner et al., 1981).

A study was conducted the next year also in Texas, that time to evaluate a before-after crash analysis for shoulder presence. The study concluded that the addition of a full-width paved shoulder to a two-lane roadway was effective in reducing the total number of crashes that occurred. At low volumes, the addition of shoulders caused a decrease in single-vehicle crashes (run-off-road and fixed-object). At moderate volumes, adding shoulders resulted in a reduction of the total number of crashes and the severity of them for both single-vehicle and multivehicle crashes. On high-volume roadways, adding paved shoulders decreased the total number of crashes, but increased the severity of them. (Rogness et al., 1982).

A study performed by Zegeer et al. for FHWA analyzed the effects of shoulder type and width related to run-off-road, head-on, same-direction-sideswipe, and opposite-direction-sideswipe crash experiences on two-lane highways. Traffic, crash, roadway, and roadside data were collected on 4,951 miles of two-lane roadways in Alabama, Michigan, Montana, North Carolina, Utah, Washington, and West Virginia to determine the effects of shoulder surfacing. (Zegeer et al., 1988). The reduction of crashes comparing paved and unpaved shoulders can be observed for each shoulder widening in Table 2.5. It is possible to conclude that paved shoulders provide greater crash reduction than do unpaved shoulders.

TABLE 2.5 Effectiveness of shoulder type and widening with respect to crash reduction

Amount of shoulder widening (ft) per side	Percent reduction in related crash types	
	Paved	Unpaved
2	16	13
4	29	25
6	40	35
8	49	43

SOURCE: Zegeer et al., 1987

A study was conducted in Australia to analyze the effects of shoulder sealing (paving). Two-lane state highways were considered in the study. The conclusions showed that paving shoulders reduced crashes by approximately 41%. (Ogden, 1992).

In 1994, Zegeer et al. published a study to quantify the crash effects of shoulder and lane widths on rural roads carrying fewer than 2,000 vehicles per day. The analysis also included the study of shoulder type impacts. The database included data on two-lane roads from Alabama, Michigan, Montana, North Carolina, Utah, Washington, and West Virginia. Shoulder type (paved or unpaved) was found not to be significantly related to crash rate. (Zegeer et al., 1994).

In 2000, a report was published by the FHWA presenting an algorithm for predicting the safety performance of a rural two-lane highway. The results were summarized and can be observed in Table 2.6. It is possible to conclude that paved shoulders usually have lower accident modification factors (AMFs, recently known as crash modification factors – CMFs) and turf shoulders have the highest ones, showing that improving surface type may decrease crash occurrence. (Harwood et al., 2000).

TABLE 2.6 Crash modification factors for shoulder types

Shoulder type	AMF							
	Shoulder width (ft)							
	0	1	2	3	4	6	8	10
Paved	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.00	1.00	1.01	1.01	1.02	1.02	1.03
Composite	1.00	1.01	1.02	1.02	1.03	1.04	1.06	1.07
Turf	1.00	1.01	1.03	1.04	1.05	1.08	1.11	1.14

SOURCE: Harwood et al., 2000

With the evolution of the methods for evaluation of safety effectiveness, some researchers started reanalyzing data from previous studies. Hauer analyzed again the data from the Heimbach et al. (1974) study. Results showed that for rural two-lane roads, paving sod shoulders that were 3 ft to 4 ft wide was expected to reduce injury crashes by 14% and property damage only crashes by 22%. (Hauer, 2000).

Abboud conducted a study to evaluate of paved shoulders offered a significant safety benefit. The data included roadway segments where 2 and 4 ft wide paved shoulders had been installed. No statistically significant decrease in crashes due to paving shoulders was found. (Abboud, 2001).

A study in Indiana investigated shoulder type and its effects on safety for county roads. It was observed that increasing quality of shoulder (from no shoulder to gravel/grass to asphalt) was associated with decreasing crash frequency. This was expected, because improved shoulder surfaces could enhance the grip of vehicle tires. (Labi, 2006).

Harkey et al. developed several studies on shoulder type and the effects on safety in North Carolina. A summary was published in 2007 and provided the analysis of grave, composite, turf, and paved shoulders. The results showed that, compared to paved shoulders, gravel shoulders experienced an increase of 3 percent in ROR crashes, composite shoulders had an increase of 7 percent, and turf shoulders presented an increase of 14 percent in ROR crashes. (Harkey et al., 2007).

Hallmark et al. conducted a before and after crash analysis to verify the impact of paving shoulders. This study was performed in Iowa and included data from 1984 to 2007 for 220 roadway segments where 143 sections had paved shoulders and 77 were considered control sections without paved shoulders. Three linear models were used to investigate the crash reductions related to paving shoulders: one for total crashes, another for ROR crashes and one for single-vehicle ROR crashes. For the total crashes model, the decrease in crashes for sections with paved shoulders was 8.9% greater than for no treatment one year after treatment and 15.9% greater after 10 years of paving shoulder. For the ROR model, one year after treatment, 1.3% fewer crashes were observed for sections with paved shoulders and, after 10 years, sites with paved shoulders had 13.5% fewer crashes than control sites. For the single-vehicle ROR model, the decrease in crashes for sections with paved shoulders was 1.6% greater than for no treatment one year after treatment and 16.4% greater after 10 years of paving shoulder. (Hallmark et al., 2009).

An analysis of safety impacts of shoulder attributes using data on Illinois state-maintained highways from 2000 to 2006 was conducted in 2011. Conclusions showed that shoulder paving was most effective for multilane highways, followed by two-lane and Interstate highways, generally for an ADT from 5,000 to 10,000. Shoulder paving was found to be more effective in reducing shoulder-related injury and PDO crashes than shoulder-related fatal crashes. (Bamzai et al., 2011).

2.9 SHOULDER RUMBLE STRIPS AND STRIPES APPLIED AS COUNTERMEASURES TO REDUCE CRASHES

2.9.1 Introduction

Rumble strips and stripes are raised or grooved patterns that can be placed on the pavement surface of a roadway or shoulder. Figures 2.3 to 2.6 illustrate rumble strips and stripes. The main purpose of applying rumble strips to a pavement is to provide drivers with an audible and tactile warning that they may need to stop, slow down, or change lanes. Rumble strips also advise motorists that they are facing changes in the roadway alignment, such as horizontal curves, that they are leaving the traveled way or that they are facing an unexpected situation, as a recent change in traffic control devices. When vehicle tires pass over the rumble strip, noise is generated and generates an audible warning. The rumble strip also induces a vibration in the vehicle that provides a tactile warning for the driver. (Harwood, 1993).

Rumble strips have been used mainly on expressways and freeways, but some states install them on two-lane rural roads with a high number of single-vehicle crashes. Shoulder rumble strips are currently used in some states for improving safety at two-lane roads, but there are not enough studies regarding the effectiveness of this countermeasure for this case. (Neuman et al., 2003).

In the U.S., many states are conducting studies to evaluate the safety benefit of shoulder rumble strips and most of them are finding that they are effective on reducing single-vehicle ROR crashes. There are many different studies available for freeways, but for two-lane rural highways, the availability of published research is very limited. (Khan et al., 2014).

The analysis of shoulder rumble strips on two-lane roads is important because these roads usually have less clear zone and more hazardous roadsides, which means that a higher proportion of departures from the travel lane may become crashes. Also, the quality of the roadway alignment is generally worse on two-lane roads compared to freeways, requiring more warning features to keep drivers on the road. In addition, lane width on most freeways is 12 ft, while many high-speed two-lane rural roads have lane widths as narrow as 10 ft. (Neuman et al., 2003).

Locations where rumble strips can be used are diverse. They are placed in the traveled way, on roadway shoulders, or outside the traveled way. When in the traveled way, rumble strips may be used to alert drivers that they are approaching an intersection, toll plazas, horizontal curves, lane drops, work zones or other locations with unexpected conditions. (Harwood, 1993).

A Federal Highway Administration technical advisory states that at least four feet of paved shoulder should exist for applying rumble strips. Also, shoulder rumble strips should be placed on all rural highways that have posted speed 50 mph or greater. Urban or rural corridors where significant ROR crashes occur also should have rumble strips. (FHWA, 2011).

Shoulder rumble strips are placed on highway shoulders, outside of the travel lane. A typical example of shoulder rumble strip installation can be observed in Figure 2.3. In some cases, it is possible to install rumble strips along the edgeline of the roadway, and they are referred to as edgeline rumble strips or rumble stripes, as it can be seen in Figure 2.4. The main purpose of shoulder rumble strips is to avoid single vehicle run-off-road crashes. When vehicle tires pass over shoulder rumble strips, a sudden rumbling sound is produced and causes the vehicle to vibrate, alerting inattentive, drowsy, or sleeping drivers of encroachment on the shoulder and possibly onto the roadside. (Neuman et al., 2003). When highways are divided, rumble strips may be installed on the right shoulder and the left shoulder.

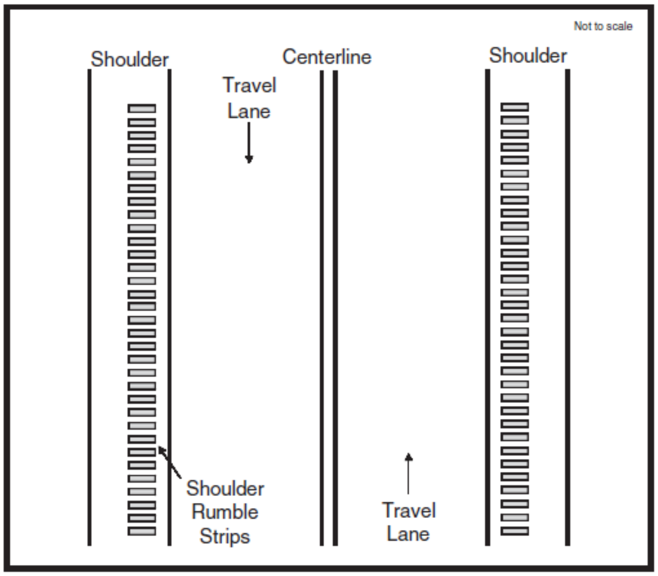

FIGURE 2.3 Typical shoulder rumble strip installation

SOURCE: Torbic et al., 2009

FIGURE 2.4 Rumble stripes

SOURCE: MnDOT, 2012

There are four basic types of rumble strips. They can be classified as milled-in, rolled-in, formed-in, and raised, and the main differences between them are the installation method, their shapes, and sizes. Each type of rumble strip produces a different amount of vibration and noise. (Torbic et al., 2009).

Milled-in rumble strips are the most frequently used by transportation agencies nowadays. Milled-in rumble strips can be implemented on existing, new, or reconstructed asphalt shoulders, thereby allowing greater flexibility for installation. Because the rumble strips are cut into the pavement, they can be installed equally well on new, existing, or reconstructed shoulders. Milled-in rumble strips are produced using a mechanical device with a rotary cutting head which results in a smooth, uniform, and consistent cut. The machine has a blade that is programmed to cut the same shape, depth, width, and length into the pavement. After the machine has cut the shape, the resulting debris is swept, collected, and discarded appropriately. (Perrillo, 1998). Figure 2.5 shows an example of milled-in rumble strips.

FIGURE 2.5 Milled-in rumble strips

SOURCE: Baxter, 2004

The main design parameters considered when applying rumble strips can be seen in Figure 2.6. They are: offset (A), length (B), width (C), depth (D), spacing (E), recovery area (F), gap (G), height (H – applies for raised rumble strips), lateral clearance (I), and departure angle (α). (Torbic et al., 2009).

States have developed several design dimensions for rumble strips, but usually they are 0.5 in deep, spaced 7 in apart, and cut into groups of four or five. (Neuman et al., 2003). Milled rumble strips have a continuous pattern and dimensions B=16 in, C=7 in, D=0.5 to 0.625 in, and E=12 in. The offset (A) vary widely from state to state. In Alabama, shoulder rumble strips are applied on urban (freeways and multilane divided) and rural (freeways, multilane divided, multilane undivided, and two-lane) roads. (Torbic et al., 2009).

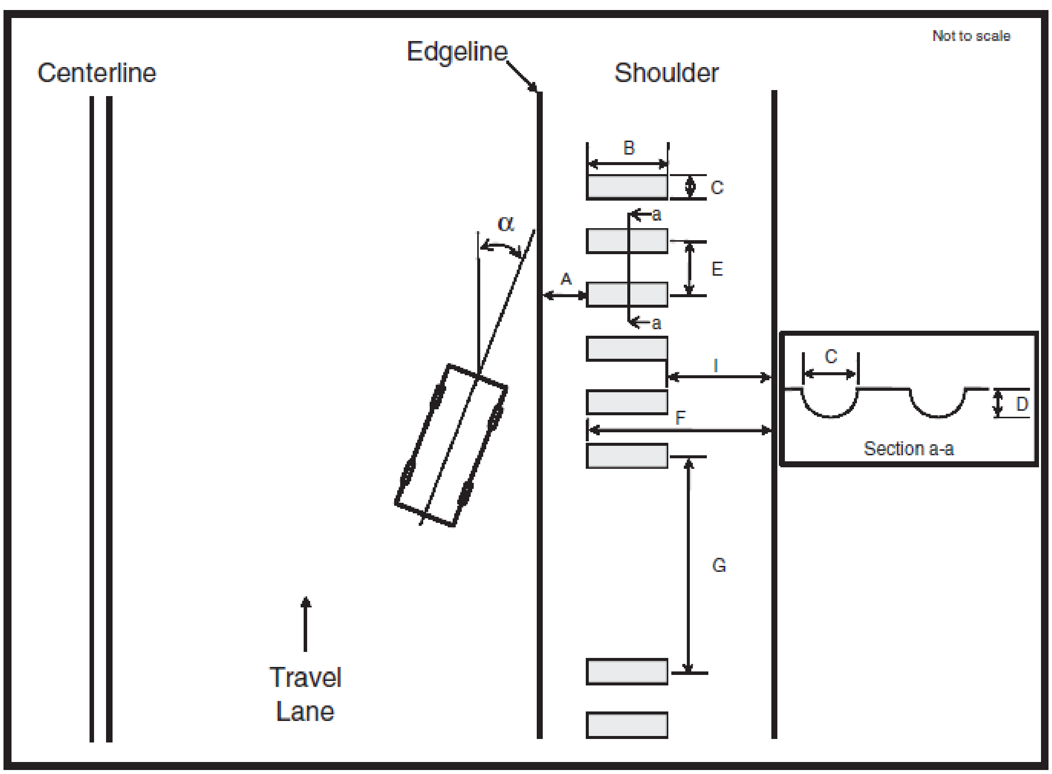

FIGURE 2.6 Design parameters associated with rumble strips

SOURCE: Torbic et al., 2009

2.9.2 Studies on the safety effectiveness of shoulder rumble strips and stripes

One of the earliest applications of rumble strips was conducted in New Jersey in 1955 on the Garden State Parkway. It considered shoulder rumble strips, at the time called the "singing shoulders". Rumble strips were made of textured concrete in Illinois during the mid 1960s, shoulder grooving was tested in Arizona in the early 1970s and Florida applied raised pavement markers as rumble strips on the highway to Key West during the late 1970s. More recently, rumble strips started to be placed continuously or at regular intervals along roadway shoulders. (Harwood, 1993).

In 1977, a study was conducted in the United Kingdom by the British Transport and Road Research Laboratory (TRRL) to investigate the effects of rumble strips on safety. This research considered 10 sites on main rural highways in the United Kingdom, including intersection approaches, roundabouts, horizontal curves, and sites at small towns considered to be critical. Results showed a decrease of 39% in total crashes and a decrease of 50% in related crashes after placement of rumble strips. (Sumner and Shippey, 1977).

The California Department of Transportation (Caltrans) conducted a study related to safety effects of rumble strips on asphalt shoulders for seven projects, which included 135 miles of rural freeway. Evaluation covered one year before and one year after the installation of rumble strips and it was based on the effects on run-off-road crashes. It was found a reduction of 63% on ROR crash rate for rumble strips on the right shoulder and a decrease of 18% for rumble strips on the left shoulder. In general, there was a 49% ROR crash rate reduction at sites where rumble strips were implemented, while the number of ROR crashes increased by 20% at control sites. (Chaudoin and Nelson, 1985). The application of these results is very limited, as only one year of data before and one year of data after were considered. Issues regarding crash fluctuations and RTM bias, for example, were not accounted for.

In 1985, the FHWA executed a before/after evaluation of rumble strips on both portland cement concrete and asphalt shoulders based on data from 10 sites in Arizona, California, Mississippi, Nevada, and North Carolina. Conclusions showed that there was a reduction of 20% of ROR crash rates while at control sites this rate increased by 9%. (Ligon et al., 1985).

In 1991, the Washington Department of Transportation investigated the effects of shoulder rumble strips at six locations, between 1986 and 1990. Raised pavement markings, raised rumble strips, and grooves rolled into the shoulder were analyzed. In general, crash frequency decreased by 18% after rumble strip installation. (WSDOT, 1991).

Between 1992 and 1996, the New York State Thruway Authority (NYSTA) installed continuous shoulder rumble strips on 3131 shoulder kilometers across the state. The crash data from the NYSTA provided one year (1991) of data before the rumble strips and one year (1997) of data after the installation of rumble strips. The reduction in ROR crashes was in a range from 65 to 70%. (Perrillo, 1998). Again, this unusual reduction in crashes may be, in part, a result of the short time period of analysis.

A study in Connecticut freeways showed that shoulder rumble strips reduced ROR crashes by 33%. It also showed that speed limit should be considered in the analysis, as in interchange areas the ROR crashes were reduced by 48.5% and on sections of roadways where the speed limit was less than 65 mph, ROR crashes were only reduced by 12.8% after rumble strips installation. The before period considered was from September, 1993 to August, 1996 and the after period was from June, 1997 to May, 2000. Approximately 1125 km were considered in the analysis. (Smith and Ivan, 2005).

Crash data on interstate highways and secondary roads in Utah were analyzed by Perrin (2006). The study included crash information from 2000 to 2002 in 68 sections in the state and considered the ROR crashes related to rumble strips. Utah data indicated that the sections of roadway without rumble strips experience a 23.6% higher crash rate than those with rumble strips. A reduction of 10 percent was found in crash-related costs for facilities containing rumble strips. This study recommended that rumble strips should be planned into projects on rural secondary roads where posted speeds are 50 mph or greater and an crash story of rumble strip related ROR crashes has been identified. It also proposed a minimum shoulder of 2 ft for installing rumble strips. (Perrin, 2006).

A study was conducted in Maine to report on the effectiveness of installing continuous shoulder rumble strips in rural Interstates. The analysis was based on how rumble strips could reduce ROR crashes. The evaluation showed that the countermeasure reduced 58% of sleep-related ROR. The overall effectiveness of continuous shoulder rumble strips was estimated to be 27% in respect to all ROR crashes. The study included data from 1994 to 2002 and covered 472 miles of highway segments. The study was a before-after analysis and used a control groups to compare the effects of rumble strips. (Garder and Davies, 2006).

A before-after study using the Empirical Bayes (EB) method in two-lane rural highways in Minnesota showed that rumble strips could reduce all single-vehicle ROR crashes by 13 percent and injury single-vehicle ROR crashes by 18 percent. Rumble strips were installed at 23 treatment sites, which represented 183 miles, and the database contained data from 1995 to 2001. (Patel et al., 2007).

A research project in Nevada evaluated the effectiveness of continuous shoulder rumble strips to reduce ROR crashes. The study included data from 1998 to 2004 in interstate freeways, U.S. routes, and state routes. A before-and-after study approach was used to evaluate the effectiveness of rumble strips. The study considered 370 segments of highways, which represented 1303 miles. This study showed that rumble strips have been effective in reducing the frequency of single-vehicle ROR crashes and corresponding crash rates. However, they did not include information related to traffic volume, vehicle miles of travel, and other variables that should be considered. (Nambisan et al., 2007).

In 2009, a report was published by the National Cooperative Highway Research Program (NCHRP) regarding, among other information, safety effectiveness of rumble strips. Data included sites in Minnesota, Missouri, and Pennsylvania. This research found that rolled shoulder rumble strips on urban and rural freeways were expected to reduce single vehicle run-off-road (SVROR) crashes by 18% and single vehicle run-off-road fatal and injury (SVROR FI) crashes by 13%. Also, milled shoulder rumble strips were expected to reduce SVROR crashes by 11% and SVROR FI crashes by 16% on rural freeways; to reduce SVROR crashes by 15% and SVROR FI crashes by 29% on rural two-lane roads; and to reduce SVROR crashes by 22% and SVROR FI crashes by 51% on rural multilane divided highways. (Torbic et al., 2009).

An analysis of the effectiveness of shoulder rumble strips was performed in British Columbia, Canada. Data were collected for three different groups of sites: treatment, comparison, and reference. The treatment group included 47 sites of undivided rural two-lane arterials and divided four-lane freeways. The comparison group had 225 sites and it was used to correct for the confounding factors of history and maturation. Different reference groups were considered, corresponding to rural two-lane arterials and divided four-lane freeways and three time periods: 2000 to 2002, 2001 to 2003, and 2002 to 2004. Shoulder rumble strips were found to reduce ROR collisions by 22.5 percent. (Sayed et al., 2010).

A study was conducted at the University of Texas at Austin to evaluate the effectiveness of shoulder rumble strips in reducing roadway departure crashes on two-lane rural highways using the Empirical Bayes (EB) Before-and-After analysis method. The database for this analysis considered crash data from 2001 to 2009 from the State of Idaho. The study found a 14% reduction in all ROR crashes after the installation of shoulder rumble strips on 178.63-miles of two-lane rural highways in Idaho. The results indicate that shoulder rumble strips were most effective on roads with relatively moderate curvature and right paved shoulder width of 3 feet and more. (Khan et. al., 2014).

2.9.3 Potential adverse effects of rumble strips and stripes

Some measures can be investigated to verify if rumble strips have adverse effects. Lateral positioning is one of the measures most often considered to evaluate the operational impacts to vehicular traffic that centerline rumble strips may cause. Most studies found that the installation of centerline rumble strips does impact the lateral positioning. (Torbic et al., 2009).

A study of fatal crashes in the state of Florida in 2000 showed that about one-third of the crashes involved running off the road as the first event, and more than 25% of the runoff- the-road (ROR) crashes involved overcorrection. Fewer than 20% of fatal ROR crashes occurred where rumble strips were present, but drivers were more than 50% more likely to overcorrect than when they were not present. On high-speed (more than 70 mph) roadways with rumble strips, there was almost an 80% higher risk of overcorrection in the crash. Therefore, rumble strips may be effective in preventing many ROR crashes, but the fact that audictory and vibratory sensations may be related to panic oversteering should also be investigated. (Spainhour and Mishra, 2008).

Noise is one of the main problems caused by vehicles passing over rumble strips. Shoulder rumble strips are less likely to disturb nearby residents because of noise, as it is generated only by errant vehicles and not for every vehicle. (Harwood, 1993). It is estimated that rolled-in rumble strips produce a low-frequency noise that increases the noise level by as much as 7dBA above the noise levels produced by traffic on normal pavements. (Higgins and Barbel, 1984). In 1993, a NCHRP report distributed a survey to highway agencies in the United States concerning the adverse effects caused by rumble strips. Among the 46 agencies that responded the survey, 16 reported receiving complaints from nearby residents related to noise generated when a vehicle traverses rumble strips. (Harwood, 1993). Most recent studies estimate that rumble strips generate 3 to 15 dBA of noise above the ambient noise level. (Torbic et al., 2009).

There are several measures to try to reduce the adverse effect of noise caused by vehicles passing over rumble strips. One suggestion is the use of noise barriers between the roadway and the residential areas. Another idea is to move the rumble strips further from the traveled lane, but this would result in less time and distance for drivers to react and correct their vehicle's path after they have passed over the rumble strips. Also, another interesting fact related to the noise is that some people who are unfamiliar with the sounds produced by rumble strips mistake the noise for car troubles, which could be solved by education campaigns on rumble strips. (Perrillo, 1998).

Rumble strips may also have adverse effects on pavements. In the NCHRP survey, several agencies reported that shoulder rumble strips could cause problems in snowplowing on the traveled way. After this fact, some agencies started placing rumble strips 2.5 ft from the edge of the traveled way. This NCHRP report also showed that shoulder rumble strips could create problems by disrupting drainage patterns on the shoulder and channeling water onto roadside slopes. When water is concentrated in the rumble strips, this also results in the erosion of the adjacent section. (Harwood, 1993). In 2008, the Minnesota Department of Transportation sent a survey to various local and state agencies to verify the effect of rumble strips in pavement deterioration. There was a general concern that pavement damage can be caused by grinding in rumble strips on an hot mix asphalt (HMA)pavement, and by the mere presence of rumble strips as they allow for water to pool on the pavement surface and increase the surface area of pavement exposed to the elements. (Watson et al., 2008). Most maintenance crews reported that heavy traffic would cause shoulder pavements with rumble strips to deteriorate faster and that the freeze-thaw cycle of water collecting in the grooves would crack the pavement. (Torbic et al., 2009).

Pavement markings may be affected by the placement of milled-in rumble strips. Some states place an asphalt fog seal over the rumble strips to prevent oxidation and moisture buildup. However, the application of the fog seal may prevent the edge line markings from adhering adequately.

Finally, bicyclist concerns were found in the NCHRP survey, as shoulder rumble strips may encourage bicyclists to ride in the traveled way where it would be preferable for them to use the shoulder. A space of 2 ft or more between traveled way and rumble strips was found to be ideal to provide bicyclists enough space to use the shoulder. (Harwood, 1993). However, increasing the distance from the rumble strip to the travel lane decreases the recovery area available to errant motor vehicles. (Torbic et al., 2009). Bicycles are generally not a concern on freeways, Interstates, and parkways, as most states prohibit bicycles on such facilities. (Perrillo, 1998).

2.10 SUMMARY OF CHAPTER 2

Run-off-road crashes represent more than 50% of total crashes in the United Stated and in Alabama. The crash severity scale applied to this study is the KABCO, as outlined in the *Highway Safety Manual*. Chapter 2 presented an overview of how safety effectiveness of countermeasures applied to reduce crashes can be evaluated. Also, the HSM predictive method applying the Empirical Bayes analysis was discussed, using both HSM SPFs and state-specific SPFs developed for Alabama conditions. An overview of the equivalent property damage only (EPDO) analysis was described as a method of evaluating crash reduction by severity. Zero-inflated models were discussed regarding its advantages and limitations when applied to crash data modeling. Finally, a summary of studies regarding the effects of paved shoulders, shoulder rumble strips and shoulder rumble stripes as countermeasures to reduce crashes was presented.

Chapter 3, Methodology, will discuss in details which procedures were applied to this study to document the state of the practice and results of prior research, to estimate reduction in run-off-road (ROR) crashes, by severity, based on the data, to develop crash modification factors for the five treatments considered in this study, to quantify the benefits and costs of the ALDOT policy, and to estimate ROR crash frequency on two-lane and multilane rural roads in Alabama, applying several statistical distributions to crash data.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Chapter 3 presents the methods applied in this study to reach the objectives listed in Chapter 1. A survey was developed to verify the state of the practice of the implementation of paved shoulders, shoulder rumble strips, and shoulder rumble stripes in two-lane rural roads in the United States.

In addition, a study was performed to evaluate the reduction in ROR in Alabama two and four-lane rural roads applying a predictive method and an analysis by crash severity. The dataset included 101 sites in the state of Alabama with shoulder width in a range from 2 to 4 ft. For two-lane rural roads, 40 sites had paved shoulder and shoulder rumble strips applied, 12 had paved shoulder and shoulder rumble stripes, and 31 had only the shoulder paved. For four-lane roads, 9 had paved shoulder and shoulder rumble strips implemented, and 9 had only the shoulder paved. Crash data were available from the software CARE 9 and CARE 10; three years of before treatment implementation data and three years of after data were considered in this analysis.

The predictive method applied to this study is the observational before-after Empirical Bayes (EB Method) described in the *Highway Safety Manual*. It is used to combine the estimation of expected average crash frequency from the statistical model with observed crash frequency at the specific site, and a weighting factor is applied to the two estimates to reflect the model's statistical reliability. An equivalent property damage-only (EPDO) analysis is performed to evaluate reduction in ROR crashes by severity. A benefit-cost analysis for each treatment is also developed.

Finally, crash data of 72 segments of two-lane rural roads and 32 segments of four-lane rural roads were modeled according to Poisson, negative binomial, zero-inflated Poisson and zero-inflated negative binomial distributions. Comparisons between models were based on the presence of overdispersion in the data and by comparing Vuong test statistics, AIC, and BIC values.

3.2 SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION IN THE UNITED STATES

This study developed a survey to determine the state of the practice of state departments of transportation in the United States regarding paved shoulders and shoulder rumble strips and stripes installation on rural highways. The survey was developed using the Qualtrics Survey Software. (Qualtrics, 2014). The agencies that completed the survey were:

a) Arizona Department of Transportation

b) Arkansas State Highway and Transportation Department

c) Delaware Department of Transportation

d) Hawaii Department of Transportation

e) Idaho Transportation Department

f) Iowa Department of Transportation

g) Kentucky Transportation Cabinet

h) Louisiana Department of Transportation and Development

i) Missouri Department of Transportation

j) Montana Department of Transportation

k) Nebraska Department of Roads

l) Nevada Department of Transportation

m) New Mexico Department of Transportation

n) North Carolina Department of Transportation

o) Ohio Department of Transportation

p) Oklahoma Department of Transportation

q) Rhode Island Department of Transportation

r) South Carolina Department of Transportation

s) Tennessee Department of Transportation

t) Texas Department of Transportation

Questions regarding their policies and studies to evaluate the effectiveness of their treatments were asked. The dimensions commonly applied to the treatments in each state were also reported, as observed in Figure 3.1 for shoulder rumble strips and Figure 3.2 for shoulder rumble stripes. The survey is shown in Appendix A.

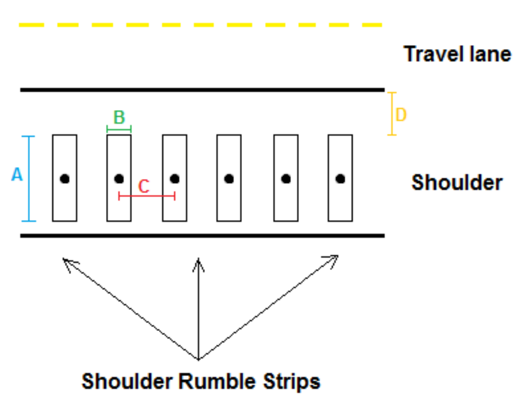

FIGURE 3.1 Shoulder Rumble Strips

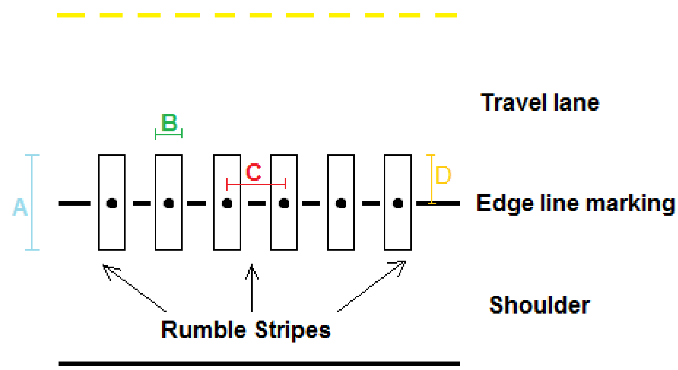

FIGURE 3.2 Shoulder Rumble Stripes

3.3 SAFETY EFFECTIVENESS OF THE IMPLEMENTATION OF PAVED SHOULDERS, RUMBLE STRIPS AND STRIPES ON RURAL ROADS IN ALABAMA

The ALDOT policy from 2006 stated that on two-lane rural roads, 2ft of full-depth pavement would be added on each side of the roadway, and in some cases, rumble strips should be scored into the pavement within the 2 ft shoulder. A list of these projects was provided by ALDOT. The information of all projects considered in this study was verified in the field, and the characteristics of the projects differed from what was stated in the policy. Projects included shoulder widening from 1 to 12 ft; number of lanes of 2, 4, and 6; treatments were paved shoulder only, paved shoulder combined with rumble strips, and paved shoulder combined with rumble stripes. The sheet used for verification of the geometric characteristics of the roadway segments can be seen in Appendix C.

3.3.1 Data description

After organizing groups of relevant sample size, this study provides an analysis of 101 projects representing 678 miles of two and four-lane divided rural roads in Alabama, with shoulder width in a range from 2 to 4 ft. Three treatments are evaluated: pavement widening without scoring, with rumble strips, and with rumble stripes. The five analyzed groups are:

1. Two-lane rural roads: 40 sites with combined paved shoulder and shoulder rumble strips;
2. Two-lane rural roads: 12 sites with combined paved shoulder and shoulder rumble stripes;
3. Two-lane rural roads: 31sites with paved shoulder
4. Four-lane divided rural roads: 9 sites with combined paved shoulder and shoulder rumble strips;
5. Four-lane divided rural roads: 9sites with paved shoulder .

The projects included in this study are listed in Tables 3.1 to 3.5 and illustrated in Figures 3.3 to 3.7.

Crash data were analyzed using the software Critical Analysis Reporting Environment (CARE) 9 and CARE 10 (CAPS, 2014). This analysis considered only roadway departure crashes; the Center for Advanced Public Safety (CAPS) at the University of Alabama, which develops CARE, defines a roadway departure crash according to the FHWA Office of Safety Design's Roadway Departure Team criteria: "a roadway departure crash is a non-intersection crash which occurs after a vehicle crosses an edge line, a centerline, or otherwise leaves the traveled way". According to the FHWA criteria, a roadway departure crash occurs when the first harmful event happens when a vehicle runs off the road or crosses a centerline or median and collides with an object. By definition, a head-on crash resulting of a vehicle crossing a centerline or median is also considered a roadway departure crash. For this study, centerline rumble strips were not evaluated as a treatment; therefore, the filter provided by CAPS was modified and only roadway departure crashes where the first harmful event was when the vehicle ran off the road to the right or left were considered. Three years of before treatment implementation data and three years of after data were considered in this analysis. Traffic data were obtained from the ALDOT traffic data website (ALDOT, 2014[2]). Safety effectiveness of the treatment is also determined and its statistical significance provides conclusions related to the importance of the treatment implementation. Finally, a benefit/cost analysis for each treatment is developed.

TABLE 3.1 Group 1: 40 projects with combined paved shoulders and shoulder rumble strips on two-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
6	3	STPAA-HSIP-0003(541)	AUTAUGA	196.00	208.00	12.00	2008	2009
5	3	EB-HSIP-0003(547)	CHILTON	208.20	216.10	7.90	2009	2010
6	5	HSIP-0005(522)	DALLAS	43.00	51.00	8.00	2009	2009
5	6	HSIP-0006(539)	PICKENS	22.00	30.30	8.30	2009	2010
6	6	STPAA-HSIP-0006(534)	BULLOCK	206.00	219.00	13.00	2008	2010
7	6	STPAA-HSIP-0006(537)	BARBOUR	226.00	238.00	12.00	2009	2010
1	7	HSIP-0007(518)	DEKALB	208.24	215.34	7.10	2008	2009
1	7	HSIP-STPAA-0007(528)	DEKALB	231.93	233.41	1.48	2010	2010
7	9	NHF-HSIPF-0009(519)	COVINGTON	12.00	19.00	7.00	2007	2007
7	9	HSIP-0009(526)	COVINGTON	25.00	34.00	9.00	2008	2008
6	9	STPAA-HSIP-0009(520)	ELMORE	131.00	140.00	9.00	2007	2008
4	9	HSIP-0009(531)	COOSA	147.80	156.40	8.60	2009	2009
1	9	NH-HSIP-0009(536)	CHEROKEE	264.60	268.20	3.60	2010	2010
8	10	STPOA-HSIP-0010(519)	WILCOX	83.01	91.25	8.24	2009	2010
6	10	STPAA-HSIP-0010(517)	BUTLER	105.00	123.00	18.00	2008	2009
6	10	99-306-074-010-001	BUTLER	123.00	125.00	2.00	2010	2010
7	10	STPAA-HSIP-0010(525)	BARBOUR	201.00	207.00	6.00	2010	2010
6	14	HSIP-0014(516)	ELMORE	181.00	189.00	8.00	2009	2009
4	21	HSIP-0021(526)	COOSA	179.20	188.30	9.10	2009	2009
7	27	HSIP-0027(508)	GENEVA	0.00	6.00	6.00	2010	2010
7	27	HSIP-0027(503)	DALE	48.00	55.00	7.00	2009	2009
6	49	HSIP-0049(501)	MACON	0.00	4.00	4.00	2008	2009
7	51	STPSA-0051(501)	COFFEE	0.00	6.00	6.00	2008	2008
7	51	STPAA-HSIP-0051(506)	BARBOUR	41.00	49.00	8.00	2009	2010
5	61	STPAA-HSIP-0061(504)	HALE	9.39	18.31	8.93	2008	2009

TABLE 3.1 (Continued) Group 1: 40 projects with combined paved shoulders and shoulder rumble strips on two-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
8	69	HSIP-0069(516)	CLARKE	22.57	30.44	7.87	2008	2009
2	74	NHF-HSIPF-0074(516)	WINSTON	54.00	56.82	2.82	2007	2008
7	87	STPAA-HSIP-0087(507)	GENEVA	10.00	16.00	6.00	2009	2009
7	87	STPAA-HSIP-0087(506)	PIKE	53.00	59.00	6.00	2009	2010
6	89	HSIP-0089(501)	DALLAS	3.00	12.00	9.00	2009	2009
7	95	HSIP-0095(500)	HOUSTON	23.00	25.00	2.00	2009	2009
5	118	STPAA-HSIP-0118(507)	LAMAR	0.00	9.21	9.21	2009	2010
7	134	HSIP-0134(502)	DALE	35.00	42.00	7.00	2008	2008
7	141	99-307-162-141-802	COFFEE	4.00	6.00	2.00	2006	2009
4	148	STPOA-HSIP-0148(502)	TALLADEGA	0.50	4.80	4.30	2010	2010
8	154	HSIP-0154(502)	CLARKE	16.14	21.88	5.74	2009	2010
7	165	HSIP-0165(501)	BARBOUR	0.00	6.00	6.00	2008	2009
7	166	STPSA-0166(500)	COFFEE	0.00	5.00	5.00	2008	2009
2	172	99-302-473-172-601	MARION	17.00	20.62	3.62	2006	2007
6	185	99-306-074-690-901	BUTLER	0.00	8.00	8.00	2009	2009

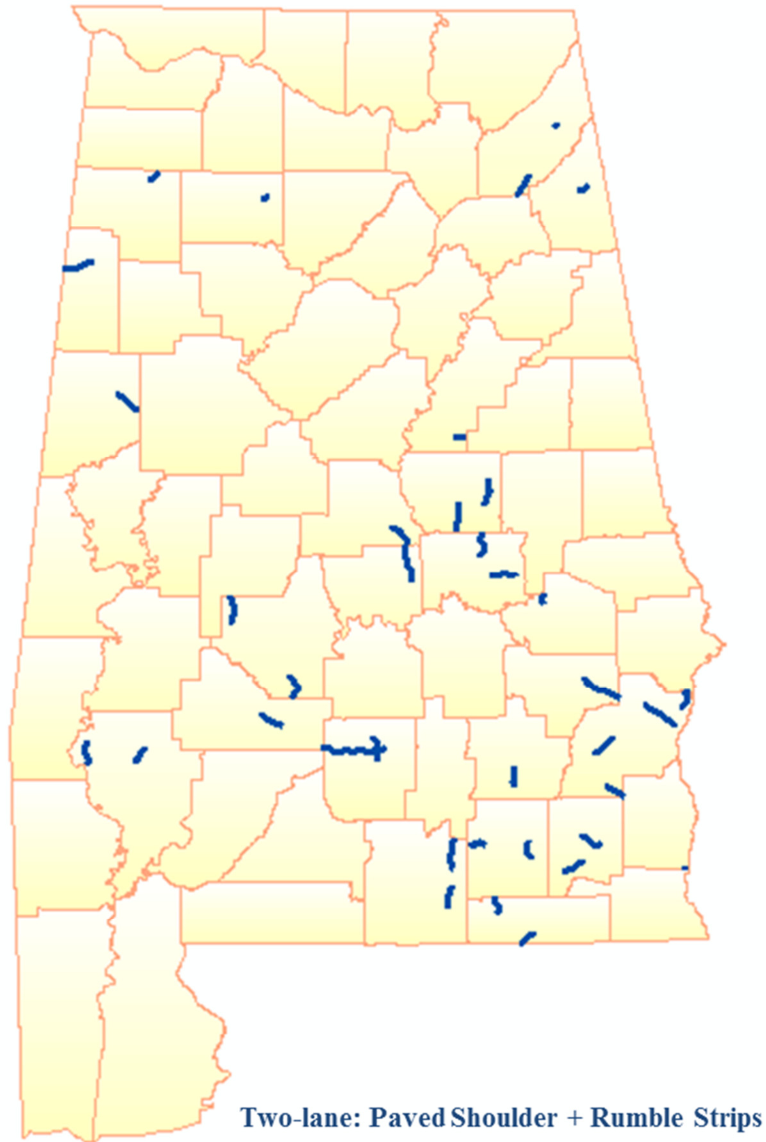

FIGURE 3.3 Group 1: 40 projects with combined paved shoulders and shoulder rumble strips on two-lane rural roads

TABLE 3.2 Group 2: 12 projects with combined paved shoulders and shoulder rumble stripes on two-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
6	3	STPAA-HSIP-0003(532)	MONTGOMERY	160.00	173.00	13.00	2007	2008
6	6	EBF-STPSAF-006(514)	AUTAUGA	115.00	125.00	10.00	2007	2008
6	8	HSIP-0008(545)	MONTGOMERY	145.00	153.00	8.00	2008	2009
8	25	99-308-462-025-606	MARENGO	5.58	10.07	4.49	2006	2007
8	28	HSIP-0028(504)	MARENGO	59.15	65.43	6.28	2008	2008
8	66	HSIP-0066(500)	MARENGO	0.08	4.33	4.25	2007	2008
8	69	HSIP-0069(512)	CLARKE	15.18	22.26	7.07	2007	2008
1	79	STPSA-0079(505)	MARSHALL	71.65	82.20	10.54	2007	2007
1	79	STPAA-HSIP-0079(507)	JACKSON	82.20	83.80	1.61	2007	2008
8	89	STPSA-0089(500)	WILCOX	0.00	3.14	3.14	2007	2007
6	229	EB-HSIP-0229(505)	ELMORE	16.00	23.00	7.00	2008	2009
6	263	EB-STPSA	BUTLER	0.00	7.00	7.00	2006	2007

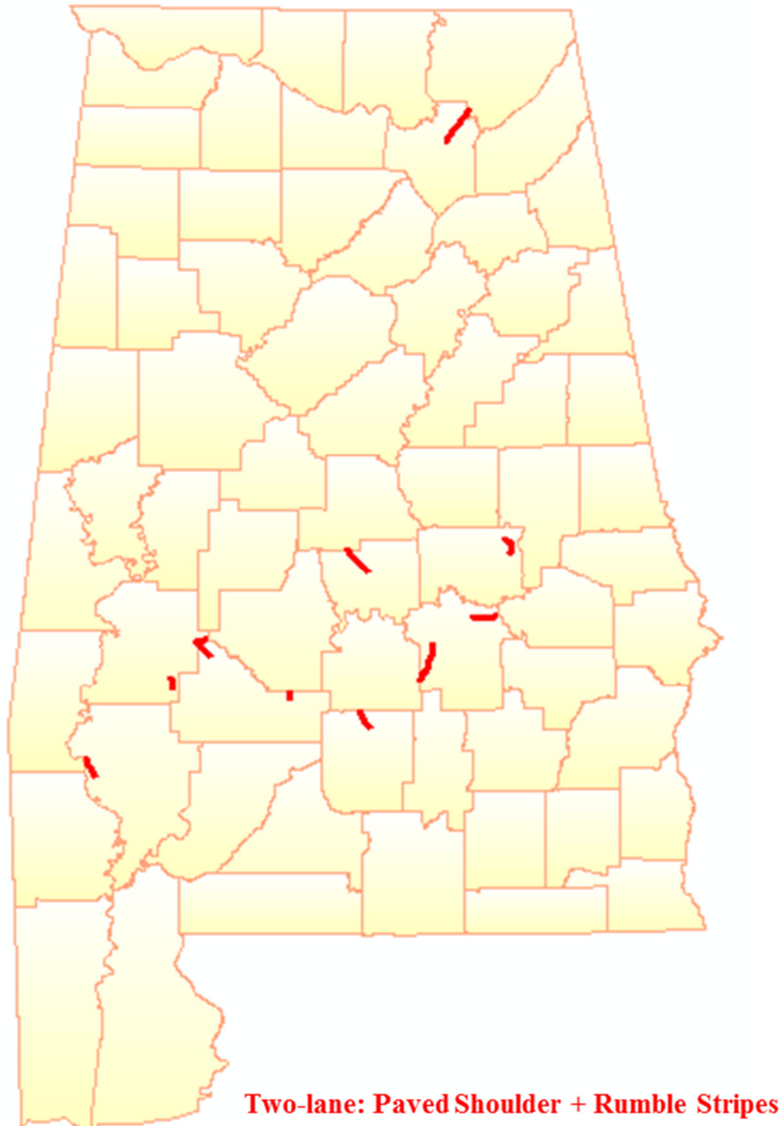

FIGURE 3.4 Group 2: 12 projects with combined paved shoulders and shoulder rumble stripes on two-lane rural roads

TABLE 3.3 Group 3: 31 projects with paved shoulders on two-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
3	3	EB-STPSA	SHELBY	245.67	252.45	6.78	2006	2007
5	5	HSIP-0005(518)	BIBB	76.74	83.10	6.36	2008	2008
5	7	99-305-323-007-601	GREENE	34.12	41.99	7.88	2006	2006
4	9	STPAA-HSIP-0009(522)	CALHOUN	219.30	230.15	10.85	2008	2010
5	13	NHF-HSIPF-0013(541)	GREENE	138.63	150.00	11.37	2007	2009
6	14	99-306-015-014-601	AUTAUGA	126.00	142.00	16.00	2006	2006
5	17	STPAA-HSIP-0017(523)	PICKENS	175.34	182.46	7.12	2008	2010
2	19	99-302-302-019-601	FRANKLIN	25.00	27.08	2.08	2007	2007
4	21	HSIP-0021(520)	TALLADEGA	204.50	207.40	2.90	2008	2009
3	25	STPSA	SHELBY	139.10	147.18	8.08	2006	2007
1	25	HSIP-0025(516)	ETOWAH	207.29	212.89	5.60	2008	2008
1	34	0034(500)	ESCAMBIA	0.90	4.69	3.79	2006	2007
2	36	99-302-402-036-601	LAWRENCE	9.00	10.88	1.88	2006	2006
2	36	99-301-521-036-602	MORGAN	13.00	16.25	3.25	2006	2006
2	67	99-301-521-067-802	MORGAN	28.00	35.67	7.67	2006	2006
1	68	STPAA-HSIP-0068(502)	CHEROKEE	41.30	46.04	4.74	2008	2008
1	74	NH-STPSA	CULLMAN	92.65	95.80	3.15	2006	2007
1	74	RECAF-HSIPF-0074(518)	BLOUNT	98.52	101.00	2.48	2008	2009
1	74	EBF-STPSAF	CHEROKEE, CLEBURNE	159.86	170.86	11.00	2006	2008
1	75	RECA-HSIP-0075(513)	DEKALB	65.20	77.80	12.60	2008	2009
1	91	99-301-224-091-703	CULLMAN	25.18	38.16	12.98	2006	2007
2	99	STPAA-HSIP-0099(503)	LIMESTONE	2.00	3.56	1.56	2010	2010
5	107	HSIP-0107(500)	FAYETTE	0.00	15.94	15.94	2008	2008
5	139	99-305-114-139-602	CHILTON	0.00	3.46	3.46	2006	2006

TABLE 3.3 (Continued) Group 3: 31 projects with paved shoulders on two-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
5	139	99-305-044-139-601	BIBB	3.46	12.58	9.13	2006	2007
1	144	STPAA-HSIP-0144(500)	ST. CLAIR	10.17	17.00	6.83	2010	2010
1	176	STPSA	DEKALB	0.00	13.67	13.67	2006	2008
6	199	HSIP-0199(500)	MACON	0.03	10.22	10.19	2008	2009
1	205	HSIP-0205(504)	MARSHALL	4.80	6.80	2.00	2008	2010
6	219	EB-STPSA	DALLAS	6.00	11.00	5.00	2007	2007
6	229	EB-STPSA-0229(502)	ELMORE	2.00	17.00	15.00	2007	2010

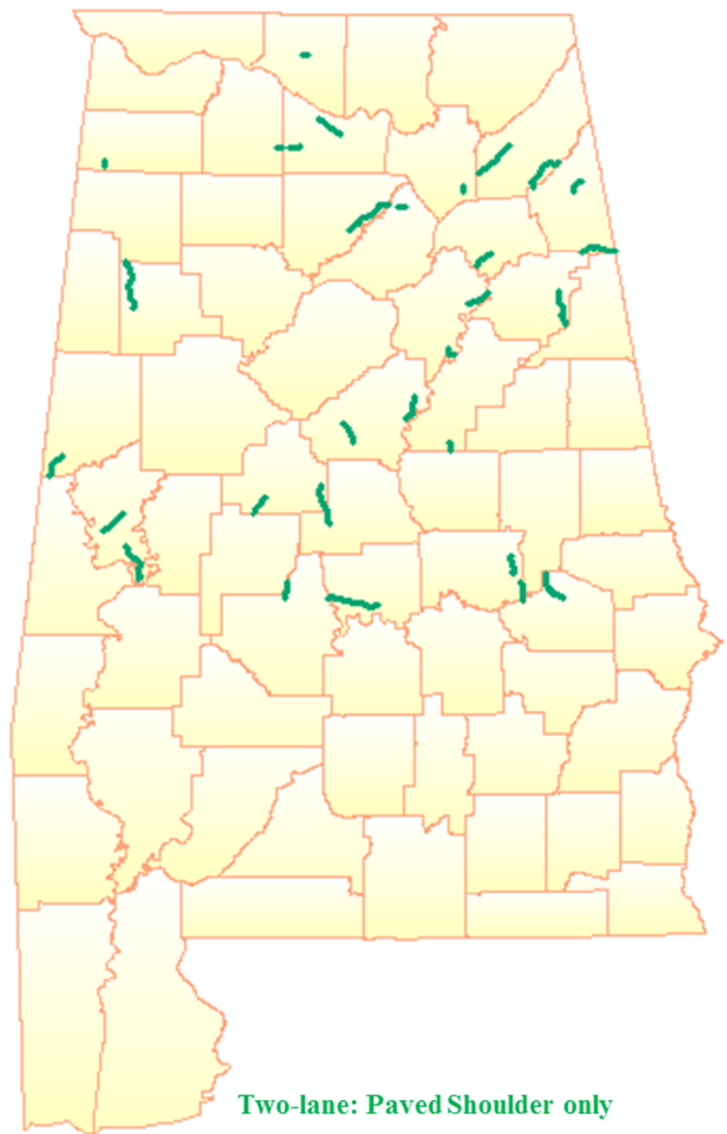

FIGURE 3.5 Group 3: 31 projects with paved shoulders on two-lane rural roads

TABLE 3.4 Group 4: 9 projects with combined paved shoulders and shoulder rumble strips on four-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
7	1	NHF-HSIPF-0001(535)	HOUSTON	17.00	23.00	6.00	2008	2008
7	1	NHF-HSIPF-0001(532)	HENRY	38.00	43.00	5.00	2007	2008
1	2	HSIPF-NHF-0002(532)	MADISON	108.60	114.20	5.60	2008	2009
1	2	NHF-HSIPF-0002(530)	JACKSON	114.20	121.04	6.84	2008	2009
6	6	EBF-STPSAF-0053(520)	MONTGOMERY	164.00	171.00	7.00	2008	2009
6	8	STPAA-HSIP-0008(551) (WB)	MACON	167.00	171.00	4.00	2009	2009
7	10	EBF-STPSAF	PIKE	172.00	178.00	6.00	2006	2007
7	53	NHF-HSIPF-0053(528)	HOUSTON	27.00	32.00	5.00	2008	2008
7	53	NHF-STPSAF-0053(525)	DALE	32.00	37.00	5.00	2007	2008

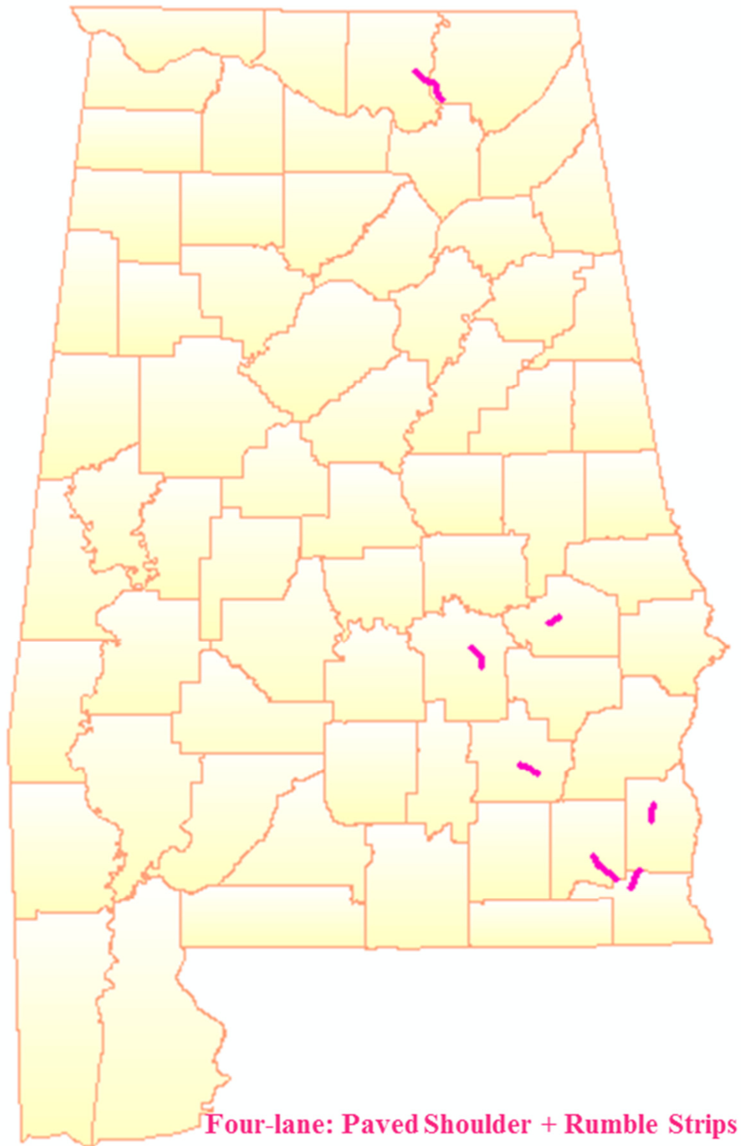

FIGURE 3.6 Group 4: 9 projects with combined paved shoulders and shoulder rumble strips on four-lane divided rural roads

TABLE 3.5 Group 5: 9 projects with paved shoulders on four-lane rural roads

Division	Route number	Project number	County	Begin MP	End MP	Segment Length (mi)	Year started	Year finished
1	1	STPOA-HSIP-0001(541)	ETOWAH	255.95	258.45	2.50	2009	2010
1	1	STPSA	ETOWAH	272.55	279.62	7.07	2006	2006
1	1	EBF-HSIPF-0001(540)	MADISON	346.73	352.96	6.23	2009	2010
2	3	STPAA-HSIP-0003(534)	MORGAN	348.00	349.97	1.97	2008	2008
2	3	STPAA-HSIP-0003(540)	MORGAN	353.00	354.77	1.77	2009	2009
2	3	STPAA-HSIP-0003(553)	LIMESTONE	362.00	362.51	0.51	2010	2010
6	8	STPAA-HSIP-0008(546) (WB)	DALLAS	84.00	88.00	4.00	2008	2008
1	53	EBF-STPSAF (SB)	MARSHALL	289.73	294.54	4.81	2006	2007
3	269	EB-STPSA	JEFFERSON	0.19	2.34	2.15	2006	2006

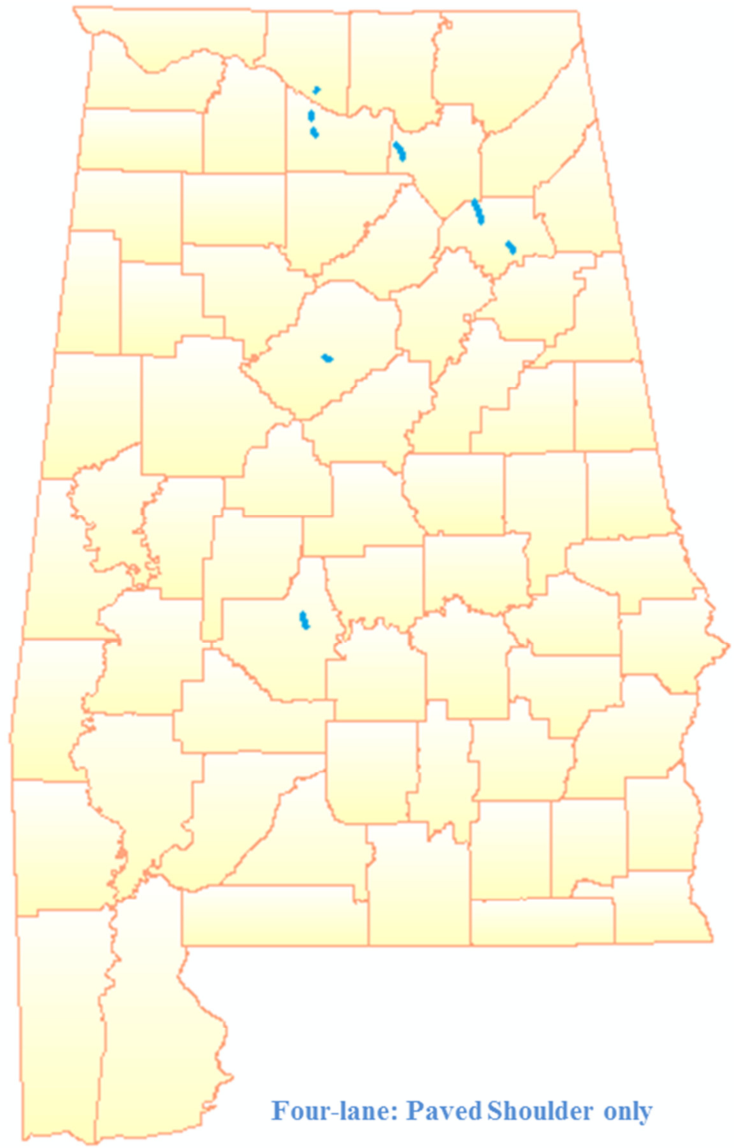

FIGURE 3.7 Group 5: 9 projects with paved shoulders on four-lane divided rural roads

3.3.2. Quality safety effectiveness evaluation

After defining the groups of projects to be analyzed in this study, the safety effectiveness of the implemented countermeasures on two and four-lane rural roads in Alabama was estimated. A common practice to determine the effectiveness of a treatment is by estimating crash modification factors applying before-after studies.

CMFs resulting from before-after studies are based on the change in safety performance due to the implementation of a treatment. Some issues regarding the quality of the CMFs from these studies are mainly related to the sample size, and to confounding variables. A low standard error of the CMF estimate is desired, and the standard error decreases as the sample size increases; therefore, the uncertainty of the CMF estimate can be reduced by increasing the sample size. Also, the observed change in crash occurrence at treated sites between the periods before and after treatment implementation may be due not only to the countermeasure, but to other factors as well, such as traffic volume changes, changes in reported crash experience, and the regression-to-the-mean bias. (Gross et al., 2010).

FHWA published a guide for developing quality CMF estimates. The Empirical-Bayes (EB) method as outlined in the *Highway Safety Manual* is one of the suggested methods to overcome the issues related to before-after studies. (Gross et al., 2010). Section 3.3.3 of this dissertation describes the estimation of CMFs applying the EB method to this study using the *Highway Safety Manual* safety performance functions; it can be seen in section 3.3.4 the EB analysis applying state-specific SPFs.

3.3.3 Highway Safety Manual Empirical-Bayes analysis applying the HSM SPFs

The analysis of the safety effectiveness of the applied treatments The *Highway Safety Manual* uses predictive methods for crash estimation and safety evaluation. The HSM predictive method estimates the expected average crash frequency of a site, facility or roadway network for a given time period, geometric design and traffic control features, and traffic volumes (AADT), by total crashes, crash severity, or collision type. (AASHTO, 2010).

The expected average crash frequency, $N_{expected}$, is estimated using a predictive model estimate of crash frequency, $N_{predicted}$ and observed crash frequency, $N_{observed}$. There are two main elements of the HSM predictive method. The first element is a predictive model estimate of the average crash frequency for a specific site type, which is done using a Safety Performance Function (SPF) developed from data for a number of similar sites. The model is adjusted to account for specific site conditions and local conditions. The second element is the use of a method, Empirical-Bayes (EB), to combine the estimation from the statistical model with observed crash frequency at the specific site. A weighting factor is applied to the two estimates to reflect the model's statistical reliability. (AASHTO, 2010).

This study applies the Safety Performance Functions (SPF) for two and four-lane divided rural roads available in the Highway Safety Manual.

a) Analysis during the before period

The SPF for two-lane rural roads can be observed in Equation 3.1, and the corresponding overdispersion parameter is shown in Equation 3.2. For multilane divided rural roads, the SPF is shown in Equation 3.3, and the overdispersion parameter is estimated as seen in Equation 3.4. For crash data, the variance typically exceeds the mean, which shows overdispersion. The degree of overdispersion is represented by the overdispersion parameter, which is estimated along with the coefficients of the regression equation. The larger the overdispersion parameter, the more the crash data vary as compared to a distribution where mean and variance are equal. (AASHTO, 2010).

$$N_{spf,2l,B} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312} \quad \text{(Equation 3.1)}$$

$$k_{2l} = \frac{0.236}{L} \quad \text{(Equation 3.2)}$$

$$N_{spf,ml} = e^{(a+b\times\ln(AADT)+\ln(L))} \quad \text{(Equation 3.3)}$$

$$k_{ml} = \frac{1}{e^{(c+\ln(L))}} \quad \text{(Equation 3.4)}$$

Where:

N_{spf} = estimated total crash frequency for roadway segment base conditions in a two-lane or multilane rural road;

$AADT$ = average annual daily traffic volume (vehicles per day);

L = length of roadway segment (miles).

The parameters a, b and c for the multilane divided SPF can be estimated for prediction of total crashes as -9.025, 1.049, and 1.549, respectively. (AASHTO, 2010).

Crash Modification Factors (CMFs) and calibration factors (C) are used to correct the HSM safety performance function to the analyzed roadway segments specific conditions that differ from base conditions. Equation 3.5 shows the predicted number of crashes after CMF and calibration factor corrections. CMFs were used in this study for lane and shoulder widths, from HSM tables, varying according to AADT for each segment (AASHTO, 2010). Calibration factors were developed by Mehta and Lou, and it is estimated as 1.522 for two-lane rural roads and 1.863 for four-lane divided rural roads (Mehta and Lou, 2014).

$$N_{predicted,B} = N_{spf\ x} \times \left(CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}\right) \times C_x \qquad \text{(Equation 3.5)}$$

The focus of this study is the analysis of run-off-road crashes, and it is important to separate the predicted crashes by severity and type. The SPF in the HSM estimates total crashes, not considering only ROR crashes, and not dividing them by severity. Therefore, CARE 9 and CARE 10 were used to estimate the percent of total crashes that are run-off-road, and the percent of ROR crashes by severity. A dataset of all crashes of all two-lane rural roads in Alabama, from 2001 to 2013, was used, including approximately 320,000 crashes. Also, a dataset for all crashes of all four-lane divided rural roads in the state was analyzed, and it included approximately 110,000 crashes. Table 3.6 shows that 48.23% of all crashes in Alabama are ROR crashes on two-lane rural roads. On four-lane divided rural roads, 35.73% of crashes are ROR. Also, for two-lane rural roads, of the ROR crashes, 2.20% are fatal, 25.48% are incapacitating injuries, 8.57% are non-incapacitating injuries, 4.65% are possible injuries, and 59.10% are property damage only. For four-lane divided rural roads, of the ROR crashes, 1.73% are fatal, 20.05% are incapacitating injuries, 6.47% are non-incapacitating injuries, 4.08% are possible injuries, and 67.67% are property damage only.

TABLE 3.6 Percent of ROR crashes by severity in Alabama

Crash Type/Severity	2-LANE RURAL ROR	4-LANE RURAL ROR
% ROR Crashes	48.23	35.73
K	2.20	1.73
A	25.48	20.05
B	8.57	6.47
C	4.65	4.08
O	59.10	67.67

The EB Method can estimate expected average crash frequency for before and after periods of the treatment implementation. It can be used at site-specific level or project-specific level. For an individual site, the EB Method combines the observed crash frequency with the predictive model estimate, as observed in Equation 3.6:

$$N_{expected,B} = w_{i,B} \times \sum_{before\ years} N_{predicted,B} + \left(1 - w_{i,B}\right) \times \sum_{before\ years} N_{observed,B} \quad \text{(Equation 3.6)}$$

Where:

$\sum_{before\ years} N_{predicted,B}$ = expected average crash frequency at site i for the entire before period;

$w_{i,B}$ = weighted adjustment factor for site i;

$\sum_{before\ years} N_{observed,B}$ = observed crash frequency at site i for the entire before period.

The weighted adjustment factor, w, is a function of the SPF's overdispersion parameter, k, to combine the two estimates, which makes w dependent only on the variance of the SPF model. The weighted adjustment factor can be calculated using Equation 3.7. The EB method pulls the crash count towards the mean, accounting for RTM bias. The expected crash frequency will lie somewhere between the observed crash frequency and the predicted crash frequency from the SPF. The overdispersion of the data affects the weight. The lower the overdispersion parameter is, the more weight will go to the observed data; conversely, the higher the overdispersion parameter is, the more the weight will go to the average predicted by the SPF.

$$w_{i,B} = \frac{1}{1 + k \times \left(\sum_{before\ years} N_{predicted,B}\right)} \quad \text{(Equation 3.7)}$$

Where:

k = overdispersion parameter

<u>b) Analysis during the after period</u>

The same SPF for the before period is used to estimate the total crash frequency for each roadway segment, with AADT values for the after period.

The expected average crash frequency at the specific site for the after period, if the treatment was not implemented, can be estimated by Equation 3.8. An adjustment factor (*r*) to account for differences between the before and after periods in duration and traffic volume at each considered site needs to be calculated.

$$N_{expected,A} = N_{expected,B} \times r_i \quad \text{(Equation 3.8)}$$

Where:

$N_{expected,A}$ = expected average crash frequency at site *i* for the entire after period in the absence of the treatment;

r_i = adjustment factor to account for the differences between the before and after periods in duration and traffic volume at each site *I*, calculated by Equation 3.9.

$$r_i = \frac{\sum_{after\ years} N_{predicted,A}}{\sum_{before\ years} N_{predicted,B}} \qquad \text{(Equation 3.9)}$$

<u>c) Safety effectiveness of the treatment</u>

An estimate of the safety effectiveness of the treatment at each site *i* can be calculated in the form of an odds ratio, OR_i, as shown Equation 3.10. An odds ratio is a measure of association between an exposure and an outcome. It represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure. In this study, the odds ratio compares the number of crashes observed in the after period, with the countermeasure, to the expected number of crashes in the after period if the treatment was not implemented.

$$OR_i = \frac{\sum_{after\ period} N_{observed,A}}{N_{expected,A}} \qquad \text{(Equation 3.10)}$$

Where:

OR_i = odds ratio at site *i*;

$\sum_{after\ period} N_{observed,A}$ = observed crash frequency at site *i* for the entire after period.

The safety effectiveness as a percentage crash change at site *i* can be calculated by Equation 3.11.

$$Safety\ Effectiveness_i = 100 \times (1 - OR_i) \quad \text{(Equation 3.11)}$$

The overall effectiveness of the treatment for all sites combined can be represented in the form of an odds ratio, OR', as it can be seen in Equation 3.12.

$$OR' = \frac{\sum_{all\ sites} \sum_{after\ period} N_{observed,A}}{\sum_{all\ sites} N_{expected,A}} \quad \text{(Equation 3.12)}$$

The overall effectiveness calculated in Equation 3.12 is potentially biased. When one or more values of expected crash frequency can have a small value, the odds ratio can be biased and exhibit high variance. The HSM suggests the adjustment shown in Equation 3.13 to obtain an unbiased estimate of the treatment effectiveness in terms of an adjusted odds ratio, OR.

$$OR = \frac{OR'}{1 + \frac{Var(\sum_{all\ sites} N_{expected,A})}{(\sum_{all\ sites} N_{expected,A})^2}} \quad \text{(Equation 3.13)}$$

Where:

$$Var\left(\sum_{all\ sites} N_{expected,A}\right) = \sum_{all\ sites} [(r_i)^2 \times N_{expected,B} \times \left(1 - w_{i,B}\right)] \quad \text{(Equation 3.14)}$$

The odds ratio (OR) represents the CMF for the treatment on the considered two-lane rural road segments. CMFs for paved 2-4 ft shoulder, for the combined effect of paved 2-4ft shoulder and applying rumble strips, and for the combined effect of paved 2-4ft shoulder and applying rumble stripes are calculated in this study for two-lane rural roads. It is important to note that the pavement of the project sites in this study was resurfaced, and the friction factor was possibly higher from before to after periods, which could influence the occurrence or ROR crashes; however, it was not possible to factor this effect out, as all sites were resurfaced.

The overall unbiased safety effectiveness is determined as a percent change in crash frequency across all sites, as it can be observed in Equation 3.15:

$$Safety\ Effectiveness = 100 \times (1.00 - CMF) \qquad \text{(Equation 3.15)}$$

It is necessary to assess whether the estimated safety effectiveness of the treatment is statistically significant. The precision of the CMF estimation needs to be calculated first, which is done by calculating its variance and standard error according to Equations 3.16 and 3.17.

$$Var(CMF) \qquad \text{(Equation 3.16)}$$

$$= \frac{(OR')^2 \left[\frac{1}{\sum_{all\ sites} \sum_{after\ period} N_{observed,A}} + \frac{Var\left(\sum_{all\ sites} N_{expected,A}\right)}{\left(\sum_{all\ sites} N_{expected,A}\right)^2} \right]}{1 + \frac{Var\left(\sum_{all\ sites} N_{expected,A}\right)}{\left(\sum_{All\ sites} N_{expected,A}\right)^2}}$$

$$SE(CMF) = \sqrt{Var(CMF)} \qquad \text{(Equation 3.17)}$$

The standard error of the safety effectiveness can then be computed by Equation 3.18:

$$SE(Safety\ Effectiveness) = 100 \times SE(CMF) \qquad \text{(Equation 3.18)}$$

According to the HSM, if the absolute value of the ratio of Safety Effectiveness by the SE(Safety Effectiveness) is lower than 1.7, the treatment effect is not significant at the approximate 90 percent confidence level; if the ratio is greater than or equal to 1.7, the treatment effect is significant at the approximate 90 percent confidence level; and if the ratio is greater than or equal to 2.0, the treatment effect is significant at the approximate 95 percent confidence level.

3.3.4 Highway Safety Manual Empirical-Bayes analysis applying state-specific SPFs

There are SPFs for the studied conditions in the HSM; however, it is recommended that state-specific SPFs should be applied, when available. Four different SPFs were developed to the Alabama conditions. Model 1 keeps the form of HSM base SPF, and can be applied to this study. Model 2 considered minor junctions as a variable for average crash frequency estimation; the role of intersections junctions is not enough to choose this model instead of the simple form of Model 1. Model 3 involves variables not available in the present study dataset; therefore, is not the best model to be applied. Finally, Model 4 considers shoulder width as a variable to estimate average crashes; the sites in this study do not have a wide range of shoulder widths, and therefore, this effect is not considered. For those reasons, Model 1 will be the considered model for Alabama SPF in this study.

The model for two-lane rural roads used in this study will be the one shown in Equation 2.5. The estimated total crashes for the before period will be calculated for each site during each year of the before period, as it can be observed in Equation 3.19.

$$\widehat{\mu_{i,2l,B}} = exp(-7.135)AADT_{i,B}^{0.916}SL_i \qquad \text{(Equation 3.19)}$$

Where:

$\widehat{\mu_{i,2l,B}}$ = estimated total crash frequency for roadway segment *i* for the before period;

$AADT_{i,B}$ = average annual daily traffic volume for site i, for the before period (vehicles per day).

As this equation was developed specifically for the state of Alabama, no CMFs or calibration factors should need to be applied. Therefore, the predicted crash frequency is the same as the estimated crash frequency, as it can be seen in Equation 3.20. Predicted crash frequency should be calculated for each site during each year of the before period. After that, a sum of all predicted crash frequencies over the before years is required for later calculations.

$$N_{predicted,B} = \widehat{\mu_{i,2l,B}} \quad \text{(Equation 3.20)}$$

Where:

$N_{predicted,B}$ = predicted average crash frequency for a specific year for site type *x* for the before period.

For the after period, same SPF is applied, as shown in Equation 3.21. The overdispersion parameter was estimated as 1.09 by the Mehta and Lou study for the considered SPF.

$$\widehat{\mu_{i,2l,A}} = exp(-7.135)AADT_{i,A}^{0.916}SL_i \quad \text{(Equation 3.21)}$$

Where:

$\widehat{\mu_{i,2l,A}}$ = estimated total crash frequency for roadway segment *i* for the after period;

$AADT_{i,A}$ = average annual daily traffic volume for site i, for the after period (vehicles per day).

The predicted average crash frequency for the after period is calculated by Equation 3.22, and it should be done for each site during each year of the after period. After that, a sum of all predicted crash frequencies over the after years is required for later calculations.

$$N_{predicted,A} = \widehat{\mu_{i,2l,A}} \qquad \text{(Equation 3.22)}$$

Where:

$N_{predicted,A}$ = predicted average crash frequency for a specific year for site type x for the after period.

The steps to analyze four-lane rural roads according to the HSM are the same for two-lane rural roads. However, the SPF and overdispersion parameter change. Equations 3.23 and 3.24 show the estimated average crash frequencies for the before and after periods, respectively. The overdispersion parameter for this SPF is 2.854.

$$\widehat{\mu_{i,4l,B}} = exp(-7.706)AADT_{i,B}^{0.974}SL_i \qquad \text{(Equation 3.23)}$$

$$\widehat{\mu_{i,4l,A}} = exp(-7.706)AADT_{i,A}^{0.974}SL_i \qquad \text{(Equation 3.24)}$$

Where:

$\widehat{\mu_{\iota,4l,B}}$ = estimated total crash frequency for roadway segment base conditions in a four-lane divided rural road for the before period;

$\widehat{\mu_{\iota,4l,A}}$ = estimated total crash frequency for roadway segment base conditions in a four-lane divided rural road for the after period;

3.3.5 EPDO Analysis

For the equivalent property damage only (EPDO) analysis, each crash is weighted based on the crash severity and the equivalent property damage only crash cost. Crash cost estimates for this study are from a National Highway Traffic Safety Administration (NHTSA) study, as shown in Table 3.7. (Blincoe et al., 2014). The number of crashes by severity is multiplied by the EPDO factor for the period before treatment implementation and for the period after treatment implementation. The comparison of the EPDO before and EPDO after can give an overview of the safety effectiveness of the considered treatment in respect to crash severity.

TABLE 3.7 Crash cost estimates by crash severity

Crash Severity	Comprehensive Costs (Dollars)	EPDO factor
K	\$9,145,998	203
A	\$1,012,161	22
B	\$284,399	6
C	\$135,123	3
O	\$45,140	1

SOURCE: Blincoe et al., 2014

3.3.6 Benefit-cost analysis

The Benefit-Cost Ratio (BCR) is the ratio between treatment benefits and costs. Treatment benefits can be estimated in a monetary value, according to the average change in crash frequency. Table 3.7 gives the approximate monetary value for avoiding crashes, by severity. (Blincoe et al., 2014). This study considers the monetary values of avoiding crashes, by severity, as the benefits of treatment implementation. The costs were given by ALDOT, in the Tabulation of Bids. (ALDOT, 2014). Because the costs provided by ALDOT were general to all projects and constant over the years, no inflation was considered in the calculations, and this analysis is an approximate estimate of benefit-cost ratios. Since cost data were not provided specific to each project, it was not possible to adjust them for inflation.

3.4 ZERO-INFLATED MODELS APPLIED TO ALABAMA CRASH DATA

There are several distributions and model forms that can be applied to crash data modeling, it is challenging to define which one is the most appropriate. In theory, a crash can be represented by a Bernoulli trial, being a “success” when there is a crash and a “failure” when there is no crash. The binomial distribution is the probability model that accounts for a series of Bernoulli trials. The binomial distribution can be approximated by a Poisson distribution when the event has a very low probability of occurrence and a large number of trials exist, as it is the case when several vehicles enter the roadway network that contains numerous segments of roads, for example. However, applying the Poisson distribution to crash data has limitations; it assumes that mean and variance of data are equal, which is usually not true for crash data. Crash data has variance usually exceeding the mean, characteristic defined as overdispersion, which makes the negative binomial distribution more suitable for modeling.

The safety performance functions in the HSM were developed assuming a negative binomial distribution. The state-specific SPFs for Alabama were also modeled based on a negative binomial distribution.

However, crash data are often characterized by “excess” zeros; therefore, dual-state models such as zero-inflated models could be a good alternative for data modeling. This study applied the traditional Poisson and negative binomial distributions to Alabama crash data, as well as the dual-state zero-inflated Poisson (ZIP) and zero-inflated negative binomial (ZINB) distributions.

The comparison of all distributions fitted to Alabama data allowed for the modeling of state-specific safety performance measures considering the distribution that best fit the data. The safety performance functions are recommended for estimating ROR crashes on two and four-lane rural roads. Base conditions considered segments of two and four-lane roads in Alabama that did not have paved shoulders or shoulder rumble stripes or stripes.

3.4.1 Data Description

This study includes data for 72 segments of two-lane rural roads and 32 segments of four-lane divided rural roads in Alabama. Data were collected from 2001 to 2010, which represents 720 observations (one segment for one year) of two-lane roads and 320 observations (one segment for one year) of four-lane divided roads. Segments evaluated in this study were homogeneous and did not have paved shoulders, shoulder rumble stripes or shoulder rumble stripes. Run-off-road crash data were obtained using the software CARE 9 and CARE 10 (CAPS, 2014). Traffic data were obtained from the Alabama Department of Transportation (ALDOT) traffic data website (ALDOT, 2014). No significant change on AADT was observed over the years.

The distribution of the frequency of crashes on two-lane rural roads in Alabama can be seen in Table 3.8. The frequency of crashes was zero for 17.92% of the observations. The histogram in Figure 3.8 shows the crash frequency distribution on two-lane rural roads in Alabama.

TABLE 3.8 Frequency of ROR crashes on two-lane rural roads in Alabama

Number of Crashes	Frequency	Percent
0	129	17.92
1	133	18.47
2	98	13.61
3	79	10.97
4	59	8.19
5	36	5.00
6	38	5.28
7	30	4.17
8	22	3.06
9	22	3.06
10	17	2.36
11	10	1.39
12	7	0.97
13	8	1.11
14	6	0.83
15	8	1.11
16	1	0.14
17	3	0.42
18	2	0.28
19	2	0.28
20	3	0.42
21	1	0.14
22	1	0.14
24	1	0.14
25	1	0.14
27	2	0.28
31	1	0.14
TOTAL	720	100.00

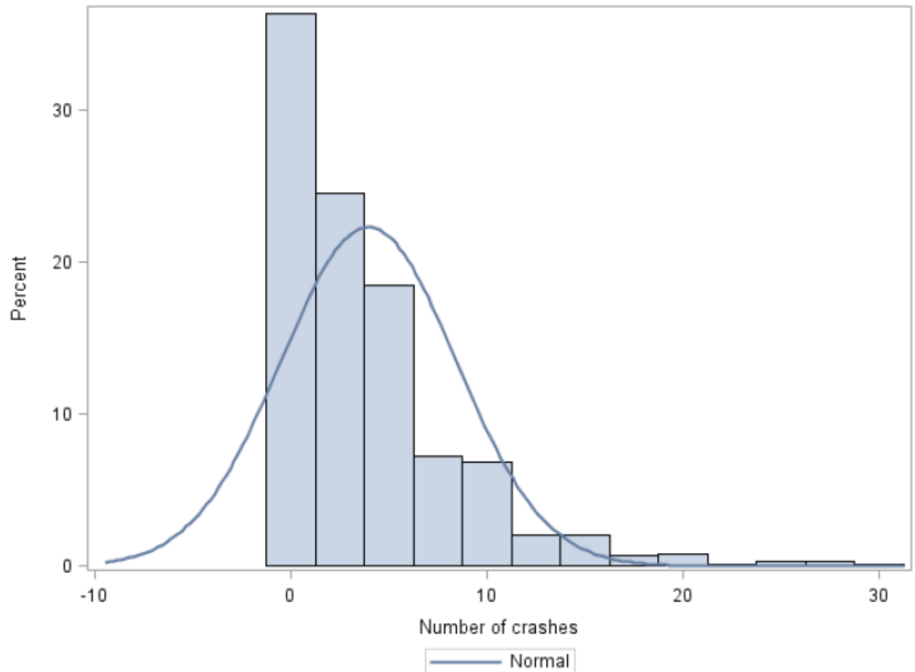

FIGURE 3.8 Histogram of ROR crashes on two-lane rural roads in Alabama

For four-lane divided rural roads in Alabama, Table 3.9 shows that for 20.00% of the observations, crash frequency is zero. The histogram on Figure 3.9 illustrates the crash frequency distribution on four-lane divided rural roads in Alabama. The high frequency of zero-crash segments for both two-lane and four-lane roads was a motivation for implementing zero-inflated models and evaluating if they fit data better than the more commonly used distributions.

TABLE 3.9 Frequency of ROR crashes on four-lane rural roads in Alabama

Number of Crashes	Frequency	Percent
0	64	20.00
1	47	14.69
2	36	11.25
3	32	10.00
4	21	6.56
5	22	6.88
6	11	3.44
7	20	6.25
8	11	3.44
9	8	2.50
10	13	4.06
11	7	2.19
12	4	1.25
13	11	3.44
14	5	1.56
16	3	0.94
17	2	0.63
19	2	0.63
21	1	0.31
TOTAL	320	100.00

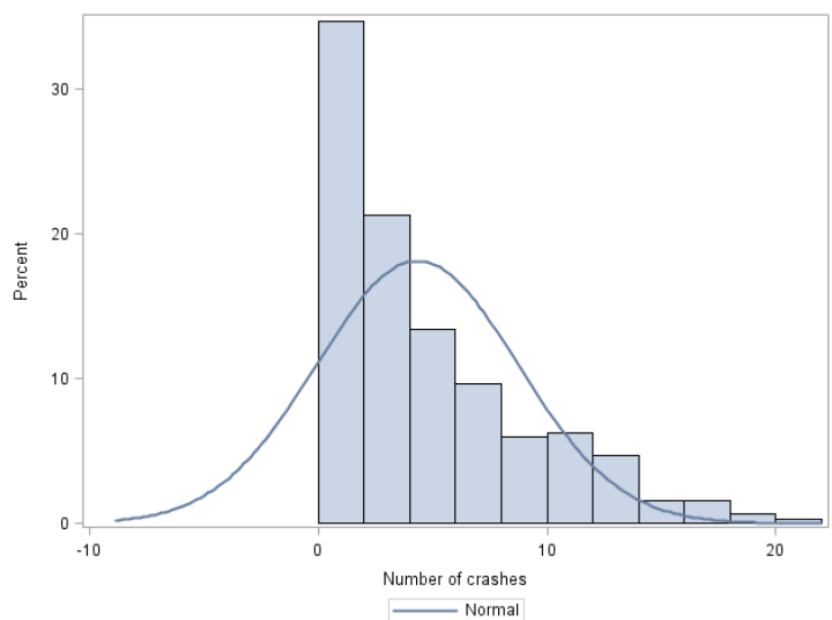

FIGURE 3.9 Histogram of ROR crashes on four-lane rural roads in Alabama

3.4.2 Data analysis

For the analysis, the variables considered were traffic data (AADT) and segment length, as these are the variables applied to these conditions in the *Highway Safety Manual* (AASHTO, 2010). The modeling of crash data was performed in SAS (2014).

To check for overdispersion in the data, the Poisson distribution was applied to both two-lane and four-lane rural roads samples. The ratio of the Pearson Chi-Square coefficient to the degrees of freedom was estimated for each case; if this ratio is greater than one, the data is overdispersed. In case of overdispersion in the data, the negative binomial (NB) distribution was applied. The comparison between a single-state negative binomial distribution versus a dual-state zero-inflated negative binomial (ZINB) distribution was performed based on the Vuong test (Vuong, 1989), and on an analysis involving the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) developed by Raftery (1995) and Hilbe (2011), respectively.

The Vuong test statistic assumes the null hypothesis that both models, NB and ZINB, fit the data equally well. The model fit is based on the Kullback–Leibler divergence (KLD) from the true model that generated the data (Kullback and Leibler 1951). The KLD divergence represents the distance between two probability distributions; in this study, the KLD represents the distance from the considered distribution (NB or ZINB) to the true distribution of the data. Therefore, the Vuong test assumes a null hypothesis that the KLD of the NB is equal to the KLD of the ZINB distribution. Equations 3.25 and 3.26 show how the Vuong test statistic is estimated.

a) Compute m_i:

$$m_i = ln\left(\frac{f_1(y_i|X_i)}{f_2(y_i|X_i)}\right) \quad \text{(Equation 3.25)}$$

Where:

$f_1(y_i|X_i)$ is the probability density function of the zero-inflated model;

$f_2(y_i|X_i)$ is the probability density function of the Poisson or negative binomial distribution.

b) Vuong's statistic:

$$V = \frac{\sqrt{n}[(1/n)\sum_{i=1}^{n} m_i]}{\sqrt{(1/n)\sum_{i=1}^{n}(m_i - \overline{m})^2}} = \frac{\sqrt{n}(\overline{m})}{S_m} \quad \text{(Equation 3.26)}$$

Where:

$\overline{m}$ = mean;

S_m = standard deviation;

n = number of observations.

At a 95% confidence level, the zero-inflated regression model (ZINB) is favored if the V value is greater than 1.96. A V value of less than -1.96 favors the negative binomial (NB) regression model. If $|V| < 1.96$, the null hypothesis cannot be rejected, and both NB and ZINB fit the data equally well.

The Akaike information criterion (AIC) (Akaike 1974) and the Bayesian information criterion (Schwarz 1978) are measures of the relative quality of a statistical model for a given data. Several models can be fitted to data; AIC and BIC estimate the quality of each model in relation to the other models. Both criteria can estimate how much information was lost when the model was applied to represent true data; therefore, the model that best fits the data should lose the least amount of information, when compared with other models, and lowest AIC and BIC values are preferred. AIC and BIC are defined as shown in Equations 3.27 and 3.28.

$$AIC = -2LL + 2P \quad \text{(Equation 3.27)}$$

$$BIC = -2LL + P(\ln(n)) \quad \text{(Equation 3.28)}$$

Where:

LL= logarithm of the maximum likelihood estimation;

P = number of model parameters;

n = number of observations.

The statistically significant difference between values of AIC and BIC of zero-inflated negative binomial (ZINB) and negative binomial (NB) models can be estimated by criteria developed by Raftery (1995) and Hilbe (2011), as shown in Table 3.10.

TABLE 3.10 Significance levels for AIC and BIC

ΔAIC for Models A and B	Result if A < B	ΔBIC for Models A and B	Result if A < B
0.0 to 2.5	No difference	0.0 to 2.0	Weak difference
2.5 to 6.0	Prefer A if n > 256	2.0 to 6.0	Positive difference
6.0 to 9.0	Prefer A if n > 64	6.0 to 10.0	Strong difference
10+	Prefer A	10+	Very strong difference

SOURCE: Raftery (1995) and Hilbe (2011)

3.4.3 State-specific safety performance functions considering "excess" zeros

After determining whether crash data in Alabama is overdispersed and if there are "excess" zeros, a distribution that best fits data is used to represent two safety performance functions: one to estimate run-off-road crashes on two-lane rural roads in Alabama and one to estimate run-off-road crashes on four-lane divided roads in Alabama. The importance of developing these SPFs is relevant, as they are specific to ROR crashes, a concern in the state, and they account for “excess” zeros in the data, which is usually a characteristic of crash data. Base conditions do not consider the presence of paved shoulders, shoulder rumble strips, or shoulder rumble stripes.

3.5 SUMMARY OF CHAPTER 3

The frequent occurrence of run-off-road (ROR) crashes and the corresponding high severity of them, especially on rural roads, made several states start new practices or update existing policies as a tentative to improve safety. Some common countermeasures applied in the United States include paved shoulders, shoulder rumble strips, and shoulder rumble stripes. This study developed a survey regarding policies, studies of treatment effectiveness, and dimensions of paved shoulders, shoulder rumble strips, and shoulder rumble stripes. Of all states in the country, 20 completed the survey.

Run-off-road crashes represent more than 50 percent of the fatal crashes in at both national and state levels, and they are a concern especially on rural roads. The Alabama Department of Transportation implemented a policy in 2006 to implement countermeasures as an effort to reduce ROR crashes on two-lane rural roads, which in practice was extended to four-lane roads. This study evaluated the safety effectiveness of the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and the effect of paved shoulder only on 101 projects in Alabama that had 2 to 4 ft of shoulder width. The effectiveness of the treatments implemented in Alabama after ALDOT policy was addressed by an application of the Empirical Bayes method, EPDO analysis, and a benefit-cost analysis.

As an effort to improve the fit of crash data in Alabama and account for the possible presence of “excess” zeros, four distributions were applied to data modeling: Poisson, zero-inflated Poisson (ZIP), negative binomial (NB), and zero-inflated negative binomial (ZINB). Data included 72 segments of two-lane rural roads and 32 segments of four-lane divided rural roads in Alabama with no paved shoulders or rumble strips and stripes, during the period from 2001 to 2010. The independent variables considered in the models were annual average daily traffic (AADT) and segment length, the same used in the *Highway Safety Manual* (HSM) for these conditions. The best model was defined based on the presence of overdispersion in the data, the Vuong test statistic, and AIC and BIC values. State-specific SPFs for two-lane and four-lane rural roads were developed based on the distribution that best fit the data.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This study provides an overview of the state of the practice of paving shoulders and applying shoulder rumble strips and stripes in prior research. It also documents state DOT's practices and compares to ALDOT's policy.

An evaluation of the effectiveness of three countermeasures, paved shoulder, paved shoulder combined with rumble strips, and paved shoulder combined with rumble stripes, is provided for the change in ROR crashes in 101 projects on two and four-lane rural roads with shoulder width of 2 to 4 ft in Alabama. Five groups are considered: 31 sites with paved shoulder only in two-lane rural roads, 40 sites with paved shoulder combined with rumble strips in two-lane rural roads, 12 sites with paved shoulder combined with rumble stripes in two-lane rural roads, 9 sites with paved shoulder only in four-lane divided rural roads, and 9 sites with paved shoulder combined with rumble strips in four-lane divided rural roads. Five new CMFs are developed for these conditions and EPDO scores are obtained for each of the five groups by severity. A benefit-cost analysis of each treatment is also performed, using B/C ratios.

Finally, a zero-inflated model approach is compared to the traditional Poisson and negative binomial distributions. The best-fitted distribution is used to model two state-specific safety performance functions to estimate ROR crashes in Alabama, one for two-lane roads and another for four-lane divided roads.

4.2 SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION IN THE UNITED STATES

4.2.1 Paved shoulders

After the evaluation of the survey responses, detailed in Appendix B, a summary of results is presented in this section. Table 4.1 shows the percentage of states that apply paved shoulders to each type of projects. It can be seen that 70% of the agencies implement paved shoulders when new pavements are constructed. Only 40% of the agencies have shoulder paving as stand-alone projects. It was not specified by the agencies if the stand-alone implementation of paved shoulders was a regular practice or only rare cases.

TABLE 4.1 When states apply paved shoulders

Paved Shoulders are Applied to	Percent of States
New pavement construction	70
Pavement resurfacing projects	55
Pavement rehabilitation projects	55
Pavement restoration projects	45
Stand-alone improvements (paving shoulder without any treatment on traveled way pavement)	40

Table 4.2 is a summary of the factors that influence the determination of shoulder width within the 20 states considered in this study. All locations consider traffic volume as a factor to determine shoulder width, and 85% also consider functional classification. Some geometric design elements, however, do not seem to be relevant factors when defining the shoulder width, as only 20 and 15% of the states consider horizontal and vertical alignment, respectively.

TABLE 4.2 Factors affecting shoulder width

Factors Influencing Shoulder Width	Percent of States
Traffic volume	100
Functional classification (Arterial, Collector, Local)	85
Speed limit	60
Administrative classification (Interstate, U.S., State, County)	55
Crash frequency/rate	55
Area type (i.e., urban vs. rural)	45
Total roadway width	40
Truck percentage	35
Bicycles	35
Travel lane width	30
Other	30
Horizontal alignment	20
Vertical alignment	15
All state-maintained rural highways	10

4.2.2 Shoulder Rumble Strips and Stripes

The most relevant factors for the implementation of shoulder rumble strips and stripes are listed on Table 4.3. It can be observed that shoulder width is the main factor to define whether shoulder rumble strips and stripes should be applied. Speed limit (70%) and area type (65%) were important for states to define if the construction of shoulder rumble strips and stripes was necessary. Most states have a policy only for rural roads with speeds higher than 50 miles per hour. It was reported by some agencies that noise would be a serious problem if rumble strips and stripes were applied in urban areas. Also, presence of bicyclists was a relevant factor (65%), which usually resulted in states applying rumble strips and stripes on shoulders at least 4-ft wide.

TABLE 4.3 Factors affecting the construction of shoulder rumble strips and stripes

Factors Influencing Rumble Strips Implementation	Percent of States
Shoulder Width	90
Speed limit	70
Bicycles	65
Area type (i.e., urban vs. rural)	65
Crash frequency/rate	50
Travel lane width	35
Functional classification (Arterial, Collector, Local)	30
Total roadway width	25
Traffic volume	25
Administrative classification (Interstate, U.S., State, County)	15
Horizontal alignment	15
Other	15
All state-maintained rural highways	10
Vertical alignment	5
Truck percentage	5

It can be observed in Table 4.4 that all states apply paved shoulders and shoulder rumble strips as a countermeasure to increase safety. However, only 80% also use shoulder rumble stripes as a way to prevent crashes. Most states have been paving shoulders and applying shoulder rumble strips since the early 1970s or even earlier, but their policies keep being updated after new studies on the effectiveness of paved shoulders and shoulder rumble strips are published, as well as which shoulder width is ideal or which type of rumble strips are the most appropriate. The range of costs of paving shoulders is wide, mainly because some states apply full shoulders, while others do not. Also, the range of shoulder widths varies from 1.5 ft to 12 ft, which affects the cost per mile. In general, most states' paved shoulders are at least 4 ft, presumably to provide bicyclists adequate space to ride. Dimensions of shoulder rumble strips and stripes also vary among the states.

Considering the 20 agencies that completed the survey, results on policies for paving shoulders and constructing shoulder rumble strips and stripes can differ significantly from one location to the other. Most states reported that no study to evaluate the effectiveness of the treatments had been conducted. Also, on the few studies that were performed, there were not enough data for a significant study such as an Empirical Bayes before/after analysis. Crash frequencies and crash rates were the most considered methods of safety evaluation. The recommendation is that states collect more after data, when they are available, and perform statistical analyses, such as those indicated in the *Highway Safety Manual* (HSM), to verify if their policies are adequate or need to be modified.

TABLE 4.4 Summary of projects

Treatment	Percent of States with Treatment Applied	Range of Year of Most Updated Policy	Range of Costs (Dollars per Mile)	Dimensions
Paved Shoulders	100	Early 1970s to 2014	40,000 to 750,000	1.5 to 12 ft
Shoulder Rumble Strips	100	Late 1970s to 2014	534 to 3,168	A= 4 to 16 in, B= 7 to 9 in, C= 9 to 15 in, D= 1 to 24 in
Shoulder Rumble Stripes	80	N/A	534 to 3,168	A= 4 to 16 in, B= 0.5 to 9 in, C= 11 to 13 in, D= 1 to 12 in

4.3 SAFETY EFFECTIVENESS OF THE IMPLEMENTATION OF PAVED SHOULDERS, RUMBLE STRIPS AND STRIPES ON RURAL ROADS IN ALABAMA

4.3.1 Highway Safety Manual Empirical-Bayes analysis applying the HSM SPFs

After the Empirical Bayes analysis applying the *Highway Safety Manual* SPF for two-lane rural roads, results can be seen in Table 4.5. The CMFs for two-lane roads for the combined effect of paved shoulder and shoulder rumble strips and stripes are 0.79 and 0.82, respectively, showing a reduction in total ROR crashes of approximately 21 and 18%. The CMF for paving the shoulder of two-lane roads is 0.72, corresponding to an approximate reduction in total ROR crashes of 28%.

TABLE 4.5 Empirical Bayes analysis using HSM SPF

Treatment	CMF	Std Err (CMF)	Z Stat: Abs(Safety Effectiveness/Std Err Safety Effectiveness)	Confidence Interval	
				Lower	Higher
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	0.79	0.04	4.63	0.70	0.88
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Stripes	0.82	0.08	2.20	0.65	0.98
Two-lane Paved Shoulder (2-4 ft)	0.72	0.04	6.26	0.64	0.81
Four-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	0.84	0.08	2.02	0.68	1.00

The CMF values for two-lane roads would suggest that it would be preferable to apply paved shoulders as a treatment and not implement shoulder rumble strips or stripes. A more detailed analysis of the results, however, shows that the confidence intervals, at a 95% confidence level, overlap for the three treatments. The CMF for the combined effect of paved shoulders and shoulder rumble strips could be as low as 0.70, and the CMF for paved shoulder-only could be as high as 0.81, for example. Figure 4.1 illustrates the overlap between CMF values for two-lane roads.

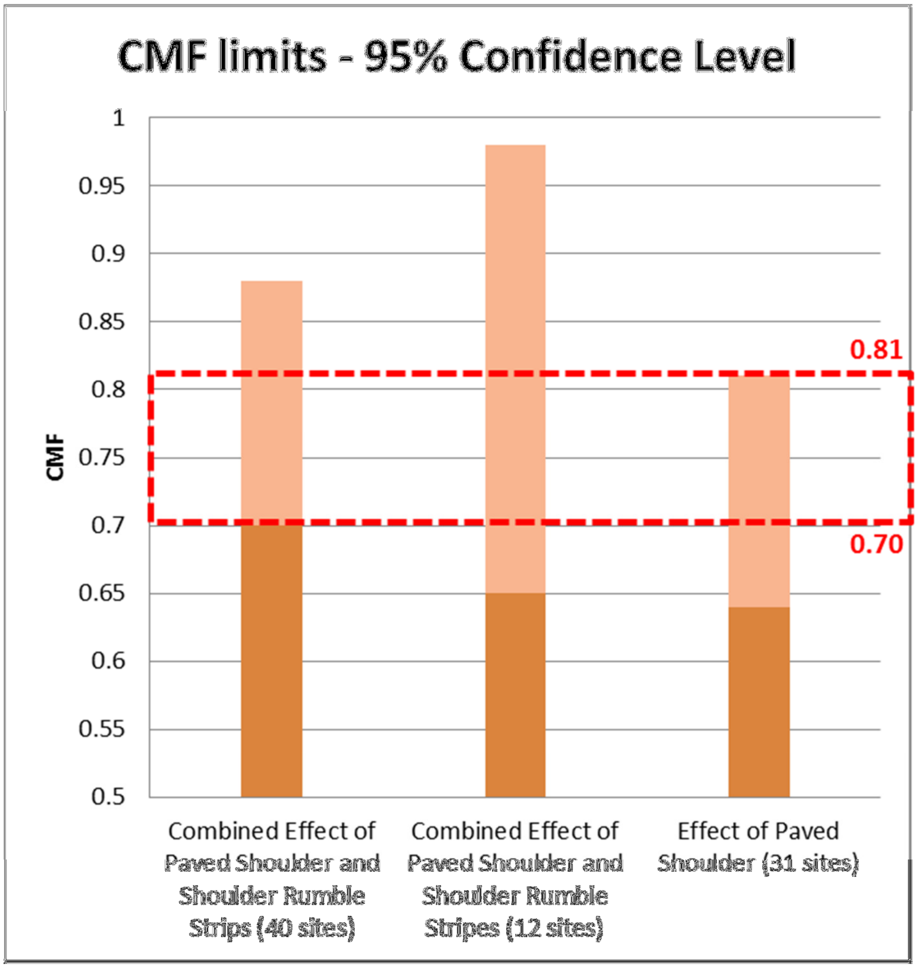

FIGURE 4.1 Overlap between two-lane roads CMFs

The results of this study show that all treatments are effective on reducing ROR crashes on rural roads; however, a comparison between treatments is not recommended as the confidence intervals overlap. For all treatments seen in Table 4.5, the absolute value of the ratio of safety effectiveness by the standard error of safety effectiveness is greater than 2.00, showing that these treatments are significant at the approximate 95 percent confidence level, and the estimate for the

CMF is strong. Also, the standard error of the CMF estimate is lower than 0.1 for all treatments, which makes the CMF estimate reliable. The CMF for paved-shoulder only treatment for four-lane roads was not significant at the 95 percent confidence level, and it was not reliable.

4.3.2 Highway Safety Manual Empirical-Bayes analysis applying the state-specific SPFs

The EB method was also performed applying a state specific safety performance function for two-lane rural roads in Alabama. Table 4.6 shows the only significant (at a 95% confidence level) and reliable calculated CMFs. The CMFs for both combined effect of paved shoulder and shoulder rumble strips and paved shoulder only treatments are bigger than one, indicating an increase in total ROR crashes after treatments were implemented. These results are not compatible with what has been seen in the literature, which shows an improvement in safety after application of paved shoulder, shoulder rumble strips, and shoulder rumble stripes. It is recommended that different approaches should be applied to model Alabama data.

TABLE 4.6 Empirical Bayes analysis using state specific SPF

Treatment:	**CMF**	**SE (CMF)**	**Z Stat: Abs(Safety Effectiveness/SE Safety Effectiveness)**	**Confidence Interval**	
				Lower	**Higher**
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	1.33	0.10	3.39	1.14	1.52
Two-lane Paved Shoulder (2-4 ft)	1.23	0.09	2.43	1.04	1.42

4.3.3 EPDO Analysis

The EPDO analysis for all 101 segments considered three years of ROR data before treatment was implemented and three years of ROR data after treatment was implemented. Table 4.7 shows the results after crash data was weighed by EPDO factors shown in Table 3.7. All treatments had improvement in the safety condition, with a percent reduction in the EPDO scores of 3.78 for the combined treatment of paved shoulder and shoulder rumble strips on two-lane roads, 3.51 for the combined effect of paved shoulder and shoulder rumble stripes on two-lane roads, 10.67 for the treatment of paved shoulder only on two-lane roads, 11.10 for the combined treatment of paved shoulder and shoulder rumble strips on four-lane roads, and 4.01 for the treatment of paved shoulder only on two-lane roads.

For two-lane roads, the results suggest that it would be preferable to apply a 2 to 4 ft paved shoulder and not implement shoulder rumble strips or shoulder rumble stripes as treatments. However, the EPDO score method does not account for regression-to-the-mean bias, it may overemphasize locations with a small number of severe crashes, and it does not account for traffic volume. Therefore, an EB analysis was also performed to consider the disadvantages of this method. The EPDO scores are still useful and recommended to agencies, especially when there is a lack of available data, as it considers severity of crashes and provides information on the safety effectiveness of a treatment. Comparison between treatments, however, should be carefully evaluated, as the method can be sensitive to small sample sizes and different traffic volumes, for example.

TABLE 4.7 EPDO scores

EPDO - NHTSA 2013 Weights			
Treatment	**Before**	**After**	**Percent Reduction (%)**
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	3519	3386	3.78
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Stripes	1397	1348	3.51
Two-lane Paved Shoulder (2-4 ft)	3796	3391	10.67
Four-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	1513	1345	11.10
Four-lane Paved Shoulder (2-4 ft)	1896	1820	4.01

4.3.4 Benefit-cost analysis

The benefit-cost analysis was performed using the crash reduction by severity resulting from the EB analysis in Alabama using the Highway Safety Manual SPF. Results can be seen in Table 4.8 showing that all B/C ratios are greater than one, which means all treatments are recommended to reduce ROR crashes on rural roads. Comparison between treatments may not be adequate, as noted before for both EPDO scores and EB analysis. A following study with more data is recommended for the purpose of comparisons.

TABLE 4.8 Benefit/Cost ratios for each treatment

Treatment	Total Benefits	Total Costs	B/C ratio
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	$90,577,462	$19,816,155	4.57
Two-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Stripes	$20,849,098	$5,777,951	3.61
Two-lane Paved Shoulder (2-4 ft)	$91,967,600	$15,961,356	5.76
Four-lane Combined Paved Shoulder (2-4 ft) and Shoulder Rumble Strips	$27,298,983	$5,988,378	4.56
Four-lane Paved Shoulder (2-4 ft)	$7,392,398	$3,637,356	2.03

4.4 ZERO-INFLATED MODELS APPLIED TO ALABAMA CRASH DATA

Data were first modeled applying Poisson and zero-inflated Poisson distributions to check for overdispersion in the data (SAS, 2014a). Overdispersion was present if the ratio of the Pearson Chi-square coefficient by the degrees of freedom was higher than 1. The ratios for two-lane rural roads were 2.6318 for the ZIP and 4.1298 for the Poisson model; for four-lane divided rural roads, these ratios were 2.0446 for the ZIP and 3.2303 for the Poisson model. These values confirmed that the data were overdispersed. Therefore, a negative binomial distribution was applied to address overdispersion.

The negative binomial model addresses overdispersion in the data; however, if data are characterized by "excess" zeros, this may not be the most appropriate distribution to use. A Vuong test was applied to verify which distribution fitted data better (SAS, 2014b). In addition, statistically significant levels of the differences on the AIC and BIC values for ZINB and NB were addressed. Results of the analyses are shown in Tables 4.9 to 4.11.

TABLE 4.9 Vuong test statistics for ZINB and NB comparison

Road type	Vuong test statistic (V)	Preferred model
2-lane rural	1.4115	No difference
4-lane divided rural	3.1182	ZINB

TABLE 4.10 AIC values

Road type	AIC ZINB model	AIC NB model	ΔAIC for Model	Preferred model
2-lane rural	3429.3297	3432.1811	-2.8514	ZINB
4-lane divided rural	1496.3431	1529.0277	-32.6846	ZINB

TABLE 4.11 BIC values

Road type	BIC ZINB model	BIC NB model	ΔBIC for Model	Preferred model
2-lane rural	3461.3845	3450.4981	10.8864	NB
4-lane divided rural	1522.7213	1544.096	-21.3747	ZINB

For both two-lane and four-lane divided rural roads, the zero-inflated model was overall a better fit than the NB distribution. The recommended safety performance functions for two-lane roads can be seen in Equations 4.1 and 4.2, with dispersion parameter of 0.5928; for four-lane divided roads, the models are shown in Equations 4.3 and 4.4, with dispersion parameter of 0.4701.

Two-lane rural roads, Zero-state:

$$\mu = e^{(0.1607 - 0.8119 AADT \times 10^{-3} - 0.2001 SL)} \quad \text{(Equation 4.1)}$$

Two-lane rural roads, Non-zero-state:

$$\mu = e^{(0.2399 + 0.0483 AADT \times 10^{-3} + 0.1157 SL)} \quad \text{(Equation 4.2)}$$

Four-lane divided rural roads, Zero-state:

$$\mu = e^{(1.2087 + 0.0880 AADT \times 10^{-3} - 2.4032 SL)} \quad \text{(Equation 4.3)}$$

Four-lane divided rural roads, Non-zero-state:

$$\mu = e^{(-0.2257 + 0.0253 AADT \times 10^{-3} + 0.2473 SL)} \quad \text{(Equation 4.4)}$$

4.5 SUMMARY OF CHAPTER 4

The results of the survey distributed to state departments of transportation in the United States can be observed in Appendix B. Of all states in the country, 20 completed the survey. All states apply paved shoulders and shoulder rumble strips as countermeasures to reduce ROR crashes, and 80% of the states also implement shoulder rumble stripes. Dates of the most recent policies vary significantly from one location to the other, as well as dimensions. Only a few states developed safety effectiveness studies, but data was not sufficient, as not “after” crash data after treatment implementation were available, or the methods were not the most recommended for these evaluations. This study recommends that, after states have enough “after” crash data, statistical methods, especially the ones suggested by the *Highway Safety Manual* (HSM), should be applied to verify if treatments are effective and adequate to each state.

The effectiveness of the treatments implemented in Alabama after ALDOT policy was addressed by an EPDO analysis, an Empirical Bayes method, and a benefit-cost analysis. For two-lane roads, the EPDO analysis showed a reduction of EPDO scores of 3.78% for the combined effect of paved shoulders and shoulder rumble strips, 3.51% for the combined effect of paved shoulders and shoulder rumble stripes, and 10.67% for paved shoulder only. For four-lane roads, there was a reduction of EPDO scores of 11.10% for the combined effect of paved shoulders and shoulder rumble strips and a reduction of 4.01% for paved shoulder only. This method does not account for RTM bias, it can overemphasize locations with a small number of severe crashes, and it does not account for traffic volume. The EPDO scores method is easy to be applied and it accounts for severity of crashes, being more robust than the Naïve method of safety effectiveness evaluation. However, a comparison between treatments should be carefully evaluated, as the method can be sensitive to small sample sizes and different traffic volumes.

The EB analysis was performed using the HSM safety performance function. For two-lane rural roads, the analysis resulted in CMFs of 0.79, 0.82, and 0.72 for the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and paved shoulder only respectively. For four-lane roads, CMF for the combined effect of paved shoulder and shoulder rumble strips was 0.84 and for paved-shoulder only it was not significant and reliable. These results were similar to the EPDO analysis, showing that all treatments reduce ROR crashes, and the CMFs are consistent with the ones commonly found in the literature. A comparison between treatments is not recommended as the confidence intervals for the CMFs overlap. After applying the state specific SPFs to the EB analysis, most CMFs were not significant and reliable, and the ones that were did not represent what is commonly seen in the literature, as they suggest an increase in ROR crashes after the implementation of the treatments. It is recommended the evaluation of different statistical distributions that could fit Alabama crash data better. Benefit-cost ratios also showed that all treatments improve safety, providing more benefits that the cost for their implementation. On two-lane roads, B/C ratios were 4.57, 3.61, and 5.76 for the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and paved shoulder only respectively. On four-lane roads, B/C ratio was 4.56 for the combined effect of paved shoulder and shoulder rumble strips and 2.03 for the paved shoulder-only treatment.

All three methods of safety effectiveness evaluation showed that ROR crashes are reduced by all three implemented countermeasures. It is recommended that ALDOT continues implementing their policy. However, as all treatments were implemented in 2006 or later, there was not much availability of “after” crash data in this study. For conclusions regarding the comparison between treatments, a following study with more data is recommended.

This study applied Poisson, zero-inflated Poisson, negative binomial, and zero-inflated negative binomial distributions to estimate run-off-road crash frequency on 72 segments of two-lane rural roads and 32 segments of four-lane divided rural roads in Alabama, from 2001 to 2010. The variables considered in the models were traffic data (AADT) and segment length, the same used in the Highway Safety Manual for these conditions. Poisson and ZIP models showed overdispersion of traffic data, suggesting Negative Binomial or ZINB models would be better to fit data. A Vuong test and AIC and BIC criteria were applied to evaluate if the zero-inflated model was more suitable than the Negative Binomial model. The ZINB was overall the best to model crash data for both two and four-lane rural roads.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 EVOLUTION OF THE IMPLEMENTATION OF PAVED SHOULDERS, SHOULDER RUMBLE STRIPS, AND SHOULDER RUMBLE STRIPES ON RURAL HIGHWAYS

A survey was distributed to all state transportation agencies in the United States to verify the state of the practice of the implementation of paved shoulders, shoulder rumble strips, and shoulder rumble stripes as countermeasures to avoid ROR crashes in two-lane rural roads. The survey was completed by 20 state transportation agencies in the country. Results showed that 70% of the agencies implement paved shoulders when new pavement are constructed, while only 40% of the agencies have shoulder paving as stand-alone projects. All agencies consider traffic volume as a factor to define shoulder width, and 85% also consider functional classification. Some geometric design elements such as horizontal and vertical alignment are not relevant factors when defining the shoulder width; only 20% and 15% of the states consider horizontal and vertical alignment, respectively, as a factor that establishes the width of the shoulder.

Shoulder width was the main factor to determine if shoulder rumble strips and stripes should be applied. The need for applying shoulder rumble strips and stripes was also highly influenced by speed limit (70% of the states) and area type (65% of the states). Most states only have a policy for rural roads when speeds are higher than 50 miles per hour. Some agencies reported that noise would be a serious problem if rumble strips and stripes were applied in urban areas. Presence of bicyclists was a relevant factor (65% of the states) when deciding which shoulder width should be the minimum for applying shoulder rumble strips and stripes; in most cases, this value is 4 ft.

All state agencies apply paved shoulders and shoulder rumble strips as an effort to prevent crashes; 80% of the agencies also apply shoulder rumble stripes. The range of shoulder widths varies from 1.5 ft to 12 ft; the general practice for most agencies is that paved shoulders are at least 4 ft wide.

The majority of the agencies reported that no study to evaluate the effectiveness of the treatments had been performed. Crash frequencies and crash rates were the most considered methods of safety evaluation for most agencies that conducted related studies, which shows limitations as the results of these methods cannot lead to conclusions as relevant as the ones resulting from an Empirical Bayes analysis, for example.

5.2 EFFECTS OF PAVEMENT WIDENING, RUMBLE STRIPS, AND RUMBLE STRIPES ON RURAL HIGHWAYS IN ALABAMA

This study evaluated data from 101 projects in Alabama representing 678 miles of segments on two and four-lane rural roads that had 2 to 4 ft of paved shoulders constructed, and in some cases, rumble strips or rumble stripes were scored into the pavement within the shoulder.

The evaluation of the effectiveness of the implemented countermeasures after ALDOT's policy was based on an EPDO analysis, an Empirical Bayes method, and a benefit-cost analysis. For two-lane roads, the EPDO analysis showed a reduction of EPDO scores of 3.78% for the combined effect of paved shoulders and shoulder rumble strips, 3.51% for the combined effect of paved shoulders and shoulder rumble stripes, and 10.67% for paved shoulder only. For four-lane roads, there was a reduction of EPDO scores of 11.10% for the combined effect of paved shoulders and shoulder rumble strips and a reduction of 4.01% for paved shoulder only. It can be inferred that all methods reduced ROR crashes; however, a comparison between treatments is not recommended, as the method can be sensitive to small sample sizes and different traffic volumes.

The EB method was first performed applying the *Highway Safety Manual* SPFs. For two-lane rural roads, the analysis resulted in CMFs of 0.79, 0.82, and 0.72 for the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and paved shoulder only respectively. For four-lane roads, CMF for the combined effect of paved shoulder and shoulder rumble strips was 0.84 and for paved-shoulder only it was not significant or reliable. Similar conclusions to the EPDO analysis resulted from the EB analysis: all treatments reduce ROR crashes. Again, a comparison between treatments is not recommended, since it cannot be assumed that it is better to implement paved shoulders without scoring, as the 95% confidence intervals for the CMFs overlap. Most of the CMFs estimated using the state-specific SPFs in the EB method were not significant or reliable. As a result, the CMFs resulting from the HSM SPFs were used in the benefit-cost analysis.

Benefit-cost ratios also showed that all treatments improve safety, providing more benefits that the cost for their implementation. On two-lane roads, B/C ratios were 4.57, 3.61, and 5.76 for the combined effect of paved shoulder and shoulder rumble strips, the combined effect of paved shoulder and shoulder rumble stripes, and paved shoulder only respectively. On four-lane roads, B/C ratio was 4.56 for the combined effect of paved shoulder and shoulder rumble strips and 2.03 for the paved shoulder-only treatment.

5.3 SAFETY PERFORMANCE FUNCTIONS FOR RURAL ROADS APPLYING ZERO-INFLATED MODELS

The HSM suggests that state agencies should develop state-specific SPFs to estimate crash frequency. The safety performance functions in the HSM as well as the existing state-specific SPFs were developed assuming a negative binomial distribution, which does not account for possible “excess” zeros in the data.

As an effort to model safety performance functions for the Alabama conditions, this study compared Poisson, zero-inflated Poisson, negative binomial, and zero-inflated negative binomial distributions applied to crash data of 72 segments of two-lane rural roads and 32 segments of four-lane divided rural roads in Alabama, from 2001 to 2010. The models included traffic data (AADT) and segment length as independent variables.

Poisson and ZIP models showed overdispersion in the data, suggesting that negative binomial or ZINB models would be better to fit Alabama data. A Vuong test and values of AIC and BIC were applied to evaluate if the zero-inflated negative binomial (ZINB) model was more appropriate than the negative binomial model. Overall, the ZINB was the best to model crash data for both two and four-lane rural roads.

5.4 RECOMMENDATIONS

This study recommends that state agencies should perform statistical analyses, especially applying methods outlined in the HSM, when data are available. This will be important to provide agencies enough information on safety effectiveness of the countermeasures applied to avoid crashes.

The safety effectiveness evaluation showed that ROR crashes are reduced by all three implemented countermeasures in two and four-lane rural roads in Alabama. It is recommended that ALDOT continues implementing their policy. For conclusions regarding the comparison between treatments, a following study with more years of data and more sites is recommended.

Limitations exist when applying zero-inflated models to data modeling; however, as crash data in Alabama has “excess” zeros, ZI models provide a better representation than the traditional single-state models. The ZINB safety performance functions are recommended to the estimation of ROR crashes on two and four lane rural roads, with no paved shoulders or shoulder rumble strips and stripes applied in the “before” period. These SPFs are important as they represent Alabama crash data well, and they are specific to the ROR crashes, which account for more than 50% of fatal crashes in the state. Several other models can be evaluated in posterior research, and due to the limitations of this study, future analyses are recommended when more data are available, especially when cause an effect of crashes can be analyzed.

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APPENDIX A

SURVEY TO DETERMINE THE STATE OF THE PRACTICE REGARDING COUNTERMEASURES TO PREVENT ROR CRASHES ON RURAL HIGHWAYS IN THE UNITED STATES

Paved Shoulders

This survey is in support of the research project "A Study of the Effects of Pavement Widening and Rumble Strips on Two-Lane Rural Highways in Alabama", a study conducted by the Highway Research Center at Auburn University. The purpose is to determine the state-of-practice of state Departments of Transportation in the United States regarding paved shoulders and shoulder rumble strips installation on rural highways. When answering all questions, consider only highways THAT ARE NOT FREEWAYS.

Thank you for participating on this survey. The approximate time to complete the questions is 15 minutes.

Please write below the name of your agency.

Question 1. Does your state have a written policy or set of guidelines concerning paving previously unpaved shoulders or widening shoulder pavement for: (Select all that apply)

- [ ] New pavement construction
- [ ] Pavement resurfacing projects
- [ ] Pavement restoration projects
- [ ] Pavement rehabilitation projects
- [ ] Stand-alone improvements (paving shoulder without any treatment on traveled way pavement)

Question 2. If available, attach the file with the policy or set of guidelines mentioned in Question 1.

Choose File No file chosen

Question 3. When most recently has your state's current practice of paving shoulders changed?

Question 4. What key factors influence the width of paved shoulders? (Select all that apply)

- [ ] Functional classification (Arterial, Collector, Local)
- [ ] Administrative classification (Interstate, U.S., State, County)
- [ ] Horizontal alignment
- [ ] Vertical alignment
- [ ] Travel lane width
- [ ] Total roadway width
- [ ] Traffic volume
- [ ] Truck percentage
- [ ] Bicycles
- [ ] Area type (i.e., urban vs. rural)
- [ ] Speed limit
- [ ] Crash frequency/rate
- [ ] All state-maintained rural highways
- [ ] Other

Question 5. If there is an additional document with information related to Question 4, please upload it here.

Choose File No file chosen

Question 6. If you selected any features on Question 4 and did not attach a file on Questions 2 or 5, please specify how they affect shoulder paving. (e.g. minimum required paved shoulder width for each speed or AADT range).

Question 7. What is the typical range of costs, or average cost, per mile, of paving shoulders in your state? How are these projects funded?

Question 8. Has your state evaluated the performance and/or effectiveness of paving shoulders using either highway safety criteria (e.g. reduction in run-off-road crashes) or using other measures of highway user satisfaction?

Question 9. If your state has evaluated the performance and/or effectiveness of paving shoulders using the methods described in Question 8, please upload a copy of the report.

Choose File No file chosen

Question 10. Have any unexpected problems or difficulties been encountered with the adoption of a policy on paved shoulders? (e.g. if too wide, vehicles may use shoulders as a regular lane and increase some types of crashes). If so, please elaborate.

Shoulder Rumble Strips

Question 1. Does your state use shoulder rumble strips on highway shoulders?

- Yes
- No

Question 2. Does your state have a written policy or set of guidelines concerning the installation of shoulder rumble strips?

- ◯ Yes
- ◯ No

Question 3. If available, attach the file with the policy or set of guidelines mentioned in Question 2.

Choose File No file chosen

Question 4. When, most recently, has your state's current practice of installing shoulder rumble strips changed?

Question 5. What features directly affect installation requirements within your state's shoulder rumble strip policy or guidelines? (Select all that apply)

- ☐ Functional classification (Arterial, Collector, Local)
- ☐ Administrative classification (Interstate, U.S., State, County)
- ☐ Shoulder width
- ☐ Horizontal alignment
- ☐ Vertical alignment
- ☐ Travel lane width
- ☐ Total roadway width
- ☐ Traffic volume
- ☐ Truck percentage
- ☐ Bicycles
- ☐ Area type (i.e., urban vs. rural)
- ☐ Speed limit
- ☐ Crash frequency / rate
- ☐ All state-maintained rural highways
- ☐ Other

Question 6. If there is an additional document with information related to Question 5, please upload it here.

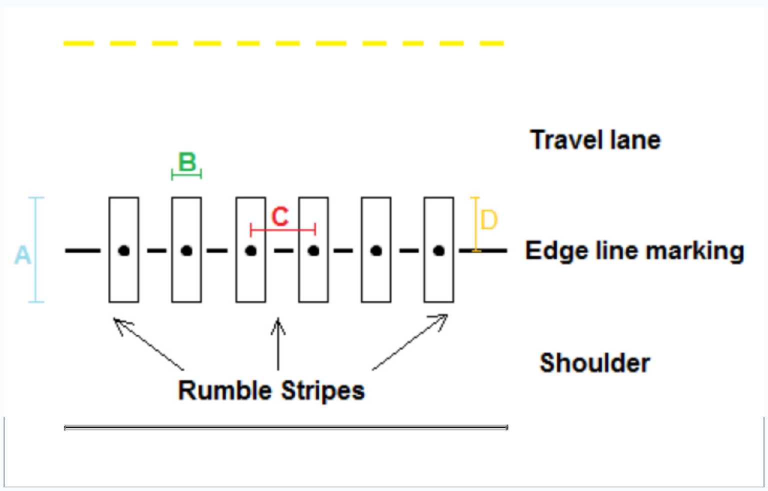
Choose File No file chosen

Question 7. If you selected any features on Question 5 and did not attach a file on Questions 3 or 6, please specify how they affect installation requirements of shoulder rumble strips. (e.g. minimum required shoulder width to apply rumble strips).

Question 8. Has your agency installed rumble stripes (rumble strips placed on edge line marking)?

- Yes
- No

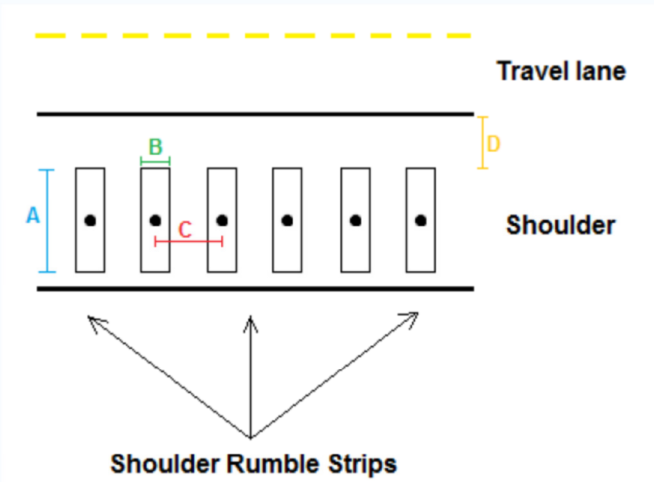
Question 9. On Question 10, please provide the dimensions A, B, C and D currently used in the milled shoulder rumble stripes, according to the figure below. (Please provide this information for all types of shoulder rumble stripes used in your state).



Question 10. Provide the dimensions A, B, C and D for the rumble stripes in Question 9

A	
B	
C	
D	

Question 11. On Question 12, please provide the dimensions A, B, C and D currently used in the milled shoulder rumble strips, according to the figure below. (Please provide this information for all types of shoulder rumble strips used in your state).



Question 12. Provide the dimensions A, B, C and D for the rumble strips in Question 11

A	
B	
C	
D	

Question 13. What is the typical range of costs, or average cost, per mile, of milled in shoulder

rumble strips in your state? How are these projects funded?

Question 14. Has your state evaluated the performance and/or effectiveness of milled SRS using either highway safety criteria (e.g. reduction in run-off-road crashes) or using other measures of highway user satisfaction?

Question 15. If your state has evaluated the performance and/or effectiveness of milled SRS using the methods described in Question 14, please upload a copy of the report.

Choose File No file chosen

Question 16. Have any unexpected problems or difficulties been encountered with the adoption of milled SRS? If so, please elaborate.

Contact

May we have the name and e-mail address of an engineer in your agency that we may contact to clarify any aspect of your response or to obtain additional information?

APPENDIX B

SURVEY DETAILED RESPONSES

a) Arizona Department of Transportation

Paved Shoulders

Arizona DOT (ADOT) has a general practice of paving shoulders that started in the early 1970s. The DOT only applies paved shoulders to new pavement construction projects. Shoulder width in Arizona is defined by functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., County), traffic volume, truck percentage, and area type (urban vs. rural). For rural multilane divided roads, paved shoulder width is 4 ft on the left and 10 ft on the right (in direction of travel); for rural two-lane roads, shoulder width is 8 ft if the design hourly volume (DHV) is greater than 200 vehicles per hour, and 6 ft for a DHV less than 200 vehicles per hour.

No cost information was provided by ADOT.

No previous study was performed in Arizona to evaluate the effectiveness of paved shoulders in rural roads.

Shoulder Rumble Strips and Stripes

ADOT has been installing shoulder rumble strips since the late 1970s, but their most recent policy is from 2011. The purpose of shoulder rumble strips in Arizona is to enhance safety by preventing run-off-road (ROR) crashes. The implementation of shoulder rumble strips is a function of shoulder width, presence of bicycles, and area type. Shoulder rumble strips should be applied to all multilane rural roads, with a minimum required shoulder widths of 4 ft (right side) and 2 ft (left); for two lane rural roads, shoulder rumble strips should be applied only when shoulder width is 4 ft or greater. If appreciable bicycle traffic exists, a minimum effective clear shoulder width of 3.5 ft should be provided. No rumble stripes are used in the state. Shoulder rumble strips basic dimensions are A = 6 to 12 in, B = 7 in, C = 12 in, and D = 1 to 10 in.

Shoulder rumble strips cost is approximately $1700 per mile per side.

No study regarding the evaluation of the effectiveness of shoulder rumble strips in Arizona was performed yet.

b) Arkansas State Highway and Transportation Department

Paved Shoulders

Arkansas State Highway and Transportation Department (AHTD) has a policy on paving shoulders for new pavement construction, pavement resurfacing projects, pavement restoration projects, and pavement rehabilitation projects since 1989. Shoulder width is defined by functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., State, County), horizontal alignment, vertical alignment, travel lane width, total roadway width, traffic volume, truck percentage, presence of bicycles, area type (urban vs. rural), speed limit, and crash frequency/rate. Usually, 2 ft paved shoulders are used on rural roads in Arkansas.

On average, the cost of adding 2 ft paved shoulders is about $388,149 per mile. Safety projects are funded using HSIP funds.

AHTD has evaluated rural two-lane highways in Arkansas and results showed that when widening the left and right paved shoulders from 2 ft to 4 ft, the total predicted crashes have reduced from 7.47 crashes to 6.90 crashes (7.63 % reduction in total crashes).

Some challenges reported by AHTD regarding paving shoulders showed that vehicles were using paved shoulders that are too wide as a potential extra lane, which may increase crash risk.

Shoulder Rumble Strips and Stripes

In Arkansas, the application of shoulder rumble strips is based on functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., State, County), shoulder width, horizontal alignment, vertical alignment, travel lane width, total roadway width, traffic volume, truck percentage, bicycles, area type (i.e., urban vs. rural), speed limit, and crash frequency/rate. Rumble strips basic dimensions are A = 16 in, B = 7 in, C = 12 in, and D = 4 in. Rumble stripes basic dimensions are A = 6 in, B = 5 in, C = 12 in, and D = 3 in.

Rumble Strips on asphalt shoulders average cost is about $0.16 per linear foot (one direction).

No study was reported by AHTD regarding the effectiveness of shoulder rumble strips.

Issues after the implementation of shoulder rumble strips in Arkansas were mainly related to noise. Residents have complained that rumble strips make too much noise that they do not want them installed near their residential area.

c) Delaware Department of Transportation

Paved Shoulders

Delaware Department of Transportation (DelDOT) defines the need of paving shoulders based on the functional classification (Arterial, Collector, Local), traffic volume, and area type (urban vs. rural). The shoulder width for rural local, collectors, and arterials are 5, 8, and 10 ft, respectively.

No cost information was provided by Delaware DOT.

No previous study to evaluate the effectiveness of paved shoulders was performed.

<u>Shoulder Rumble Strips and Stripes</u>

DelDOT has a policy last updated in 2011 on guidelines of implementation of shoulder rumble strips. The application of shoulder rumble strips is based on functional classification (Arterial, Collector, Local), shoulder width, presence of bicyclists, area type (i.e., urban vs. rural), and crash frequency/rate. Shoulder rumble strips should be installed on all rural two-lane roadways with a minimum of 11 ft lanes, 5 ft shoulders, and a posted speed limit or 85th percentile speed of 40 miles per hour or higher. Shoulder rumble strips should also be installed on all multilane rural roads. Rumble strips basic dimensions are A = 16 in, B = 7 in, C = 12 in, and D = 12 in. Rumble stripes basic dimensions are A = 6 in, B = 7 in, C = 12 in, and D = 3 in.

In Delaware, shoulder rumble strips cost approximately $3,000 per mile, including maintenance of traffic and other associated costs. Federal safety funds are used.

DelDOT mentioned that they just started a study regarding the effectiveness of shoulder rumble strips. No results are available yet.

Some issues faced by DelDOT were related to the placement of shoulder rumble strips and bicycle traffic. They use “bike-friendly” rumble strips, with at least 4 ft of usable shoulder beyond the rumble strip and they also determine there should be gaps with no rumble strips; however, some contractors did not consider the bicycle guidelines when implementing shoulder rumble strips. This has resulted in several complaints by the bicycle community, and DelDOT is currently working to solve the problem.

d) Hawaii Department of Transportation

Paved Shoulders

Hawaii Department (HDOT) has a policy for paving shoulders that has been updated in 2010. Paved shoulders are applied on pavement resurfacing projects, pavement restoration projects, and pavement rehabilitation projects. Shoulder width varies according to the design speed, traffic volume, type of terrain, functional classification, and area type. For rural roads, shoulder width varies from 3 to 6 ft.

In Hawaii, projects are normally funded by state special maintenance funds and are occasionally federalized.

No previous study was performed to evaluate the effectiveness of paved shoulders in Hawaii.

Lessons learned by the HDOT usually result from the fact that designers provide for only minimum paved shoulder width, limiting installation of shoulder rumble strips.

Shoulder Rumble Strips and Stripes

HDOT does not have a written policy for shoulder rumble strips implementation; however, installations have been increasing and are usually a function of shoulder width, total lane width, total roadway width, presence of bicyclists, crash frequency/rate, and area type. Although no written policy exists, 3 ft minimum of paved shoulder width is required between shoulder rumble stripes and edge of paved shoulder, and 5 ft minimum of paved shoulder width is required between shoulder rumble strips and edge of paved shoulder. Rumble strips basic dimensions are A = 12 in, B = 6 to 9 in, C = 12 in, and D = 4. Rumble stripes basic dimensions are A = 4 in, B = 6 to 9 in, C = 12 in, and D = 2 in.

Shoulder rumble strips costs can be funded through various sources since they can be included in most projects. Funding can come from state special maintenance to capital improvement and can be federalized with safety, National Highway Performance Program (NHPP), Surface Transportation Program (STP), etc.

No study has been developed in Hawaii yet to evaluate the effectiveness of shoulder rumble strips.

Most difficulties HDOT faces regarding shoulder rumble strips are noise and bicyclists complaints.

e) Idaho Transportation Department

<u>Paved Shoulders</u>

Idaho Transportation Department (ITD) has a policy for paving shoulders that has been unchanged for more than 20 years. The determination of the shoulder width is based on the roadway area (rural or urban), traffic volume, percent trucks, and design speed. For rural roads, shoulder width varies from 2 to 6 ft. It is recommended a shoulder width of 5 ft where bicyclists are present, to provide them enough space to ride. The policy is valid for paving previously unpaved shoulders for new pavements being constructed, for pavement resurfacing projects, for pavement restoration projects, for pavement rehabilitation projects, and as stand-alone improvements.

The costs for paving the shoulders in Idaho are the same as the costs for constructing the rest of the roadway. They range from $80,000 to $250,000 per mile. Projects are funded by the Surface Transportation Program (STP).

One lesson learned by the ITD was that It is important to have either a slope shoe or safety edge at the pavement edge, avoiding a pavement drop-off.

Shoulder Rumble Strips and Stripes

The ITD has a new policy, from 2013, regarding the application of shoulder rumble strips or stripes in the state. Pavement scoring should be applied on a minimum shoulder width of 4 ft. A Safety Index following the procedures in the Highway Safety Manual was calculated by the ITD to define sections of roadways that needed rumble strips, as they consider rumble strips do not provide a benefit where there are few incidences of ROR crashes. Bicycle usage is also a factor when deciding where to implement rumble strips, and even if a minimum shoulder width of 4 ft is required, 5 ft is the desirable for bicyclists. If the shoulder is in poor condition and the project does not include an overlay, Idaho Department of Transportation does not include rumble strips. Rumble strips basic dimensions are A = 12 in, B = 7 in, C = 12 in, and D = 12. Rumble stripes basic dimensions are A = 12 in, B = 7 in, C = 12 in, and D = 2 to 3 in.

The average cost of scoring the pavement is $973.87 per mile. Projects are funded through either safety or as generally cost in the project.

In 2012, potential crash reduction benefits of shoulder rumble strips were analyzed by the University of Idaho. The evaluation was done using two different evaluation methods: Comparison Groups (CG) before-and-after analysis and Empirical Bayes (EB) before-and-after analysis. For cases where control section data was limited or not available, naive before-and-after analysis was used. Based on Idaho's crash data, the installation of shoulder rumble strips on 2-lane rural highways resulted in a 15 percent reduction in all ROR crashes and a 74 percent reduction in severe ROR crashes. The percent reduction in all ROR crashes and severe ROR crashes when shoulder rumple strips were installed in 4-lane rural highways were 60 percent and 45 percent, respectively.

f) Iowa Department of Transportation

Paved Shoulders

The policy of Iowa DOT regarding paved shoulders is recent, from 2014. To determine if it is appropriate to have the shoulder paved, factors such as roadway classification and design year traffic volume have to be analyzed. Other considerations include the likely presence of pedestrians and/or bicyclists and specific geometric issues. The minimum shoulder width is 2 ft. If bicycles are accommodated, a minimum 4 ft shoulder is recommended for 45 mph or less, and wider shoulders are recommended for higher speeds or if rumble strips are to be placed.

The approximate cost for paving a shoulder can vary from $28,00 to $80,00 per linear foot, depending on the thickness of the shoulder.

Iowa DOT has relied on paved shoulders research from other states. In the future, they plan on having their own evaluation, after they have a few years of crash history.

Shoulder Rumble Strips and Stripes

Iowa DOT's most recent policy on shoulder rumble strips is from 2013. The application of shoulder rumble strips is based on administrative classification (Interstate, U.S., State, County), traffic volume, area type (urban vs. rural), and crash frequency/rate. No shoulder rumble stripes are used in the state. Rumble strips basic dimensions are A = 12 in, B = 7, C = 12 in, and D = 6 in.

Average cost of shoulder rumble strips is $1.61 per linear foot and funds come from the same source as the rest of the project.

No study was performed yet to evaluate the effectiveness of shoulder rumble strips in Iowa.

g) Kentucky Transportation Cabinet

Paved Shoulders

Kentucky Transportation Cabinet (KYTC) has a policy on paving shoulders for new pavement construction and pavement restoration projects. Shoulder width is defined by functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., State, County), and traffic volume. Shoulder width varies from 2 to 10 ft on rural roads.

The approximate cost for paving a 4 ft shoulder, common practice in Kentucky, is $40,000 per mile.

No previous study to evaluate the effectiveness of paved shoulders was performed.

KYTC reported that they have limitations on the amount of usable shoulder to install a paved shoulder on our 2-lane rural routes. Usually, less than 2 feet of shoulder between the pavement and the ditch can be observed.

Shoulder Rumble Strips and Stripes

KYTC's policy regarding the implementation of shoulder rumble strips was last updated in 2012. The application of shoulder rumble strips is based on shoulder width and speed limit. Pavement scoring should be applied on shoulders of facilities with posted speed limits greater than 45 MPH and shoulder widths 4 feet or greater. Rumble strips basic dimensions are A = 16 in, B = 7 to 7.5 in, C = 12 in, and D = 1. Rumble stripes basic dimensions are A = 8 to 12 in in, B = 7 to 7.5 in, C = 12 in, and D = 4 to 6 in.

Average cost of shoulder rumble strips is $0.25 per linear foot and funds come from the same source as the rest of the project.

A study was performed in 2008 by the University of Kentucky to evaluate the safety benefits associated with the application of shoulder rumble strips on 2-lane rural roads in Kentucky. A three-year crash history was available, and the analysis was conducted in terms of crash rates for control sites and sites with shoulder rumble strips. Sections with rumble strips had a lower crash rate than those without (2.67 Crashers per MVM vs. 3.91 Crashes per MVM). A regression analysis was also performed to verify if crash rates were significantly different (at a 90% confidence level) between control sites and sites with shoulder rumble strips. Roads with shoulder rumble strips had statistically significant lower total crash rate than roadways without shoulder rumble strips. The difference between control sites and sites with shoulder rumble strips was not significant for run-off-road crash rates.

h) Louisiana Department of Transportation and Development

<u>Paved Shoulders</u>

Louisiana Department of Transportation and Development (LaDOTD) updated their policy on paved shoulders in 2010. Paved shoulders are applied on pavement resurfacing projects, pavement restoration projects, and pavement rehabilitation projects. Shoulder width varies according to the posted speed, traffic volume, lane width, functional classification, percent trucks, and area type. For rural roads, shoulder width varies from 2 to 6 ft.

The costs of LaDOTD for paving shoulders are between $80 and $100 per ton of Superpave asphalt placed.

No previous study was performed to evaluate the effectiveness of paved shoulders in Louisiana.

<u>Shoulder Rumble Strips and Stripes</u>

LaDOTD has a policy for shoulder rumble strips implementation that was last updated in 2012. Designers are instructed to include shoulder rumble strips in all projects that include all new construction, reconstruction, and preservation/rehabilitation/replacement where incorporation of rumble strips woll not delay the project letting date in Louisiana. Rumble strips use is limited to rural roads where speed limit is 50 MPH or more. Rumble strips basic dimensions are A = 12 in, B = 6.5 to 8.5 in, C = 12 to 14 in, and D = 6. No information was provided by LaDOT regarding rumble stripes.

Shoulder rumble strips costs can be funded through various sources since they can be included in most projects. Funding can come from state special maintenance to capital improvement and can be federalized with safety, National Highway performance Program (NHPP), Surface Transportation Program (STP), etc.

No study has been developed in Hawaii yet to evaluate the effectiveness of shoulder rumble strips.

Most difficulties HDOT faces regarding shoulder rumble strips are noise and bicyclists complaints.

i) Missouri Department of Transportation

Paved Shoulders

Missouri Department of Transportation (MoDOT) has a policy concerning paving previously unpaved shoulders for new pavements being constructed, and for pavement resurfacing projects. The policy was changed in 2012, and determines the need of paving shoulders based on functional classification, roadway width, traffic volume, presence of bicyclists, and speed limit.

Where a paved shoulder is provided on major rural routes, the full thickness of the travel way pavement should be extended laterally to a longitudinal joint of 1 ft. Minor road shoulders should be aggregate stabilized except when maintenance or safety concerns (e.g., edge drop off, high run-off road (ROR) occurrence) justify an alternate treatment. When conditions warrant, a 1 or 2 ft. lateral extension of the mainline pavement should be considered as an initial option on minor rural roads.

The costs of paved shoulders range from $70,000 to $120,000 per mile, depending on grading need. Projects are funded by both Highway Safety Improvement Program and Open Container funding sources.

In 2005 and 2006, the Missouri Department of Transportation (MoDOT) undertook a major program, known as the Smooth Roads Initiative (SRI), to improve both the rideability and the visibility of over 2,300 mi of major roadways in Missouri. MoDOT was able to have MRIGlobal complete a study of rural routes in the state after paving the shoulders. The evaluation of SRI improvements was conducted using a before/after Empirical Bayes method, with 3 years of crash data before implementation of SRI improvements and 3 years of crash data after SRI implementation. 1,453.1 miles of rural roads were evaluated in this study, including freeways, multilane divided highways, multilane undivided highways, and two-lane highways.

After the implementation of wider pavement markings and paved shoulders after resurfacing, there was a reduction on fatal and disabling injuries of 21% on rural freeways, of 34% on rural multilane divided highways, and of 46% on rural multilane undivided highways.

Main challenges faced by MoDOT were related to change in crash types over the year. They noticed an increase on single-vehicle lane departure crash type, and it's still their goal to minimize them. Also, the constructability of shoulders is difficult for some of the current roadway structures, as when shoulder width may involve a great deal of grading if the existing roadway has minimal unpaved shoulder.

Shoulder Rumble Strips and Stripes

MoDOT has a policy for shoulder rumble strips implementation that was last modified in 2004. the need of applying shoulder rumble strips is based on functional classification, shoulder width, traffic volume, and speed limit. Rumble strips can be installed with a minimum of 2 ft shoulders and the basic dimensions are A = 12 in, B = 7 in, C = 12 in, and D = 4 in. The state agency also has rumble stripes applied to rural roads, with dimensions A = 12 in, B = 7 in, C = 12 in, and D = 6 in.

Costs of striping the pavement are in the range of $1,000-$1,500 per mile. Most are funded by the Highway Safety Improvement Program (HSIP) funding or Open Container penalty funding.

As a result of the SRI study by MRIGlobal, wider markings and rumble strips on paved shoulder after resurfacing caused a decrease on fatal and disabling injuries of 26% on rural freeways, and of 49% on rural multilane divided highways. Wider markings and rumble stripes on paved shoulder after resurfacing caused a decrease on fatal and disabling injuries of 25% on rural freeways, and of 24% on rural multilane divided highways. Single-vehicle crashes appear to have increased, which the state explains it was a result from a statewide trend of increases in lane-departure crashes rather than from an effect of the striping and delineation improvements.

Overall, MoDOT considers scoring the pavement very successful. The only observed issue was some deterioration of the shoulder rumble strips as the life of pavement nears the end.

j) Montana Department of Transportation

Paved Shoulders

Montana Department of Transportation (MDT) has a policy for paving previously unpaved shoulders for new pavements being constructed, for pavement rehabilitation projects, and as stand-alone improvements. The policy in Montana is the same as it was 40 years ago. The MDT developed a Route Segment Plan, which defined the required shoulder widths for all rural routes on the state system, with the exception of Secondary routes. The Route Segment Plan was developed to meet the essential needs of the transportation network with the funding available. Shoulder width is a function of functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., State, County), total roadway width, traffic volume, presence of bicyclists, area type (rural/urban), and crash frequency/rate. The maximum shoulder width for rural roads is 8 ft.

Since the cost of paving shoulders is based on a number of variables, such as shoulder width, pavement thickness (MDT uses the same thickness of pavement on the shoulders as it uses on the travel lanes), there is not an average cost that could provide any applicable information. In addition, shoulder paving in Montana is mostly performed in conjunction with paving the travel lanes; if shoulders were paved separately, the costs would be higher due to economy of scale. This is especially true for narrower shoulders.

No study has been performed in Montana to evaluate the performance and/or effectiveness of paving shoulders.

Shoulder Rumble Strips and Stripes

The MDT is currently revising their policy on shoulder rumble strips. The implementation of shoulder rumble strips in the state are based on shoulder width, presence of bicyclists, area type (urban vs. rural), speed limit, and crash frequency/rate. Rumble strips basic dimensions are A = 12 in, B = 6 7/8 to 8 3/8 in, C = 12 in, and D = 6 in.

The average cost of scoring the pavement is $725 per mile. MDT is using reduced widths and shallower grinds and reduced offsets for various installations when the shoulder width is narrower than 4'. MDT uses an intermittent pattern where every 60' includes a 13' gap.

A study was conducted in 2003 by Marvin and Associates to evaluate shoulder rumble strips on two-lane rural roads in Montana. The study included 106.4 miles of roadway. Run-off-road crash rates decreased by 17.6% on roads where shoulder rumble strips were applied, but the severity rate increased by 3.5%. On corresponding control segments, no change on crash rates was observed, but there was a severity rate decrease by 23.2%. This indicates that the addition of shoulder rumble strips may have improved roadway safety as far as crash frequency is concerned, but an increase in crash severity rates occurred at the same time.

The Montana Department of Transportation reported the concern regarding a bicycle community issue on installing shoulder rumble strips on certain routes that they use for recreation and bike events. Also, there have been noise issue raise in several places.

k) Nebraska Department of Roads

Paved Shoulders

Nebraska Department of Roads (NDOR) has a policy from 2008 on how to apply paved shoulders. Shoulders should be paved for new pavement construction, pavement resurfacing projects, pavement restoration projects, and pavement rehabilitation projects. Shoulder width is specified according to traffic volume, vertical alignment, horizontal alignment, number of lanes, and lane width. For rural two-lane roads, shoulder widths vary from 2 to 8 ft; for multilane rural roads, shoulder widths vary from 5 to 6 ft (left) and 10 to 12 ft (right). The Minimum Design Standards specify ranges of ADT for which shoulders will be surfaced. However, if a project does not meet these warrants, the District Engineer may request approval from the Roadway Design Engineer to surface a 2 ft shoulder. In these cases, some aspects have to be evaluated: apparent shoulder distress, annual shoulder maintenance costs, the existing turf shoulder width, how close the future traffic is to the meeting the warrants, the adjacent land use, and the crash history that relates directly to shoulder condition.

Average costs of paving shoulders in Nebraska are $40,000 to $150,000 per mile. Either Highway Preservation funds or GSIP funds are utilized.

No study regarding the evaluation of the effectiveness of shoulder rumble strips in Nebraska was performed yet.

Shoulder Rumble Strips and Stripes

NDOR has a policy with guidelines to implement shoulder rumble strips that was last updated in 2014. Shoulder rumble strips should be constructed on 6 ft or wider shoulder for all new construction and reconstruction projects on rural high-speed two-lane rural roads. Shoulder rumble stripes should be constructed on two-lane highways that have 12 ft lanes with a minimum of 2 ft and maximum of 6 ft shoulder width, for ADT greater than 500 vehicles per day, on segments with a ROR crash history, and posted speed limit of 50 MPH or greater. No information of the dimensions of the rumble strips and stripes was provided.

No cost information was provided by NDOR.

No study regarding the evaluation of the effectiveness of shoulder rumble strips in Nebraska was performed yet.

l) Nevada Department of Transportation

<u>Paved Shoulders</u>

Nevada Department of Transportation (NDOT) has paved shoulders for new pavement construction, pavement resurfacing projects, pavement restoration projects, and pavement rehabilitation projects for some time, but since 2010 they have been pursuing stand-alone shoulder widening and paving projects. The width of the shoulder is based on functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., State, County), traffic volume, truck percentage, presence of bicyclists, area type (urban vs. rural), speed limit, available right-of-way, terrain, and crash frequency/rate. Minimum shoulder width for rural roads is 4 ft, and the maximum is 10 ft.

In Nevada, costs of paving shoulders vary from $200,000 per mile to $ 750,000 per mile, depending on the level of work required and the width of paving. Projects are funded through the HSIP program and some through the 3R program, both state and federal funds.

NDOT uses benefit/cost analyses to prioritize potential locations to apply paved shoulders, and crash reduction is measured as crash frequency. Widening shoulders to 5 ft showed a B/C ratio of 1.15.

A concern regarding paved shoulders that was reported by NDOT was an observed increase on speeds after the treatment was implemented.

Shoulder Rumble Strips and Stripes

Rumble strips policy in Nevada are from 2005, and the implementation of pavement scoring is based on functional classification (Arterial, Collector, Local), administrative classification (Interstate, U.S., State, County), shoulder width, presence of bicyclists, area type (urban vs. rural), and speed limit. Rumble strips basic dimensions are A = 16 in, B = 7 in, C = 12 in, and D = 0 in.

The approximate cost of applying rumble strips in Nevada is $300 per mile. Rumble strips projects are funded by the HSIP.

No study was reported by NDOT regarding the effectiveness of shoulder rumble strips.

m) New Mexico Department of Transportation

Paved Shoulders

New Mexico Department of Transportation (NMDOT) has a policy regarding paved shoulders that was last updated in 2001. It determines the need of paving shoulders based on functional classification, administrative classification, traffic volume, speed limit, and funding available. Shoulder width on rural roads in New Mexico varies from 4 to 8 ft.

No cost information was provided by NMDOT.

The only study regarding the effectiveness of paved shoulders performed by NMDOT was a literature review to evaluate if 2 ft shoulders were adequate to be implemented in New Mexico. Their conclusion was that shoulders may be used for a variety of purposes, but few of these purposes can be achieved with shoulders that are only 2 ft wide. They found no compelling evidence to suggest that the construction of narrow shoulders on most of New Mexico's rural two-lane highways would result in a safety benefit commensurate with the cost of installing the treatment. As a result, this treatment is not recommended by NMDOT.

Shoulder Rumble Strips and Stripes

NMDOT has a policy for shoulder rumble strips implementation that was recently modified in 2013. The need of applying shoulder rumble strips is based on shoulder width, presence of bicyclists, area type (urban vs. rural), and speed limit. To implement shoulder rumble strips, the roadway section has to be rural and have a high enough operating speed. Also, the paved shoulder should be in fair to good pavement condition and the width has to be greater than 4 ft. No rumble stripes are implemented in New Mexico.

Costs have historically ranged from $0.13 to $0.60 per linear foot. Most of these projects are funded as part of other projects using a variety of funding sources. Since 2001, the New Mexico Highway Safety Improvement Program has always placed a high priority in encouraging NMDOT Districts to propose shoulder rumble strips as safety projects to be funded with federal HSIP funds.

No study has been performed by NMDOT regarding the effectiveness of shoulder rumble strips on rural roads.

n) North Carolina Department of Transportation

Paved Shoulders

The North Carolina Department of Transportation (NCDOT) paved shoulder policy from 2013 incorporates the findings of an in-depth study of construction, maintenance, safety, operational and economic issues related directly to the usage of paved shoulders. Factors that determine the width of paved shoulders are: functional classification, administrative classification, travel lane width, total roadway width, traffic volume, speed limit, and crash frequency/rate. Shoulder widths vary from 1.5 to 8 ft. The policy is valid for paving previously unpaved shoulders for new pavements being constructed, for pavement resurfacing projects, for pavement restoration projects, for pavement rehabilitation projects, and as stand-alone improvements.

Costs for paved shoulders in North Carolina are highly variable. They depend on a wide range of factors such as the availability of right of way, utilities involved, drainage adjustments needed, how wide a shoulder is being constructed, traffic control costs, among others. Depending on the magnitude of the effort, the funding mechanism could be as high order as a State Transportation Improvement project or a smaller Small Construction type of project. The modernization of a network of over 80,000 centerline miles of state maintained roads requires the utilization of all available internal and external partnering mechanisms.

A study has been performed in 2010 in the state to verify the performance and/or effectiveness of paving shoulders on some smaller safety funded projects. Results were not consistent through the different state divisions. For example, for 1.5 ft paved shoulders on 2-lane rural roads, a naive before and after analysis was performed for 6 years of data before and 6 years of data after the treatment implementation, and resulted in a 51 percent increase in total crashes and a 60 percent increase in run-off-road crashes for Division 3; for Division 4, this same type of study considered 5 years of before data and 5 years of after data, but results were a 32 percent reduction in total crashes, and a 48 percent reduction in run-off-the-road. For 2 ft paved shoulders, the same inconsistency of results could be observed for sections of 2-lane rural roads; a naive before and after analysis in Division 2 considering 4 years of before and 4 years of after data resulted in a 40 percent reduction in total crashes, and a 39 percent reduction in run-off-road crashes; for Division 6, the naive before and after analysis using 3 years of before and 3 years of after data resulted in a 4 percent increase in total crashes, and a 27 percent decrease in run-off-road crashes. These inconsistencies may be due to the limitations of a method like the naïve before and after; an Empirical Bayes method could be implemented later on to verify these results.

The NCDOT found several challenges when paving shoulders, such as having to secure right of way, regrade or rebuild ditches, relocate utilities, and attempt to re-establish or improve roadside clear areas (embankments, trees, etc).

<u>Shoulder Rumble Strips and Stripes</u>

NCDOT has a policy from 2012 that establishes as the standard practice the implementation of rumble strips or stripes at locations on partially controlled or non-controlled facilities that have a documented pattern of treatable lane departure events. Non Freeway rumble strip use is very case specific and limited to safety evidence driven locations. Rumble strips should be applied considering shoulder width, travel lane width, area type (urban vs. rural), presence of bicyclists, speed limit, and crash frequency/rate. It is desirable that a nominal width of four (4) feet of useable shoulder between the outside edge of the shoulder rumble strip/stripe to the edge of pavement exists, so bicyclists have enough space to ride. Rumble strips basic dimensions are A =

16 in, B = 7 in, C = 12 in, and D = 6 in. The state agency also has rumble stripes applied to rural roads, with dimensions A = 16 in, B = 7 in, C = 12 in, and D = variable, depends on each case.

Funding for shoulder rumble strips and stripes in North Carolina is very limited and restricted to specific safety evidence driven segments. Initial funding may be via spot safety or HSIP (Federal Hazard Elimination), with subsequent resurfacing responsible for the re-installation of the rumble strip or stripe. General cost is $0.15 per linear foot. Small projects solely to add rumble strips that absorb full traffic control are expected to result in higher costs.

The safety effectiveness of shoulder rumble strips was also evaluated with a naive before and after analysis, which provided inconsistent results. For example, for a 2-lane rural road with 2 ft paved shoulders, the implementation of shoulder rumble strips, in an analysis of 4 years before and 4 years after, showed a that total crashes remained relatively unchanged, while run-off-road crashes experienced a 33 percent decrease on the southbound direction but a 17 percent increase on the northbound direction. Empirical Bayes method is also recommended to verify this analysis.

NCDOT reported that rumble strip installations have not been well received by the host communities where they have been utilized. Residents do not appreciate the audible feature (frequency of engagement) and the bicycling community is adverse to any surface imperfections in or along a paved road's surface. Some of the marketed run-off-road crash reductions have been difficult to achieve and some of the results obtained have been less than expected with regard to the crash modification for road departures. There have also been problems with rumble stripes installations with application/adhesion, surface prep, and service life and overall performance of the thermo marking within the grooved slot.

o) Ohio Department of Transportation

Paved Shoulders

Ohio Department of Transportation (ODOT) has a policy on paving shoulders for new pavement construction, and the shoulder width is a function of functional classification (Arterial, Collector, Local), traffic volume, area type (urban vs. rural), and speed limit.

No cost data was provided by the ODOT.

No study was performed to evaluate the effectiveness of paved shoulders in Ohio.

Shoulder Rumble Strips and Stripes

ODOT has a policy regarding the implementation of shoulder rumble strips, and the most recent version was released in 2013. The application of shoulder rumble strips is based on shoulder width, travel lane width, presence of bicyclists, area type (i.e., urban vs. rural), and speed limit. Shoulder rumble strips and stripes should be places on 2-lane rural roads where the speed limit is greater than 50 mph, on asphalt of at least 1-1/4 in thickness, on a 2 ft or greater shoulder. Rumble strips basic dimensions are A = 16 in, B = 7 in, C = 12 in, and D = 6 in for shoulders 4 to 6 ft, 10 in for shoulders > 6 ft. Rumble stripes basic dimensions are A = 6 in, B = 0.5 in, C = 12 in, and D = 1 in.

Average cost of rumble strips and stripes is $900 per mile. Some initial costs are covered by the Safety Program. The cost is now included in resurfacing projects.

No study was reported by ODOT regarding the effectiveness of shoulder rumble strips and stripes.

It was reported by ODOT that initially they installed shoulder rumble strips and stripes on meeting certain condition standards; however, they now install them mainly as part of resurfacing operations on new pavement. Also, a concern they usually receive is that the bike community was very concerned about the installation of shoulder rumble strips and stripes. They started to use a more shallow 3/8 in depth and leave gaps to allow movement between the shoulder and traveled way.

p) Oklahoma Department of Transportation

Paved Shoulders

Oklahoma Department of Transportation (ODOT) defines the need of paving shoulders only for new pavement construction. Their policy was last updated in 2002, and shoulder width is determined as a function of functional classification (Arterial, Collector, Local), travel lane width, traffic volume, and crash frequency/rate. Even with a set of guidelines, the common practice in Oklahoma is to place paved shoulders in every new pavement being constructed, regardless of the roadway characteristics. Shoulder width varies from 4 to 8 ft on 2-lane rural roads, and it is 8 ft for the other rural roads.

No cost information was provided by Oklahoma DOT.

No previous study to evaluate the effectiveness of paved shoulders was performed.

A main concern in Oklahoma regarding paving shoulders is related to the right-of-way purchasing process. ODOT sometimes has to implement only 2 ft paved shoulders on 2-lane rural roads, even if the policy states a minimum of 4 ft, because of the right-of-way limits.

Shoulder Rumble Strips and Stripes

ODOT has a policy last updated in 2011 on guidelines of implementation of shoulder rumble strips. The application of shoulder rumble strips is based on the shoulder width. Rumble strips basic dimensions are A = 16 in, B = 6 to 8 in, C = 9 to 15 in, and D = 3 to 6 in for shoulders of 4 ft or less, 6 in to shoulders greater than 4 ft. No rumble stripes are implemented in Oklahoma.

In Oklahoma, shoulder rumble strips cost approximately $0.10 per linear foot.

No study regarding the effectiveness of shoulder rumble strips was performed in Oklahoma yet.

q) Rhode Island Department of Transportation

Paved Shoulders

Rhode Island DOT usually widens paved shoulders on highways that are being resurfaced. The state tries to meet AASHTO guidelines, but they also consider crash history (ROR crashes), total roadway width (some roads are very narrow with not enough space for shoulders), traffic volume (reducing the number of lanes through road diet allows an increase of shoulder width), bike presence, and speed limit (narrowing traffic lanes for traffic calming allows an increase of shoulder width). No specific policy or set of guidelines was provided by the Rhode Island DOT.

The costs of paved shoulders range from $80,000 to $250,000 per mile. Projects are funded by the Surface Transportation Program (STP).

The majority of the shoulders in the state are paved. No study was finished yet, but there is an ongoing evaluation of projects involving safety related countermeasures such as shoulder widening to reduce ROR crashes.

Shoulder Rumble Strips and Stripes

Rhode Island DOT (RIDOT) is currently updating the existing shoulder rumble strips policy, and should have a revised one by the end of 2014. The implementation of shoulder rumble strips is based on functional classification, shoulder width, travel lane width, presence of bicyclists, and crash frequency/rate. The previous policy is from 2005, and determined that shoulder rumble strips shall be installed on new, reconstructed, and resurfaced shoulders only on highways with a high incident of run-off-road crashes. Rumble strips basic dimensions are A = 16 in, B = 7 in, C = 12 in, and D = 12 in. The state agency does not have rumble stripes, but has future plans of implementing them.

Rumble strips costs are approximately $1,600 per mile. Most are funded by STP or HSIP funding sources.

No evaluation of the performance and/or effectiveness of shoulder rumble strips has been performed in Rhode Island previously. Since rumble strips are a FHWA proven safety countermeasure, studies are not required to install them in the state. However, before and after studies on all new rumble strip/stripe installations will be performed by the RIDOT.

r) South Carolina Department of Transportation

<u>Paved Shoulders</u>

South Carolina Department of Transportation (SCDOT) has a policy from 2006 that establishes the guidelines for paving previously unpaved shoulders for new pavements being constructed, for pavement resurfacing projects, for pavement restoration projects, for pavement rehabilitation projects, and as stand-alone improvements. Factors that determine the need of paving shoulders are: functional classification, horizontal alignment, travel lane width, total roadway width, traffic volume, truck percentage, presence of bicyclists, area type (rural vs. urban), speed limit, and crash frequency/rate.

All of the factors listed above influence the need to widen shoulders for a safety section project, but SCDOT is usually limited due to available right-of-way, environmental constraints, and available funding.

The typical costs per mile of paving shoulders in South Carolina are currently in the range of $170,000.00 to $200,000.00.

No study has been performed yet in the state to verify the performance and/or effectiveness of paving shoulders. There is the plan of starting soon the evaluation of projects initiated in 2012 using highway safety criteria.

<u>Shoulder Rumble Strips and Stripes</u>

The policy for shoulder rumble strips and rumble stripes was modified by the SCDOT in 2011. Rumble strips shall be placed on all shoulders or edgelines of all controlled access highways or freeways. Rumble strips shall be placed on shoulders or edgelines of all partial and non-controlled access roadways if the roadway is rural, the ADT is 500 vehicles per day or greater, the posted speed limit is 45 mph or greater, the total roadway width is greater than 20 ft, and the roadway is not part of the statewide bicycle touring route. Rumble strips are applied to roads with shoulder width of at least 4 feet, while rumble stripes are applied when the shoulder width is smaller than 4 ft. Rumble strips basic dimensions are A = 16 in, B = 7 in, C = 14 in, and D = 4 in. The state agency also has rumble stripes applied to rural roads, with dimensions A = 16 in, B = 7 in, C = 14 in, and D = 0 in.

Costs of striping the pavement are approximately $534 per mile.

Main challenges include the tentative of using fog seal but the material did not adhere well. The SCDOT also reports that they get complaints about noise frequently. Several complaints are received from bicyclists. The SCDOT is trying to implement a gap method (48' of rumble with a 12' gap) to give bicyclists an exit point from the shoulder into the lane.

s) Tennessee Department of Transportation

Paved Shoulders

Tennessee DOT (TDOT) has a policy for paving previously unpaved shoulders for new pavements being constructed, for pavement resurfacing projects, and as stand-alone improvements. The policy for paved shoulders in Tennessee has changed within the last 5 years. Shoulder width is a function of administrative classification (Interstate, U.S., State, County), traffic volume, speed limit, and crash frequency/rate.

The estimated cost for paving shoulders in Tennessee is $350,000 per mile. This is a new initiative through the Project Safety Office that is in the pilot stage. They use HSIP funds.

No study has been performed in Tennessee to evaluate the performance and/or effectiveness of paving shoulders.

TDOT reported that the main concern they have when paving shoulders is the elevated cost of the right-of-way and utilities.

Shoulder Rumble Strips and Stripes

The TDOT last revised their shoulder rumble strips policies in 2014. The implementation of shoulder rumble strips in the state are based on shoulder width, presence of bicyclists, area type (urban vs. rural), speed limit, and crash frequency/rate. Rumble strips basic dimensions are A = 4, 8, or 16 in, B = 5 in, C = 12 in, and D = 12 in. Rumble stripes basic dimensions are A = 4, 8, or 16 in, B = 5 in, C = 12 in, and D = 0 in.

Implementing shoulder rumble strips in Tennessee has an average cost of $507.00 per mile. Funds also come from HSIP.

No study regarding the effectiveness of shoulder rumble strips and stripes was developed in Tennessee.

t) Texas Department of Transportation

Paved Shoulders

Texas Department of Transportation (TxDOT) defines the shoulder widths to be applied based on total roadway width, traffic volume, truck percentage, area type (rural or urban), and crash frequency/rate. There is ongoing research of the Highway Safety Improvement Program (HSIP) and a statewide systemic widening program to define critical ADT, truck % and number of K and A crashes on rural 2-lane highways to determine shoulder width.

TxDOT reported that the range of costs depends on the amount of pavement being added. General construction funds and Highway Safety Improvement Program (HSIP) funds are used to widen highways.

In 2013, a report was released by TxDOT regarding several safety programs, one of them being the High Risk Rural Roads (HRRR) Program. The HRRR Program is part of the HSIP. Approximately 55% of fatalities in Texas occur in rural roads; therefore, the purpose of the program is to achieve a significant reduction in traffic fatalities and incapacitating injuries on rural roads. The program included construction of 1 to 4 ft paved shoulders where no shoulders existed previously. There was a 25% reduction factor in run-off-road crashes. The reduction factor represents the percentage reduction in crash costs or severity that can be expected as a result of the construction or widening of paved shoulders.

Shoulder Rumble Strips and Stripes

The current practice of installing shoulder rumble strips in Texas changed in 2013. The implementation of shoulder rumble strips is a function of shoulder width, speed limit, and pavement depth. Shoulder width dictates which type of rumble strip is available to use, and pavement depth limits where milled in shoulder texturing can be installed (2 inch minimum required). Rumble strips should not be placed on roadways with a posted speed limit of 45 MPH or less. Rumble strips basic dimensions are A = 8 to 16 in, B = 7 in, C = 12 in, and D = 6 in minimum. Rumble stripes basic dimensions are A = 8 to 16 in, B = 7 in, C = 12 in, and D = 4 to 12 in.

The average cost of scoring the pavement is $0.16 per linear foot on asphalt. Rumble strips projects are also funded by the HSIP.

The 2013 HSIP report included installation of milled-in or rolled-in rumble strips along the shoulder. There was a 50% reduction factor in run-off-road crashes. The reduction factor represents the percentage reduction in crash costs or severity that can be expected as a result of the implementation of shoulder rumble strips.

APPENDIX C

EXAMPLE OF SHEET USED FOR VERIFICATION OF GEOMETRY OF STUDY SITES FOR THE STUDY OF THE EFFECTS OF PAVEMENT WIDENING, RUMBLE STRIPS, AND RUMBLE STRIPES ON RURAL HIGHWAYS IN ALABAMA

Alabama Department of Transportation

Shoulder Rumble Strips Field Measurements Worksheet

Division: 4

Target Start Date: 5/27/2011

Route Number: 1

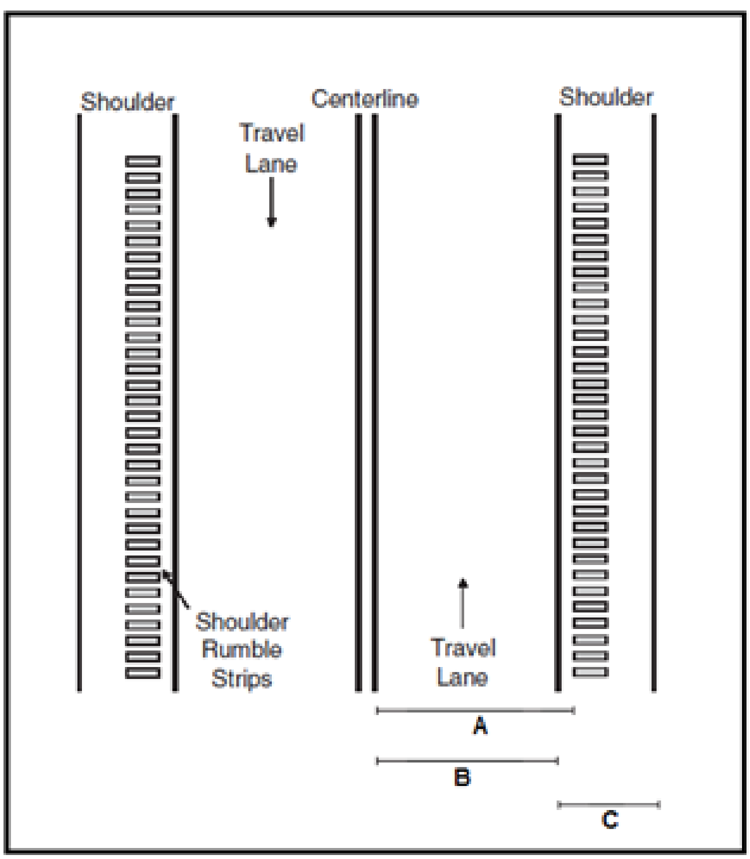
Target Completion Date: 8/31/2012

Project Number: EB-HSIP-0001(566)

County: Cleburne

Begin Milepost: 211.333

End Milepost: 221.027



Measurements:

# of Lanes: __________

A: ______________

B: ______________

C: ______________

Field Checked Begin Milepost:

____

Field Checked End Milepost:

____

Legend:

A: Distance from Centerline to beginning of Rumble Strips

B: Lane Width

C: Shoulder Width