

# JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION  
AND PURDUE UNIVERSITY



## Effective Shoulder Width on Rural Highway System Related to Roadway Departure Crashes



**Mario Barahona, Vamsi Krishna Bandaru,  
Mario Romero, and Andrew Tarko**

## RECOMMENDED CITATION

Barahona, M., Bandaru, V. K., Romero, M., & Tarko, A. (2025). *Effective shoulder width on rural highway system related to roadway departure crashes* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2025/38). West Lafayette, IN: Purdue University. <https://doi.org/10.5703/1288284318601>

## AUTHORS

**Mario Barahona, MS** 

Purdue University

**Vamsi Krishna Bandaru, PhD** 

Purdue University

**Mario Romero, PhD** 

Purdue University

**Andrew Tarko, PhD** 

Purdue University

(765) 494-5027

[tarko@purdue.edu](mailto:tarko@purdue.edu)

*Corresponding Author*

## ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Joint Transportation Research Program (JTRP) and the Indiana Department of Transportation (INDOT) for funding this study. We extend our appreciation to the engineers from various Indiana districts who took the time to respond to the survey, significantly contributing to the success of this research. Additionally, we would like to acknowledge the invaluable guidance and assistance provided by the SAC members throughout the course of this project: Michael Holowaty, Luis Laracuenta, Thomas Ford, Shuo Li Dwayne Harris, Dave Boruff, Dana Platter, and Enass Zayed.

## JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. Learn more at [engineering.purdue.edu/JTRP](http://engineering.purdue.edu/JTRP).

Published reports of the Joint Transportation Research Program are available at [docs.lib.purdue.edu/jtrp/](http://docs.lib.purdue.edu/jtrp/).

## NOTICE

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views and policies of the Indiana Department of Transportation or the Federal Highway Administration. The report does not constitute a standard, specification, or regulation.

## TECHNICAL REPORT DOCUMENTATION PAGE

<b>1. Report No.</b> FHWA/IN/JTRP-2025/38	<b>2. Government Accession No.</b>	<b>3. Recipient's Catalog No.</b>	
<b>4. Title and Subtitle</b> Effective shoulder width on rural highway system related to roadway departure crashes	<b>5. Report Date</b> December 9, 2025		<b>6. Performing Organization Code</b>
	<b>8. Performing Organization Report No.</b> FHWA/IN/JTRP-2025/38		
<b>7. Author(s)</b> Mario Barahona, MS ( <a href="https://orcid.org/0009-0006-3119-898X">https://orcid.org/0009-0006-3119-898X</a> ) Vamsi Krishna Bandaru, PhD ( <a href="https://orcid.org/0000-0002-9222-257X">https://orcid.org/0000-0002-9222-257X</a> ) Mario Romero, PhD ( <a href="https://orcid.org/0000-0002-8206-6956">https://orcid.org/0000-0002-8206-6956</a> ) Andrew Tarko, PhD ( <a href="https://orcid.org/0000-0001-9301-3270">https://orcid.org/0000-0001-9301-3270</a> )	<b>10. Work Unit No.</b>		
<b>9. Performing Organization Name and Address</b> Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	<b>11. Contract or Grant No.</b> SPR-4853		
	<b>13. Type of Report and Period Covered</b> Final Report		
<b>12. Sponsoring Agency Name and Address</b> Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204	<b>14. Sponsoring Agency Code</b>		
	<b>15. Supplementary Notes</b> Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		
<b>16. Abstract</b> Roadway design plays a crucial role in traffic safety, particularly on rural roads. This research investigates the safety effectiveness of shoulder width on Indiana's rural two-lane highways, and to use this understanding to provide a basis for more effective shoulder improvement programs. Although previous studies have established the benefits of shoulder widening in other states, limited research has been conducted in Indiana conditions. This research aims to evaluate the safety effectiveness of shoulders on rural roads in Indiana and to propose a practical and systemic approach to identifying road segments that require additional attention and possible need for shoulder improvements.  A negative binomial model with random effects was implemented to evaluate run off road crash frequency on two lane rural roads in relation to shoulder width. Nine years of crash data from 2015 to 2023 from more than 5,000 miles of Indiana rural highways was used. This model incorporates geometric factors including shoulder width, traffic exposure, and the presence of rumble strips to quantify the impact of shoulder width on crash frequency.  Crash Modification Factors (CMFs) were developed based on the existing combinations of shoulder and lane width, and proposed design alternatives. This allows for a comparison among different configurations. Findings indicated that increasing shoulder width generally reduces crash frequency. Installing a 5- or 6-ft shoulder in a location that previously did not have a shoulder resulted in the highest reduction in crashes according to CMFs. Shoulders equal to or exceeding 7 ft showed diminishing safety benefits when compared to shoulders of 5–6 ft. This is potentially due to the additional risk-taking by drivers under seemingly safer conditions. The presence of roadside rumble strips was found to reduce run-off-road (ROR) crashes by 9.1%.			
<b>17. Key Words</b> shoulder width, rural highways, run off road crashes, safety counter measure, rumble strip, road safety		<b>18. Distribution Statement</b> No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
<b>19. Security Classif. (of this report)</b> Unclassified	<b>20. Security Classif. (of this page)</b> Unclassified	<b>21. No. of Pages</b> 28	<b>22. Price</b>

## EXECUTIVE SUMMARY

### Introduction

Run-off-road (ROR) crashes account for a substantial proportion of severe and fatal accidents on rural roads. In Indiana, more than 70% of the state-administered highway network consists of rural two-lane roads. A considerable number of these highways were constructed under previous design standards. The nonstandard shoulder width on these highways may present a safety concern since shoulders provide a recovery space to errant vehicles and they may reduce crash severity.

The presented study investigates the relationship between shoulder width and ROR crash frequency based on data collected on more than 5,000 mi of rural roads in Indiana. A negative binomial regression model with random effects was developed to estimate the crash reduction effects of different shoulder widths, while controlling for the other factors such as lane width, traffic volume, horizontal alignment, rumble strips, and intersection density. Crash Modification Factors (CMFs) were derived to help compare design alternatives.

### Findings

Statistical modeling results confirm that shoulder width is a key determinant of ROR crash frequency. Roads with shoulder widths of 0, 1, or 2 ft exhibit significantly higher crash frequency when compared to those with wider shoulders. Three main findings emerged from the analysis:

1. **Safety Increases with Shoulder Width:** Shoulder widths of 3–6 ft are associated with substantially lower number of ROR crashes than roads with narrower shoulders. More specifically, segments with 5–6-ft shoulders showed the lowest crash frequencies among all the studied shoulder widths. Sufficiently wide shoulders offer space for drivers to recover after unintentional lane departures. This result supports the function of shoulders as a safety feature that enhances roadway forgiveness.
2. **Reduced Benefit of Excessively Wide Shoulders:** While the trend indicates that wider shoulders generally lead to improved safety, the benefits do not continue to grow beyond seven ft. Seven-ft shoulders and wider are, in fact, associated with a detectable increase in crash risk compared to 6-ft shoulders.

3. **Interaction Effects of Lane-Shoulder Widths:** The safety benefits of widening a road's shoulders depend directly on the width of the driving lanes. Widening shoulders (up to 6 ft) without narrowing the driving lane increases safety. Widening shoulders by reducing the lane width may lead to increase in number of crashes depending on the initial and final conditions. Drivers experience the highest crash risk on narrow roadways of less than 10 ft with no shoulders.

These findings emphasize the importance of a balanced cross-section design. A table with CMFs for a variety of initial and final shoulder width and lane width combinations is provided.

In addition to cross-sectional dimensions, the presence of rumble strips on shoulders or at edge lines was shown to reduce ROR crashes by approximately 9.1% (CMF = 0.9098).

### Implementation

To support the Indiana Department of Transportation (INDOT) and other transportation agencies in applying these findings, a methodology for project-level implementation was developed. It includes:

1. **Crash severity estimation using safety performance functions (SPFs):** Given the limited availability of clear zone and roadside hazard data, severity proportions were estimated using exposure-based SPFs for PDO and non-PDO crashes.
2. **Crash frequency estimation using full model and Empirical Bayes (EB) method:** The expected number of ROR crashes on a road segment is estimated using the developed equation. The EB method combines observed crash history with model-based estimates to produce the best crash frequency estimate which is then split into PDO and non-PDO severity categories using the SPF-derived proportions from the previous step.
3. **CMFs applications:** Once crash frequencies are calculated, the expected impact of design changes (e.g., shoulder widening) is quantified using the provided CMFs. These factors reflect Indiana specific road conditions, and they offer Indiana specific guidance unlike the national averages. The study provides the CMFs for a wide combination of shoulder and lane widths.
4. **Integration into benefit-cost analysis:** The user-attainable output includes crash reduction estimates (total and by severity) to be converted into monetary benefits by using the Indiana unit crash costs. These elements are compatible with INDOT's economic evaluation framework for prioritization of roadway improvement projects.

The proposed methodology is meant to help INDOT assess the safety impacts of cross-section improvements when roadside data are not available. An Excel-based tool was developed to facilitate the use of SPFs, CMFs, and EB estimates.

## CONTENTS

1. INTRODUCTION . . . . .	8
1.1 Research Problem . . . . .	9
1.2 Research Scope . . . . .	9
1.3 Report Outlines . . . . .	9
2. CURRENT STATE OF PRACTICE AND KNOWLEDGE . . . . .	10
2.1 Literature Review . . . . .	10
2.2 Indiana Practice . . . . .	11
2.3 Summary of Findings and Implications . . . . .	11
3. DATA DESCRIPTION . . . . .	12
3.1 Geometric Features . . . . .	12
3.2 Clear Zones . . . . .	14
3.3 Crash Data . . . . .	14
3.4 Traffic Data . . . . .	15
3.5 Intersections . . . . .	15
3.6 Rumble Strips . . . . .	15
3.7 Data Descriptive Summary . . . . .	16
4. STATISTICAL MODEL DEVELOPMENT . . . . .	17
4.1 Model Type Selection . . . . .	17
4.2 Model Estimation . . . . .	18
4.3 Discussion of Modeling Results . . . . .	19
5. MODEL APPLICATION . . . . .	19
5.1 Crash Modification Factors . . . . .	19
6. IMPLEMENTATION . . . . .	21
6.1 Estimating the Safety Effect of a Shoulder Width Change . . . . .	21
6.2 Example Safety Benefit Estimation . . . . .	21
6.2.1 Crash Severity Distribution . . . . .	21
6.2.2 Safety Performance Functions Based on Exposure . . . . .	22
6.2.3 Estimating Safety Benefit . . . . .	23
7. CLOSURE . . . . .	24
7.1 Summary . . . . .	24
7.2 Future Research . . . . .	25
REFERENCES . . . . .	25

## LIST OF TABLES

<b>Table 3.1</b>	Shoulder Width Distribution by Number of Segments and Number of Miles.	12
<b>Table 3.2</b>	Total Number of Miles Per Shoulder Width and Shoulder Type.	13
<b>Table 3.3</b>	Total Crashes and Percentages Per Shoulder Width.	14
<b>Table 3.4</b>	Total Crashes Per Severity Per Shoulder Width.	15
<b>Table 3.5</b>	Relation Between Shoulder Width and Rumble Strips Type.	16
<b>Table 3.6</b>	Statistical Summary of Variables.	16
<b>Table 4.1</b>	Results From Modeling.	18
<b>Table 5.1</b>	Crash Modification Factors Results.	20
<b>Table 6.1</b>	Road Characteristics.	21
<b>Table 6.2</b>	Crash Counts for 5 Years.	21
<b>Table 6.3</b>	Cost of Crashes by Severity (\$1000).	21
<b>Table 6.4</b>	Safety Performance Functions Based on Exposure.	23
<b>Table 6.5</b>	Empirical Bayes Method for Crash Estimation.	23
<b>Table 6.6</b>	Existing Conditions and Design Alternatives for a Segment.	23
<b>Table 6.7</b>	EB Method for Crash Estimation.	24
<b>Table 6.8</b>	Estimated Annual Reduction in Crashes by Severity.	24
<b>Table 6.9</b>	Estimated Annual Savings by Crash Severity.	24

## LIST OF FIGURES

<b>Figure 1.1</b>	Roadway Cross Section Elements (AASHTO, 2018).	8
<b>Figure 3.1</b>	Example of Bituminous Concrete Shoulder (Map Image: Google Street View ©).	13
<b>Figure 3.2</b>	Example of Portland Cement Concrete Shoulder (Map Image: Google Street View ©).	13
<b>Figure 3.3</b>	Example of Stabilized Shoulder (Map Image: Google Street View ©).	13
<b>Figure 3.4</b>	Example of Earth Shoulder (Map Image: Google Street View ©).	13
<b>Figure 3.5</b>	Histogram Relating Shoulder Width and Lane Width.	14
<b>Figure 3.6</b>	Histogram Relating Shoulder Width and AADT.	15
<b>Figure 3.7</b>	Histogram Relating Shoulder Width and Number of Minor Intersections Crossed.	15
<b>Figure 4.1</b>	Example of the Introduction of Random Effects to the Model.	17
<b>Figure 6.1</b>	PDO Model Results.	22
<b>Figure 6.2</b>	KABC Model Results.	23

## 1. INTRODUCTION

Motor vehicle collisions constitute a major public health crisis and impose a substantial economic burden (Haghighi et al., 2018; Llopis-Castelló et al., 2021). In 2023, the United States recorded 40,990 traffic-related fatalities (National Highway Traffic Safety Administration, 2024), such incidents are the leading cause of death for Americans aged 44 and younger (S. Chen et al., 2019). The associated economic impact is severe—an estimated \$836 billion in 2015, or 1.6% of the U.S. GDP, a figure that includes both tangible and intangible losses (Labi et al., 2017).

Mitigating these economic outcomes requires effective roadway design and rigorous safety analysis. Safety performance models are a critical tool that mathematically link roadway and traffic characteristics to crash frequency and severity (Tarko, 2012). The development of these models is fundamental to understanding key safety factors and helps implement effective countermeasures to reduce roadway injury and death (E. Chen & Tarko, 2014; Llopis-Castelló et al., 2021).

Because of the high rate of crashes on rural roads, rural road safety is an area of research of high interest (American Association of State Highway and Transportation Officials [AASHTO], 2022). According to Labi et al. (2017), in 2013, 19% of the U.S. population lived in rural areas, but rural road fatalities accounted for more than 53% of all road traffic fatalities. Peng et al. (2012) mentions that almost 80% of run-off-road (ROR) crashes happened on rural roads, with 90% of these crashes on two-lane rural roads. ROR crashes are defined as a crash which occurs after a vehicle crosses the center line, edge line, or otherwise leaves the way of travel (Federal Highway Administration [FHWA], 2023). ROR crashes, often involving a single vehicle, represent a significant share of serious and fatal traffic accidents. These accidents have a higher likelihood of occurring in rural rather than in urban areas. This can be attributed to differences in driving behavior and road conditions. Rural roads typically feature higher speed limits, lower traffic volumes, and fewer safety measures (S. A. Khan et al., 2023).

The FHWA (2015) reported that, in 2012, rural areas accounted for 54% of all traffic fatalities in the United States. This discrepancy, rural population size and fatality rates, underscores the need for targeted safety improvements on rural roads (Ben-Bassat & Shinar, 2011).

Although two-lane rural roads carry lower traffic volumes when compared to other types of roads, they have a relatively high crash rate (Schrock et al., 2011). This is partly because rural roads are often designed, constructed, and maintained to lower geometric standards due to their lower traffic volumes. These standards frequently result in the absence of shoulders, narrower lanes, and sharper curves, especially on low-volume roads (Ewan et al., 2016). Another reason is that in the early stages of highway engineering development, roadside design was based on limited knowledge (Ewan et al., 2016).

The main objective of geometric design consistency is to minimize the emergence of unexpected events when road users traverse a road segment. Thus, a consistent road provides a harmonious driving experience free of surprises, whereas an

inconsistent road might lead to numerous unexpected events for drivers, inciting an anomalous behavior and increasing the likelihood of a crash occurrence. Drivers' behavior is constantly changing along a road segment, so drivers might behave differently in response to the same road elements located on different road sections (Llopis-Castelló et al. 2021).

One of the most important tasks in traffic safety analysis is to investigate the relationship between crashes and geometric design of highways (Peng et al., 2012). Curve radius, lane width, and shoulder width have been identified as key geometric variables to analyze (Geedipally et al., 2019). However, Garber and Ehrhart (2000) found lane width and shoulder width among the main geometric characteristics that influence the safety of two-lane roads. Upgrading roadway features such as increasing lane and shoulder widths, reducing curves, and improving roadside conditions was identified as a viable means to reducing fatalities and injuries (Hadi et al., 1995; Haghighi et al., 2018). If other factors are constant, an increase in lane width and shoulder width was shown to reduce crash risk (Tarko et al., 2015). Due to the high cost of highway accidents, highway safety improvements are an important objective of transportation engineering (Karlaftis & Golias, 2002).

The FHWA (1990) defines shoulder width as “the portion of the roadway continuous with the traveled way for accommodation of stopped vehicles for emergency use, and for lateral support of the base and surface courses” (Figure 1.1). In recent years, these purposes of shoulder width have expanded with additional ones: expediting surface runoff from the roadway, providing safe space for maintenance and construction activities, accommodating slow moving equipment and bicycles, and adding an important safety feature for drivers who unintentionally steer from the traffic lanes (Souleyrette et al., 2001).

Wide shoulders provide an increased chance for drivers to regain control over vehicles and return to a travel way. It also provides an opportunity to swerve towards a shoulder to avoid collision with another vehicle. On the other hand, narrow shoulders may not be much help if the driver does not have sufficient recovery space during an unintentional lane departure. In this scenario, the likelihood of full road departure increases leading to a potential off-road crash if the roadside is unforgiving (Ben-Bassat & Shinar, 2011). Furthermore, sufficiently wide paved shoulders can improve both the comfort and safety of driving (J. Y. Chen & Tian, 2012), while unpaved shoulders, such as those made of gravel or dirt, are less effective in crash mitigation (Labi, 2006).

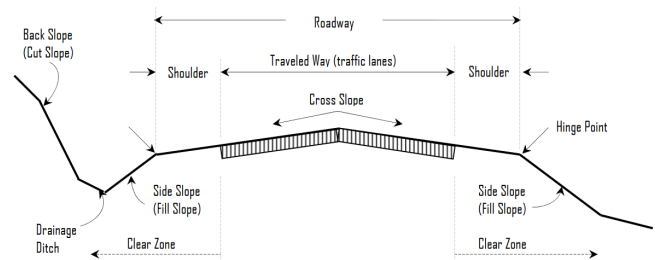


Figure 1.1 Roadway Cross Section Elements (AASHTO, 2018).

A key component influencing the severity of ROR crashes is the roadside environment, particularly the concept of the clear zone. The clear zone is defined as the unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles (AASHTO, 2018). A properly maintained clear zone allows vehicles that leave the roadway to recover safely without colliding with fixed objects such as trees, utility poles, or embankments (White, 2023). However, the absence of a well-defined and consistently applied clear zone increases the likelihood of severe crashes, especially on rural roads where road departures are more frequent.

Insufficient shoulder width can increase the risk of vehicles immediately encountering unforgiving roadside features, leading to severe or fatal injuries (Benekahal & Hashmi, 1992). However properly designed and adequately wide shoulders can act as an extension of the clear zone, improving roadway forgiveness and reducing crash severity (Park & Abdel-Aty, 2016).

In general, widening and properly surfacing shoulders are among the road safety countermeasures known to reduce crashes (Park & Abdel-Aty, 2016). The reason is that if a driver loses control over the vehicle and runs off the traffic lane, a wider shoulder provides the opportunity to return safely to traffic (Peng et al., 2012). Several studies have demonstrated the effectiveness of widening shoulders in preventing crashes, especially running off road (Hallmark et al., 2013; Peng et al., 2012). However, too liberal design, such as too wide shoulders and lanes combined with flat curves, may lead to overconfidence and speeding which can offset safety benefits (Shinar, 2007, as cited in Ben-Bassat & Shinar, 2011).

### 1.1 Research Problem

Prior research by Purdue University's Center for Road Safety (CRS) has significantly contributed to roadway safety improvements in Indiana. Their research has contributed significantly to identifying high-crash locations through systematic network screening, such as the development of the Safety Needs Identification Program (SNIP2), which optimizes countermeasure selection for crash reduction (Tarko et al., 2011). Additionally, CRS has evaluated the impact of geometric deficiencies on road safety through a performance measure-based screening and project evaluation framework, which supports the Indiana Department of Transportation's (INDOT) asset management process by identifying road segments with inadequate geometry (Tarko et al., 2015). Further, their research has examined speed factors on two-lane rural highways, identifying key roadway and curvature variables affecting mean speed and speed dispersion, which influence crash risk (Medina & Tarko, 2005). Despite these advancements, the specific safety effects of shoulder width on rural highways remain insufficiently explored for Indiana roadway conditions. This gap in research points out to the need for a study focused on the shoulder width influence on crash frequency.

This research aims to evaluate the safety effect of shoulders on rural roads in Indiana and to propose a practical and systemic approach to identifying road segments that require more attention and possible shoulders' improvement. To support

INDOT in this task, the study attempts to develop a set of Crash Modification Factors (CMFs) that reflect the safety effects of widening shoulders under both various design alternatives and wide range of road and traffic conditions. The study presented here uses the ROR crash data collected for Indiana rural two-lane roads during the 2015–2023 period.

The study scope includes a comparative evaluation of the safety effects of shoulder width on rural highway segments under various conditions. This is planned to be accomplished by estimating crash reduction attributed to shoulder widening and by expressing the results through CMFs that reflect the Indiana conditions.

### 1.2 Research Scope

A cross-sectional analysis will be applied to compare the safety performance (roadway departure crashes) of rural roads across sites with various shoulder designs while controlling for local factors such as traffic volume and road geometry. Rural state-administered highways will be included in the analysis. Road segments affected by nearby intersections, collisions with animals, and crashes that do not fall within the project's scope, such as rear-end collisions, right angle collisions with vehicles from minor roads, and others, will be excluded from the analysis.

### 1.3 Report Outlines

This report is organized into seven chapters, each examining specific aspects of the research on shoulder widths and their influence on crash frequency and severity. The organization of the document is as follows.

The first chapter introduces the topic of shoulder width and its significance for roadway safety. It provides an overview of the research scope, and it highlights the motivation of the study. The research objectives and scope of this research are introduced, and the key objectives identified to be properly addressed throughout the report.

The second chapter provides a comprehensive review of previous research related to shoulder width and its possible effect on roadway safety. It summarizes key findings, results, challenges, and research gaps identified in literature. Additionally, the chapter offers insights into the current Indiana practices and policies in place and related to the topic at hand.

The third chapter describes the data sources used in the study and the dataset characteristics. It presents an initial exploration of the data, including descriptive statistics and data visualization to overview the available information.

The fourth chapter presents the development of the statistical model used to estimate crash frequency and evaluate the impact of shoulder width and other roadway characteristics. It introduces the negative binomial (NB) model with random effects, explaining its formulation, assumptions, and suitability for the research problem. The estimation process is detailed, including variable selection, model fit criteria, and statistical significance of the variables. The chapter presents the modeling results, analyzing the influence of key variables, along with a discussion of how these factors contribute to roadway safety.

The fifth chapter presents the application of modeling results through CMFs, developed to quantify the expected safety impact of different lane and shoulder width configurations.

The sixth chapter explains how to use the modeling results and obtained CMFs in estimating the safety benefit of changing shoulder and lane width. Further, a detailed example that illustrates the step-by-step procedure to calculate the safety benefit is provided.

Finally, the seventh chapter provides closure by summarizing the research. It also identifies the limitations of the current study and highlights areas for future research. Potential directions for improving the accuracy and applicability of crash prediction models are discussed.

## 2. CURRENT STATE OF PRACTICE AND KNOWLEDGE

### 2.1 Literature Review

The relationship between shoulder width and roadway safety has been a subject of interest for several decades manifested through multiple studies that examined the impact of shoulder design on crash rates, particularly of ROR crashes. Early research by Zegeer et al. (1981) indicated that wide shoulders significantly reduced the crash rates by up to 21% for 9-ft shoulders compared to no shoulders. Their study examined crash types such as ROR, head-on, and sideswipe crashes on rural two-lane roads in the US, with a reported reduction of 16% when widening the shoulders (both sides) from 2 to 8 ft on an average section of rural, two-lane highway.

Hadi et al. (1995) expanded the earlier findings by utilizing negative binomial regression models to assess various highway types in the state of Florida. Their study found that the lane and shoulder widths associated with the lowest crash rates for two-lane rural highways were 13 ft for lane width and 10–12 ft for shoulder width.

Souleyrette et al. (2001) further examined the influence of roadway geometry on crash rates on rural roads, reinforcing the findings that wider shoulders reduced the ROR crash rates, as well as head-on and sideswipe crashes. In general, their study found that the most effective benefits from paved shoulders occur with a minimum width of 2–3 ft. Additionally, their study highlighted that the use of rumble strips on paved shoulders further reduces ROR crashes. Their report also mentions that while reduced crash rates with paved shoulders have been observed in various studies, the study was unable to verify this with confidence in Iowa due to the limited availability of comparable two-lane rural roads with paved shoulders for analysis.

A case-controlled study of roads in Pennsylvania was conducted to estimate the effect of shoulder width on crash rates (Gross & Jovanis, 2007). This study found that crash rates decreased as shoulder width increased, particularly for shoulders greater than 2.44 m (8 ft). However, the study did not include geometric design elements in the analysis and instead focused on driver, vehicle, and environmental factors, limiting the broader applicability of its findings. A related study from Gross et al. (2009) examined safety improvements on rural two-lane undivided roads, confirming that lane-shoulder

combinations provided variable safety benefits. The study found CMFs of 0.87 for 8-ft shoulders, reinforcing the safety benefits of wider shoulders.

A study of rural roads in Kansas from Schrock et al. (2011) concluded that the CMFs for shoulder widening from 2 ft (0.61 m) to 8 ft (2.44 m) was 0.95, while the CMF for adding passing lanes was 0.65. This study specifically analyzed run-off-road and single-vehicle crashes, emphasizing the role of shoulder widening and lane additions in reducing crash risk.

Labi (2011) analyzed geometric characteristics' effects on crash rates and proposed safety performance models. Their findings indicated that the effectiveness of shoulder widening varied across different road classifications, with the greatest reductions in PDO crashes observed on rural principal arterials (6–33%) and the least on rural major collectors (1–6%). Similarly, for fatal and injury crashes, the impact of increased shoulder width was highest on rural principal arterials (9–43%) and lowest on rural major collectors (3–17%). While their study found that increasing shoulder is an effective countermeasure, its primary objective was to demonstrate the necessity of classifying rural two-lane highways into distinct subclasses for more precise safety analyses.

Gross et al. (2009) examined case-control and cross-sectional methods to estimate CMFs for lane and shoulder widths, highlighting that both methodologies produced consistent results when study design and model specifications were carefully considered. Their analysis, conducted on two-lane rural highway segments in Pennsylvania, found that CMFs for shoulder widths varied by less than 10% between the two methods for widths ranging from 0–8 ft. However, for shoulder widths of 9 and 10 ft, larger discrepancies were observed due to the small sample size available for analysis. Their study emphasized the importance of controlling roadway features and traffic volumes in cross-sectional studies to approximate case-control results, while also acknowledging the limitations of both methodologies in estimating CMFs.

Hallmark et al. (2013) reinforced previous findings by focusing on rural highways in Iowa, where they observed that wider shoulders reduced ROR crashes more effectively than shoulder paving. Their study reported a reduction of ROR crashes by 7.3–8.9% per additional foot of shoulder width.

Park & Abdel-Aty (2016) conducted a detailed analysis of the safety effects of shoulder widening on rural multilane roads in Florida, using a cross-sectional methodology that considered interactions between lane width, shoulder width, and traffic volume. Their study found that increasing shoulder width was particularly effective in reducing severe crashes. Their study estimated CMFs for various shoulder width changes at different annual average daily traffic (AADT) levels, demonstrating that safety benefits increased as AADT increased. Additionally, their study highlighted the nonlinear relationship between lane width and crash rates, emphasizing that while increasing lane width initially reduced crash frequency, the effect diminished beyond a certain width. Interaction effects between lane and shoulder width were also observed, with narrower lanes reducing the safety benefits of shoulder widening. Their findings suggest that optimizing shoulder and lane widths in conjunction with AADT

considerations is crucial for maximizing safety improvements on rural roads.

Labi et al. (2017) explored the safety effects of roadway design features, specifically examining the impacts of lane width, shoulder width, and other geometric characteristics on crash outcomes on rural two-lane highways. Their study developed an optimization framework using nonlinear programming techniques to determine the optimal distribution of total roadway width (lane + shoulder) while minimizing total life-cycle costs. This framework accounts for both life-cycle agency costs and life-cycle user (safety) costs, ensuring a balanced approach to roadway design decisions. Their study utilized data from previous research in 2006 which analyzed multiple geometric factors on rural two-lane roads to estimate their effects on crash reduction. Therefore, their study identified several data quality and completeness issues, such as missing road inventory data, inconsistencies in crash descriptions, and difficulties in merging datasets.

Pokorny et al. (2020) further examined the relationship between lane and shoulder width on rural highways with the objective of quantifying their impact on crash rates and severity. Their study found significant correlations between wider lanes and shoulders and lower crash frequencies. The reported CMF for lane width was 0.85, meaning that increasing lane width by 1 ft led to a 15% reduction in crash rates. More importantly, the study emphasized that wider shoulders contribute to improved roadway safety by providing drivers with additional space to maneuver, particularly in emergency situations. Their findings suggested that increasing shoulder width could significantly reduce the incidence of ROR crashes, which are commonly associated with narrow shoulders. While their study confirmed the safety benefits of shoulder widening, the authors acknowledged key limitations, including the need to explore additional roadway characteristics, such as pavement condition and curvature, and the potential influence of environmental factors.

Finally, Mecheri et al. (2022) investigated the influence of paved shoulders on driver behavior while navigating left and right curves on two-lane rural roads, with a specific focus on how shoulder presence and width affect lateral control of the vehicle. Using a driving simulator, they tested participants under conditions with and without oncoming traffic. Their study found that shoulders significantly influenced lateral positioning, particularly in right curves where drivers deviated more toward the inner lane edge, increasing the risk of lane departure. Specifically, lateral deviation on right curves was greater in the presence of both 0.75-m (2.46-ft) and 1.25-m (4.10-ft) shoulders compared to no shoulder, confirming the direction-specific impact of shoulders. However, the study found minimal effects of shoulder width on lateral control across different traffic conditions. The authors emphasized the need for further research on the interaction between shoulder presence, oncoming traffic, and roadside configurations.

The studies reviewed in this section provide substantial evidence supporting the safety benefits of wider shoulders, particularly for ROR crashes. However, critical gaps were also identified, including the effects of wider shoulders on driving behavior, regional variations in safety outcomes, and diminishing returns for excessively wide shoulders.

These findings will be briefly revisited in Section 2.3, which emphasizes the importance of a context-driven approach. However, given this study's specific context—two-lane rural roads in Indiana—it is important to first review Indiana's specific situation regarding practice and implementation of shoulder widths on rural roads before summarizing the findings and implications of the above literature.

## 2.2 Indiana Practice

The design and implementation of shoulder width on roads in Indiana, particularly on rural two-lane roads, adhere to specific guidelines established by INDOT and AASHTO. These standards aim to enhance road safety while accommodating varying road contexts and traffic conditions.

For rural two-lane roads, the INDOT Design Manual (2013) specifies a minimum shoulder width of 4 ft. However, many existing roads in Indiana do to meet this standard. According to Labi (2006) a large number of Indiana's rural two-lane state highways have shoulder widths of 4 ft or less. Additionally, a study of a sample of county roads in Indiana found that more than 90% lack discernible shoulders, posing significant safety risks for drivers (Labi, 2011). These figures highlight the disparity between older road designs and current standards outlined in the INDOT Design Manual and AASHTO's (2018) "Green Book," which recommend lane widths of 11–12 ft and shoulder widths of 4–6 ft for rural two-lane roads (Fitzpatrick et al., 2016).

Regarding the clear zone, AASHTO provides a general definition; however, its practical application varies, and the actual implementation often depends on engineering judgment rather than strict guidelines (White, 2023).

Indiana's state highway network spans more than 11,000 mi, of which rural two-lane roads account for 70%, making them the largest single group in the highway network (Labi, 2006). Many of these roads were constructed under outdated design standards, as a large portion of Indiana's rural two-lane roads were built before modern geometric guidelines were established. The flexibility provided by the INDOT Design Manual (2013) and AASHTO (2018) guidelines helps accommodate these challenges, allowing designers to balance safety improvements with economic feasibility (Jiang et al., 2013). For instance, design exceptions may be employed where following recommended dimensions is impractical due to site-specific constraints.

## 2.3 Summary of Findings and Implications

The reviewed literature highlights the complex role of shoulder width in roadway safety particularly on two-lane rural roads. Studies consistently demonstrate that wider shoulders reduce ROR crashes by increasing the recovery space for drivers and by increasing the road forgiveness for driving errors and making them an important safety feature (Hallmark et al., 2013; Park & Abdel-Aty, 2016).

Numerous studies have addressed the safety benefits of shoulder width, few have focused on the interaction between clear zone characteristics, roadside objects, and crash severity

(I. U. Khan et al., 2024; White, 2023). Roadside hazards, such as trees, utility poles, and embankments, have been shown to significantly increase crash severity in ROR crashes (Benekohal & Hashmi, 1992; Schneider et al., 2009). In particular, collisions with fixed roadside objects, especially trees, have been associated with high fatality rates with tree-related crashes resulting in fatalities at nearly twice the rate of other fixed-object collisions (Wolf & Bratton, 2006, as cited in White, 2023).

While many studies affirm the general safety benefits of wider shoulders, other research indicates that these benefits may vary depending on factors such as speed limit, drivers' risk perception, and road conditions (Ben-Bassat & Shinar, 2011; Mecheri et al., 2022). For instance, excessively wide shoulders have been associated with higher operating speeds and riskier driving behaviors, which may offset their intended safety benefits. This phenomenon suggests that drivers may adjust their behavior based on perceived safety improvements (Labi et al., 2017; Rahman Shaon & Qin, 2016).

These insights emphasize the need for a balanced approach, where shoulder width is optimized to address specific roadway and traffic characteristics rather than applied uniformly. Design guidelines, such as those provided by INDOT (2013) and AASHTO (2018), should consider the interplay between lane width, shoulder width, and traffic conditions to achieve the best safety outcomes (Fitzpatrick et al., 2016; Jiang et al., 2013).

The following chapters focus on evaluating the specific conditions of two-lane rural roads in Indiana, considering their unique geometric designs and traffic characteristics. The findings here aim to provide valuable insights to inform future roadway design and safety standards, ensuring that shoulder configurations are both effective and aligned with the specific needs of the state's rural roadways.

### 3. DATA DESCRIPTION

In this study, data from various sources were combined to evaluate the safety performance of two-lane rural roads in Indiana and to understand the influence of roadway design and external factors on crash frequency and severity. The database is constructed with a comprehensive set of variables encompassing geometric features, crash data, traffic volume, and other countermeasures commonly used, such as rumble strips. The primary data were provided by INDOT's Geographic Information Office. Additionally, the facilitation of data for this project was made possible through the support of the CRS, whose contributions were essential in compiling and structuring the database. These datasets provide the foundation for analyzing the relationship between road design elements and crash occurrences.

#### 3.1 Geometric Features

The focus of this analysis is to evaluate the safety effectiveness of shoulder widths on two-lane rural roads in Indiana. The main source of information for determining the geometric features of each road segment is INDOT's road inventory. Information pertaining to functional classification, lane width (feet), shoulder width (feet), shoulder type, and length of

each segment (miles), and other pieces of data are included in INDOT's road inventory. The data were reorganized around the categorized shoulder widths—the focus of the study. All shoulder width and lane width values were provided by INDOT as whole numbers. The distribution of shoulder widths is presented in Table 3.1.

INDOT's inventory defines seven different shoulder categories based on the presence of curb and shoulder's surface. Table 3.2 summarizes the total length of roads with specific shoulder types and their widths in Indiana.

To illustrate the differences among the INDOT shoulder types, a compilation of their examples are presented in Figure 3.1, Figure 3.2, Figure 3.3, and Figure 3.4.

As mentioned in the literature review, the combination of lane and shoulder widths (Figure 3.5) influences driver's behavior and affects the risk of ROR occurrences. Widths of lanes and shoulders affect how drivers position their vehicles. Narrower lanes typically lead to more centered driving and lower speeds, whereas wider shoulders can prompt drivers to edge closer to the roadway's limit, potentially increasing collision risks (Ben-Bassat & Shinar, 2011; Mecheri et al., 2017). Optimizing roadway design requires a good balance with often recommended 11 or 12 ft for lane width. However, lane widths on many Indiana rural two-lane roads do not meet current design standards.

Horizontal alignment characteristics such as total deflection angle, average curvature, and number of curves are calculated along each segment with the assistance of a software tool developed at the CRS. This software was applied to determine the curvature characteristics of road segment as described below.

Calculating the curvature of a segment represented with a polyline involved finding the curvature at discrete points along the polyline. A segment curvature estimated based on a series of connected polyline segments was used to measure the horizontal curve sharpness. This calculation needed angles between consecutive polyline segments. The operations presented below include calculating these angles, segment curvature, and number of curves.

TABLE 3.1  
Shoulder Width Distribution by Number of Segments and Number of Miles.

Shoulder Width (ft)	No. of Segments	No. of Miles
0	5,471	3,444
1	163	105
2	1,930	1,273
3	274	187
4	128	69
5	53	24
6	71	41
7	25	8
8	76	45
9	31	17
10	129	69
11	2	1
12	13	12
14	1	1
15	1	1
Total	8,368	5,297

TABLE 3.2  
Total Number of Miles Per Shoulder Width and Shoulder Type.

Shoulder Width (ft)	Shoulder Type							Total
	Curb	None or Inadequate	Bituminous Concrete	Portland Cement Concrete	Stabilized	Combination	Earth	
0	80	3,364	0	0	0	0	6	3,444
1	0	7	104	1	0	0	0	105
2	0	0	616	0	656	0	1	1,273
3	0	0	132	2	53	0	0	187
4	0	0	57	6	6	0	0	69
5	0	0	20	2	2	0	0	24
6	0	0	34	2	5	0	0	41
7	0	0	7	1	0	0	0	8
8	0	0	40	4	1	0	0	45
9	0	0	14	3	0	0	0	17
10	0	0	65	4	0	0	0	69
11	0	0	1	0	0	0	0	1
12	0	0	11	1	0	0	0	12
14	0	0	1	0	0	0	0	1
15	0	0	1	0	0	0	0	1
<b>TOTAL</b>	<b>80</b>	<b>3,364</b>	<b>1,103</b>	<b>26</b>	<b>723</b>	<b>0</b>	<b>1</b>	<b>5,297</b>



Figure 3.1 Example of Bituminous Concrete Shoulder (Map Image: Google Street View ©).



Figure 3.3 Example of Stabilized Shoulder (Map Image: Google Street View ©).



Figure 3.2 Example of Portland Cement Concrete Shoulder (Map Image: Google Street View ©).



Figure 3.4 Example of Earth Shoulder (Map Image: Google Street View ©).

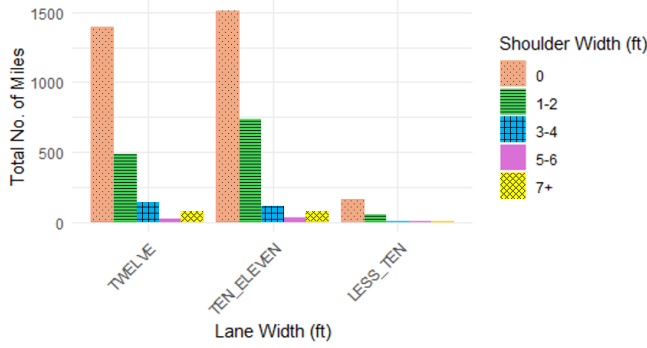


Figure 3.5 Histogram Relating Shoulder Width and Lane Width.

For each consecutive triplet of points  $(P_{i-1}, P_i, P_{i+1})$ , two vectors are calculated:

$$\vec{v}_i = P_i - P_{i-1}, \vec{w}_i = P_{i+1} - P_i \quad (\text{Eq. 3.1})$$

Then, the angle  $\theta_i$  between these two vectors is obtained:

$$\theta_i = \arccos\left(\frac{|\vec{v}_i \cdot \vec{w}_i|}{|\vec{v}_i| |\vec{w}_i|}\right) \quad (\text{Eq. 3.2})$$

The total segment deflection angle  $\delta$  along the segment (small individual errors tend to cancel out when summed along the segment):

$$\delta = \sum_{i=1}^{n-1} |\theta_i| \quad (\text{Eq. 3.3})$$

The total segment deflection angle to left  $\delta_L$  and to right  $\delta_R$  (turn direction determined with the sign of the vectors cross product) is:

$$\delta_L = \sum_{i=1}^{n-1} \begin{cases} |\theta_i| & \text{if cross product is positive} \\ 0 & \text{if cross product is negative} \end{cases} \quad (\text{Eq. 3.4})$$

$$\delta_R = \sum_{i=1}^{n-1} \begin{cases} |\theta_i| & \text{if cross product is negative} \\ 0 & \text{if cross product is positive} \end{cases}$$

The deflection rates are calculated as the total deflection rate divided by the segment length. The sequences of deflection angles of the same sign and of sufficient length indicate the presence of horizontal curves. Other road segment horizontal alignment characteristics derived from their polylines are not found to significantly affect road safety and are not presented.

### 3.2 Clear Zones

The available information provided by INDOT did not include any shapefile related to the clear zones. As a result, it was not possible to identify roadside features such as trees, utility poles, or ditches. Manually obtaining this information, even with the available video-log equipment in Indiana, is highly labor intensive. Conducting such analysis for all two-lane rural roads in Indiana was not feasible due to time constraints.

### 3.3 Crash Data

The needed police crash reports were obtained from the Automated Reporting Information Exchange System (ARIES) database. The information contained crash specifics, location, number of vehicles involved, type of crash, type of vehicles, and manner of collision. The latitude and longitude of each crash were used to assign individual crashes to the analyzed road segments for analysis and to relate the crashes to the shoulder width (Table 3.3). The crashes were classified into three categories: ROR, head-on, and other types of crashes.

- ROR: This type of crash involves vehicles leaving the roadway to the right or left, typically due to loss of control or driver error.
- Head-on: This type of crash occurs when a vehicle crosses the centerline of the road and collides with another vehicle traveling in the opposite direction.
- Other types of crashes: This category includes various crash types such as rear-end collisions, sideswipe collisions (both same and opposite directions), and angle collisions (e.g., T-bone crashes).

The database includes indicators to specify whether a crash (any type) was related to the use of alcohol or if an animal was involved. The definitions for these indicators are presented below:

- Crashes involving animals: This category includes all crashes where a vehicle collides with an animal, most commonly deer.
- Crashes involving alcohol intoxication: This category includes all crashes where the driver was found to have alcohol in their system, as indicated by a blood alcohol concentration (BAC) test.

All crashes were also categorized by their severity outcome according to KABCO scale, where K represents fatal injury, A represents incapacitating injury, B represents minor injury, C represents possible injury, and O represents a property-damage-only (PDO) crash. Due to relatively low number of crashes in each of the individual injury severity levels, the crashes were grouped into three categories, namely: KA (fatal or incapacitating injury), BC (minor or possible injury), and PDO (property damage only)

TABLE 3.3  
Total Crashes and Percentages Per Shoulder Width.

Shoulder Width (ft)	ROR	Head-On	Other	Total
0	13,545 (64%)	1,134 (58%)	32,954 (62%)	47,633
1	515 (2%)	72 (4%)	1,348 (3%)	1,935
2	5,353 (25%)	458 (24%)	12,122 (23%)	17,933
3	638 (3%)	88 (5%)	2,179 (4%)	2,905
4	347 (2%)	43 (2%)	927 (2%)	1,317
5	106 (0%)	14 (1%)	415 (1%)	535
6	140 (1%)	23 (1%)	471 (1%)	634
7	57 (0%)	5 (0%)	137 (0%)	199
8	174 (1%)	16 (1%)	626 (1%)	816
9	74 (0%)	10 (1%)	175 (0%)	259
10	310 (1%)	79 (4%)	1,335 (3%)	1,724
11	1 (0%)	0 (0%)	4 (0%)	5
12	29 (0%)	0 (0%)	108 (0%)	137
14	5 (0%)	0 (0%)	10 (0%)	15
15	1 (0%)	0 (0%)	9 (0%)	10
<b>Total</b>	<b>21,295 (100%)</b>	<b>1,942 (100%)</b>	<b>52,820 (100%)</b>	<b>76,057</b>

TABLE 3.4  
Total Crashes Per Severity Per Shoulder Width.

Shoulder Width (ft)	KA_ROR	BC_ROR	PDO_ROR	KA_head-on	BC_head-on	PDO_head-on	KA_other	BC_other	PDO_other
0	2,341	1,787	9,417	492	176	466	2,107	2,115	28,732
1	74	57	384	36	7	29	101	125	1,122
2	867	742	3,744	181	75	202	757	891	10,474
3	92	67	479	29	5	54	153	126	1,900
4	48	46	253	22	7	14	69	60	798
5	14	12	80	3	1	10	36	25	354
6	34	15	91	14	2	7	41	35	395
7	11	10	36	1	-	4	7	8	122
8	23	19	132	7	3	6	46	36	544
9	5	10	59	3	-	7	22	11	142
10	43	40	227	20	14	45	69	116	1,150
11	-	-	1	-	-	-	1	-	3
12	6	5	18	-	-	-	5	7	96
14	1	1	3	-	-	-	-	-	10
15	-	1	-	-	-	-	-	-	9
<b>Total</b>	<b>3,559</b>	<b>2,812</b>	<b>14,924</b>	<b>808</b>	<b>290</b>	<b>844</b>	<b>3,414</b>	<b>3,555</b>	<b>45,851</b>
<b>%</b>	<b>5%</b>	<b>4%</b>	<b>20%</b>	<b>1%</b>	<b>0%</b>	<b>1%</b>	<b>4%</b>	<b>5%</b>	<b>60%</b>
<b>Cumulative</b>		<b>21,295</b>			<b>1,942</b>			<b>52,820</b>	
<b>Cumulative %</b>		<b>28%</b>			<b>3%</b>			<b>69%</b>	

for a better analysis of the crash severity model (Table 3.4). ROR crashes represented approximately 28% of all crashes recorded in the studied segments. Approximately 30% of all ROR crashes resulted in injuries. The rest resulted in property damage only.

All ROR crashes were included in the analysis, even if they also involved other factors such as animal-related impacts or drivers with high BAC levels.

### 3.4 Traffic Data

The information of the volume of traffic on rural roads in Indiana was obtained from the shapefiles provided online by INDOT. The historic traffic zone shapefiles are published yearly, and they are free to access on INDOT's [Traffic Data Site](#). If information about the AADT is missing for a road in a specific year, then the missing information is calculated by taking the AADT of a different year for that road and dividing it by the adjustment factors also provided by INDOT. Seasonal factors for monthly adjustment of the traffic are also found on INDOT's repository. Each segment is associated with its corresponding AADT for every year in the analysis and is related to the corresponding geometric characteristics (Figure 3.6).

### 3.5 Intersections

To ensure that the analysis does not include the effects of major intersections, crashes that occurred at major intersections and within 250 ft from them along the studied segments were removed. A major intersection is defined as an intersection of a state administered road and an arterial or collector. Unlike major intersections, minor intersections were retained for the analysis together with other geometric characteristics of studied segments (Figure 3.7). Their effects on crashes are accounted for by including the number of minor intersections each segment crosses as a variable in the model among the other variables.

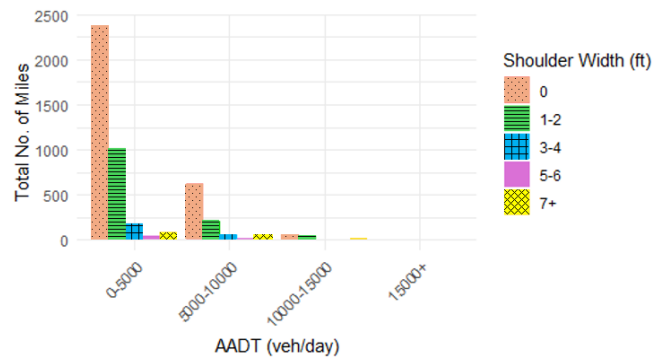


Figure 3.6 Histogram Relating Shoulder Width and AADT.

### 3.6 Rumble Strips

Rumble strips are among commonly used countermeasures to avoid ROR and head-on crashes on road segments. Rumble strips are installed on the side of the road (edge or shoulder), in the centerline of the road, or in combination. Rumble strips are



Figure 3.7 Histogram Relating Shoulder Width and Number of Minor Intersections Crossed.

meant to be a preventive measure against driver error and not to mitigate deficiencies of roadway design. They provide audible and vibratory warnings to drivers to increase the likelihood of corrective and timely action against ROR (FHWA, 2018).

Information about the installation of rumble strips includes rumble strip type (conventional or sinusoidal), rumble strip width (16 or 12 in.), and rumble strip placement (center, edge, shoulder, or combination). As both shoulders and rumble strips

are commonly used as countermeasures to reduce ROR crashes, their interaction becomes important to analyze (Table 3.5).

### 3.7 Data Descriptive Summary

The descriptive summary of the variables used in modeling are presented in Table 3.6. In total, there were 8,368 road segments included in the dataset. They represent approximately 5,300 mi

TABLE 3.5  
Relation Between Shoulder Width and Rumble Strips Type.

Shoulder Width (ft)	No RS		Unknown type		Conventional		Sinusoidal	
	Miles	Segments	Miles	Segments	Miles	Segments	Miles	Segments
0	2,451	3,869	201	342	467	748	326	512
1	59	80	4	8	33	55	9	20
2	974	1,464	55	98	132	200	112	168
3	126	189	31	42	21	27	9	16
4	39	77	1	3	5	8	24	40
5	16	34	2	5	5	11	1	3
6	23	38	5	7	10	22	2	4
7	6	16	0	2	1	5	0	1
8	29	46	2	5	9	16	5	9
9	13	21	0	1	3	6	1	3
10	51	90	8	14	4	12	6	13
11	1	2	0	0	0	0	0	0
12	10	12	0	0	2	1	0	0
14	1	1	0	0	0	0	0	0
15	1	1	0	0	0	0	0	0

TABLE 3.6  
Statistical Summary of Variables.

Continuous Variables						
Variable	Explanation	Min	Max	Mean	Standard Deviation	Mode
AADT	Annual Average Daily Traffic in veh/day	25.00	35,231.00	3,665.06	2,721.91	1,450.00
L	Length of the roadway segment in miles	0.05	2.87	0.64	0.46	0.07
SW	Shoulder width in feet	0.00	15.00	1.00	1.89	0.00
LW	Lane width in feet	7.00	12.00	10.82	1.17	12.00
SL	Speed limit in mph	10.00	60.00	48.91	9.43	55.00
DA	Total deflection angle (in degrees) per mile	0.00	3,256.11	47.63	104.96	0.00
Crv	Total number of curves per mile	0.00	73.78	2.76	4.67	0.00
Int	Number of minor intersections per mile	0.00	1,379.32	15.24	46.19	0.00
Categorical variables						
Variable	Explanation	Levels	Count	Percent		
$FC_{PA}$	Functional Class	Principal Arterial	14,922	19.99		
$FC_{MA}$		Minor Arterial	21,222	28.43		
$FC_{Coll}$		Collectors	38,376	51.41		
$FC_{Local}$		Local Roads	126	0.17		
$SW_{0,1,2}$	Shoulder Width	0–1–2 ft	67,761	90.78		
$SW_{3,4}$		3–4 ft	3,501	4.69		
$SW_{5,6}$		5–6 ft	1,089	1.46		
$SW_{7+}$		7 + ft	2,295	3.07		
$LW_{<10}$		Lane Width	< 10 ft	9,027	12.09	
$LW_{10,11}$	10–11 ft		34,551	46.29		
$LW_{12}$	12 ft		31,068	41.62		
Y2020	Indicator for observations during the year 2020 (COVID-19)	1	8,368	11.21		
	Otherwise	0	66,278	88.79		
RS	No rumble strip	0	65,136	87.26		
	Rumble strip installed	1	9,510	12.74		

of roads. Rows in the table provides summary statistics for model variables applied to segment annual observations. Nine years of crash data (2015–2023) were assigned to the respective observations along with traffic, geometry, and rumble strip settings. In total, there were 74,646 observations.

#### 4. STATISTICAL MODEL DEVELOPMENT

The focus of this research is to evaluate how certain geometric elements influence ROR crashes to develop strategies that help keep vehicles on the road. This objective is achieved by developing a crash frequency model which evaluates how different cross-section elements impact crash occurrence. The evaluation of these countermeasures is expressed through CMFs, which quantify the expected change in crash frequency associated with the implementation of design alternatives.

##### 4.1 Model Type Selection

Crash frequency data is inherently overdispersed, meaning that the variance of numbers of observed crashes often exceeds the mean value. This fact makes the Poisson model, which assumes an equal mean and variance, unsuitable for crash frequency analysis (Lee et al., 2023| Lord & Mannering, 2010). The NB model addresses this limitation by introducing a dispersion parameter that allows the variance to be greater than the mean, making it one of the most widely used models in transportation safety research (Islam et al., 2014). In essence, the NB model extends the Poisson model by assuming that its mean follows a gamma distribution, thereby accounting for the unobserved heterogeneity in roadway segments (Lord & Mannering, 2010).

The NB model has been questioned by several authors regarding its applicability under conditions of low sample mean and limited crash data, where many roadway segments report no crashes over the study period. Previous studies suggested that low mean crash counts, often skewed toward zero, may lead to improperly estimated parameters and incorrect inferences (Llopis-Castelló et al., 2021; Lord & Mannering, 2010; Rahman Shaon & Qin, 2016). Concerns have also been raised about potential estimation issues arising from incomplete or poor roadway data, which may further affect model reliability. To the contrary, Hall & Tarko (2019) demonstrated the validity the NB-based modeling for low-volume and low-crash rural roads. By applying proper tests, they confirmed an unbiased model estimate for the entire range of observed values including locations with low counts. Small samples and under-reporting issues apply to data and not to modeling methodology. Researchers continue applying NB modeling to a variety of conditions including low-mean data samples.

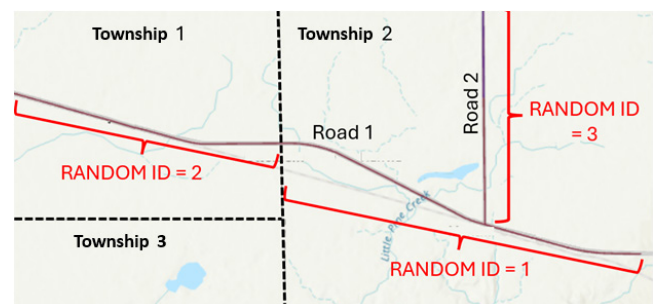
One of possible enhancements of the NB model is including random effects in the model structure if observations may be grouped in some meaningful way and these cluster-specific effects are not captured by observed variables. One natural grouping is annual observations having their own year effects not captured otherwise. In transportation safety studies, roadway segments within the same geographic region or functional classification often share similar unmeasured characteristics

that influence crash frequency. These effects can be represented as random effects attributed to these groupings (clusters). Thus, the random-effects structure improves model accuracy by capturing this group-level unobserved heterogeneity and ensuring that parameter estimates reflect true variations across segments and are not biased by omitting group-level components (Lord & Mannering, 2010). This is particularly important for studies analyzing extensive networks where roadways are influenced by local geometric, environmental, and operational factors that are difficult to measure directly.

The NB model with random effects offers several advantages over other modeling approaches. By explicitly accounting for overdispersion, it provides more reliable parameter estimates than the Poisson model (Islam et al., 2014). The ability to model roadway-specific variations through random effects enhances its predictive accuracy, making it particularly useful for large-scale studies where crash frequency distributions differ across locations (Lord & Mannering, 2010). Furthermore, NB-based models allow for flexible variance structures, enabling transportation researchers to develop more realistic safety performance functions that can inform roadway design and policy decisions.

To evaluate the safety effectiveness of shoulder width, the NB-based modeling methodology was applied to associate crash frequency with the studied shoulder presence, width, traffic, and road geometry. More than 5,000 mi of rural two-lane highways across Indiana were included in the analysis. Specifically, 9 years of crash data (2015–2023) were assigned to more than 8,000 segments. For each segment, traffic (AADT), geometry (such as length, number of curves, deflection angle rate, lane width, and shoulder width), and rumble strip settings (type, location, and width) were used for analysis.

As discussed earlier in this section, a random-effects NB model was applied to account for potential heterogeneity among groups of segments coming from the same roadway. To capture this heterogeneity (Figure 4.1), a grouping variable (named `RANDOM_ID`) was added to the model to capture a common random effect for segments that belong to the same road and the same township. Thus, segments on the same road within the same township were assigned to the same category and shared the same random factor. This approach acknowledges local variations and unobserved factors that may differ across townships and roads, thereby potentially enhancing the robustness of the safety analysis.



**Figure 4.1** Example of the Introduction of Random Effects to the Model.

The model structure is shown in Equation 4.1. The log of mean value  $\mu$  is expected to have a linear relationship with explanatory variables ( $X_1, X_2, \dots, X_j$ ). Typically, the explanatory variables include traffic volume (AADT), geometry variables (length, lane width, shoulder width, curvature), and, in the case considered here, rumble strips presence and location. Because the proposed model includes random effects attributed to segments (grouped within roads and counties), the model intercept includes additional term  $\alpha_{ID}$ , which represents the unobserved heterogeneity attributed to random effects. Variance,  $\delta$ , is the summation of two terms, mean  $a_i$  and multiple of square of mean and dispersion parameter,  $\rho$ . When dispersion parameter,  $\rho$ , is close to zero, the negative binomial model descends to its Poisson version.

$$\begin{aligned}
 \text{CrashNum}_i &\sim \text{NegativeBinomial}(a_i, \delta) \\
 a_i &= \exp(\alpha_0 + \alpha_{ID} + \beta_1 X_{i1} + \beta_2 X_{i2} + \dots + \beta_j X_{ij}) \\
 \alpha_{ID} &\sim \text{Normal}(0, \sigma_{ID}) \\
 \delta &= a_i + \rho a_i^2
 \end{aligned}
 \tag{Eq. 4.1}$$

In summary, the NB model in Equation 4.1 with random effects  $\alpha_{ID}$  is a suitable tool for crash frequency analysis, effectively addressing overdispersion and unobserved heterogeneity. By incorporating segment-level variations, this approach enhances the reliability of crash frequency predictions and provides a practical foundation for roadway safety assessment and intervention planning.

The proposed model is meant to enable transportation safety officials to make data-driven assessments of key roadway features, such as shoulder width, traffic exposure, and geometric design in Indiana rural areas, ensuring that the safety evaluation reflects real-world conditions for safety-oriented infrastructure planning, selection of adequate countermeasures aimed at reducing crash risks.

## 4.2 Model Estimation

The final model was the result of an iterative modeling process. The selected model was defined after evaluating all available information, where measures such as AIC, BIC, and LogLikelihood were employed to compare model fitness. Starting with a simple model, additional variables were incorporated one at a time to assess their significance and impact on the results, with nonsignificant variables dropped from the analysis. Various groupings of the shoulder width variable were tested, and the final grouping was chosen when the optimal values for AIC, BIC, and LogLikelihood were achieved, respecting the significance of the variable. Moreover, interactions among variables were explored, but only the interaction between shoulder width and lane width contributed to the significance of the model.

Speed limit was not a significant variable in the modeling process, as nearly all rural roads in the dataset have a speed limit of 55 mph. This lack of variation limits the ability of the model to detect any meaningful statistical differences related to speed. Since the speed limit remains constant across most

observations, it does not contribute to explaining differences in crash occurrence or severity. As a result, including it in the model would not provide additional insights.

To determine the optimal grouping for the shoulder width (SW) variable, multiple configurations were tested during the modeling process. The initial grouping followed the same classification used in the data exploration phase 0, 1 and 2, 3 and 4, 5 and 6, and 7+. However, due to the statistical insignificance of one or more SW levels and the distribution of the dataset, alternative groupings were explored. For the final grouping, widths of 0, 1, and 2 ft were combined, as there is no significant difference in a driver's ability to recover from a lane departure across these widths. Additionally, the grouping strategy was informed by current industry standards to ensure practical relevance. The final selection was based on achieving the best statistical significance for all variables in the model while maintaining alignment with roadway design practices.

The modeling procedure results are presented in Table 4.1, which shows the magnitudes of the effects of each variable to the model, as well as the statistical significance of each variable.

Based on the model results, the equation to compute the expected number of crashes is given as follows:

$$\begin{aligned}
 a &= 0.036 \cdot \text{AADT}^{0.282} \cdot L^{0.640} \cdot \exp[-0.144 \cdot \text{SW}_{3,4} - 0.290 \\
 &\quad \cdot \text{SW}_{5,6} - 0.212 \cdot \text{SW}_{7+} + 0.001 \cdot \text{DA} + 0.019 \cdot \text{Crv} \\
 &\quad + 0.002 \cdot \text{Int} - 0.095 \cdot \text{RS} - 0.108 \cdot \text{Y2020} + 0.114 \\
 &\quad \cdot \text{LW}_{<10} + 0.066 \cdot \text{LW}_{10,11} + 0.018 \cdot \sqrt{\text{SW} \cdot \text{LW}}]
 \end{aligned}
 \tag{Eq. 4.2}$$

The results of the negative binomial model with random effects provide an insight into the factors influencing the frequency of ROR crashes. Since the dependent variable represents the count of ROR crashes, the estimated coefficients indicate how each independent variable affects the expected number of

TABLE 4.1  
Results From Modeling.

Term	Estimate	StdErr	Pr >  t
Intercept	-3.317	0.118	< 0.001
LN (AADT)	0.282	0.014	< 0.001
LN (L)	0.640	0.013	< 0.001
DA	0.001	0.000	< 0.001
Crv	0.019	0.003	< 0.001
Int	0.002	0.001	< 0.001
RS	-0.095	0.028	0.001
$LW_{<10}$	0.114	0.043	0.008
$LW_{10,11}$	0.066	0.025	0.008
$LW_{12}$	0.000		
$SW_{3,4}$	-0.144	0.050	0.004
$SW_{5,6}$	-0.290	0.085	0.001
$SW_{7+}$	-0.212	0.069	0.002
$SW_{0,1,2}$	0.000		
Y2020	-0.108	0.027	< 0.001
$\sqrt{\text{SW} \cdot \text{LW}}$	0.018	0.006	0.001
Over-dispersion parameter		1.41346	

such crashes. In a negative binomial model, a positive coefficient means an increase in ROR crashes, while a negative coefficient suggests a reduction in ROR crashes. A statistically significant estimate (p-value < 0.05) indicates that the effect of the variable is unlikely to be due to random chance.

### 4.3 Discussion of Modeling Results

The overdispersion parameter was statistically significant justifying the use of negative binomial model over Poisson model. Further, the Random\_ID variable was statistically significant (p-value < 0.001) justifying the specification of random effects.

AADT has a statistically significant effect on the frequency of crashes. This aligns with the expectation that increasing traffic volumes increase the exposure to crashes. Similarly, longer roadway segments experience more crashes due to the increased exposure.

The model obtained highlights the importance of widening narrow shoulders as a countermeasure against ROR crashes. The baseline category, representing 0-, 1-, and 2-ft shoulders, suggests that drivers may perceive little difference between having no shoulder and having a 2-ft shoulder, as both offer minimal opportunity for corrective maneuvers in case of lane departure.

Wider shoulders, on the other hand, contribute to improving safety by providing extra space for errant vehicles to recover and go back to the road. However, the relationship is not linear. While increasing SW is associated with fewer ROR crashes, excessively wide shoulders, particularly those of 7 ft or more—may lead drivers to adopt a more aggressive behavior. Roadways with wide shoulders (7+ ft), combined with 12-ft lanes, can lead to drivers' overconfidence, higher speeds, and a reduced caution, which may offset some of the expected safety benefits. This concept aligns with previous findings that driver behavior is not solely dictated by roadway dimensions but also by perceived risk. When drivers feel more secure in a forgiving roadway environment, they may adopt more aggressive driving behaviors, such as speeding, which in turn increases crash risk. Additionally, it is important to recognize that design standards generally recommend SW values lower than those at the upper end of the CMF table (Table 5.1). According to INDOT (2013) and FHWA (2015) guidelines, the recommended SW for two-lane rural roads are 4 ft and 6 ft, respectively.

The results also indicate that reducing lane width (LW) increases ROR crash risk. Both categories,  $LW_{10,11}$  and  $LW_{<10}$ , have positive coefficients. The positive sign of the estimates suggests that even a modest reduction from 12 ft results in increased ROR crash risk, likely due to reduced maneuvering space and a higher potential for lane departure.

The findings indicate that increasing SW generally leads to crash reductions, though the relationship is not strictly linear. Roadways with 2-ft shoulder or smaller experience higher crash frequencies, as the limited recovery space restricts a driver's ability to correct lane departures. Widening these narrow shoulders generally improves safety, particularly when paired with balanced LW configurations. However, the effect of SW varies depending on the existing LW. The relation between LW

and SW suggests that simply increasing shoulder width without considering lane dimensions may not yield optimal safety benefits. Instead, an integral approach to cross-section design should be adopted, considering how different width combinations influence driver behavior and crash risk.

Another key finding is the effectiveness of rumble strips in reducing ROR crashes. The presence of rumble strips along the roadside was associated with a statistically significant reduction in crash frequency, supporting their continued implementation as a proven countermeasure. This aligns with previous research findings, where it has been found that rumble strips provide enough vibration and noise to alert the drivers when they are about to leave the road.

In addition, the model also shows the influence of roadway curvature and intersection density on ROR crashes. An increase in the total deflection angle and a greater number of curves lead to more ROR crashes, confirming that curved road segments pose a higher risk for vehicles. Increased number of intersections per mile also contribute to increased crash risk, likely due to the additional conflict points they introduce.

To account for the change in traffic pattern caused by the COVID-19 pandemic during the year 2020, the variable Y2020 was used, and it was found to be statistically significant in the model.

In summary, the results of the NB model with random effects provide valuable insights into the factors influencing ROR crashes, highlighting the role of traffic exposure, roadway geometry, lane and shoulder width, and rumble strips. The findings emphasize the importance of a balanced cross-section design, where lane and shoulder widths are optimized together to provide adequate recovery space for errant vehicles.

## 5. MODEL APPLICATION

### 5.1 Crash Modification Factors

To estimate the CMFs, the expected number of crashes must be first calculated using Equation 4.2. To determine the CMFs for each design alternative, the expected number of crashes was first computed for an initial (existing) condition of SW and LW and then recalculated for a new (proposed) condition. The CMF for a specific change in design was then determined using the formula:

$$CMF = \frac{a_{new}}{a_{exist}} \quad (\text{Eq. 5.1})$$

where:

$a_{new}$  is the expected crash frequency for the new roadway condition,

$a_{exist}$  is the expected crash frequency for the existing condition.

A CMF value below 1.0 indicates a reduction in crash risk after the change, whereas a CMF above 1.0 suggests an increased risk.

For each combination of shoulder width and lane width groups CMFs were calculated as follows. For each group, the average shoulder width weighted by number of miles was computed. These weighted averages were then used in the model equation to obtain the expected number of crashes for a given

condition. Finally, the CMFs were calculated using Equation 5.1. This approach ensured that the computed CMFs reflected the distribution of data across varying width categories, accounting for variations in sample sizes within each group.

The CMFs table (Table 5.1) is designed to assess the anticipated impact of modifications to a combination of LW and SW on crash frequency. The rows (BEFORE) represent the existing conditions of the roadway, categorized by a specific combination of LW and SW. To use the table, one must first identify the current lane and shoulder width in the BEFORE section. From there, the corresponding row is followed to the right to locate the desired implementation, located in the columns (AFTER), where the associated CMF value indicates the expected change in crash risk.

Table 5.1 provides CMFs estimated under the assumption that the BEFORE scenario reflects the current roadway conditions while the AFTER scenario represents modifications to the cross-section. These modifications may involve either maintaining the total paved width while redistributing lane and shoulder widths, adjusting pavement markings to reallocate space, or expanding the total paved area by increasing the cross-section width. These assumptions are fundamental for accurately interpreting the CMFs and ensuring that the anticipated crash effects align with real-world roadway modifications.

A key advantage of this table is its ability to systematically evaluate all possible lane and shoulder width combinations. This allows a comparison among various design alternatives and understanding their potential influence on crash risk. By offering a structured and quantitative approach, the table supports evidence-based decision-making and facilitates the selection of safer roadway designs.

In general, the CMF table shows the following key trends:

- Shoulder width of 0–2 ft has the highest CMF values compared to any other category.
- The shoulder width category of 5–6 ft has the lowest CMF values for the same lane width.
- Similarly, lane width of 12 ft has the lowest CMF values for the same shoulder width.

- Widening the shoulder from existing width category to a higher width category results in a CMF less than 1. Unless, when moving from 5–6 ft to 7+ ft in which case, there is an increase in ROR crashes.
- For the same paved area, increasing the lane width while keeping the shoulder width in the same category results in a lower CMF.

However, it is important to note that shoulders wider than 6 ft are generally beyond the standard recommendations provided by major transportation agencies. According to INDOT (2013) design standards, the typical recommended shoulder width is 4 ft, while FHWA (2016) guidelines suggest 6 ft as an optimal shoulder width for rural highways. As a result, the results for 7-ft or wider shoulders should be interpreted with caution, as they may be included for reference rather than practical design recommendations. While wider shoulders can serve additional functions such as emergency stopping areas or bicycle lanes, the safety benefits beyond 6 ft appear to be limited.

Additionally, to the CMFs presented on the table, the presence of rumble strips on the side of the road also proved to be an effective countermeasure for reducing ROR crashes. The magnitude of the CMF for implementing rumble strips on the side of the road is calculated as follows:

$$CMF_{Rumble\ Strips} = e^{-0.0945} = 0.909 \quad (\text{Eq. 5.2})$$

This means that implementing rumble strips on the side of the road results in a 9.1% reduction in crashes. This result aligns well with previous research on the effectiveness of rumble strips. For example, Minnesota’s implementation of shoulder rumble strips on two-lane rural highways led to a 13% reduction in total ROR crashes (Patel et al., 2007).

To estimate the benefits of the combined effect of adding rumble strips on the side of the road an upgrade on the configuration of the cross-section, the calculation is as follows:

$$CMF_{TOTAL} = CMF_{LW \cdot SW} \cdot CMF_{Rumble\ Strips} \quad (\text{Eq. 5.3})$$

TABLE 5.1  
Crash Modification Factors Results.

		AFTER (Design Alternatives)												
		SW		0, 1, 2			3, 4			5, 6			7+	
BEFORE (Existing Conditions)	SW	LW	< 10	10,11	12	< 10	10,11	12	< 10	10,11	12	< 10	10,11	12
		< 10	1.000	0.963	0.899	0.917	0.884	0.834	0.819	0.791	0.746	0.913	0.891	0.843
	0,1,2	10,11	1.038	1.000	0.934	0.953	0.918	0.866	0.850	0.821	0.774	0.948	0.925	0.875
		12	1.112	1.071	1.000	1.020	0.983	0.928	0.911	0.880	0.829	1.016	0.991	0.937
		< 10	1.090	1.050	0.980	1.000	0.963	0.909	0.893	0.862	0.813	0.995	0.971	0.918
	3,4	10,11	1.132	1.090	1.017	1.038	1.000	0.944	0.927	0.895	0.844	1.033	1.008	0.953
		12	1.199	1.154	1.078	1.100	1.059	1.000	0.981	0.948	0.894	1.095	1.068	1.010
		< 10	1.221	1.176	1.098	1.120	1.079	1.019	1.000	0.966	0.911	1.115	1.088	1.029
	5,6	10,11	1.264	1.217	1.137	1.160	1.117	1.055	1.035	1.000	0.943	1.155	1.126	1.065
		12	1.341	1.291	1.206	1.230	1.185	1.119	1.098	1.061	1.000	1.225	1.195	1.130
		< 10	1.095	1.054	0.984	1.005	0.968	0.914	0.897	0.866	0.817	1.000	0.976	0.923
	7+	10,11	1.122	1.081	1.009	1.030	0.992	0.936	0.919	0.888	0.837	1.025	1.000	0.946
		12	1.187	1.143	1.067	1.089	1.049	0.990	0.972	0.939	0.885	1.084	1.057	1.000

## 6. IMPLEMENTATION

### 6.1 Estimating the Safety Effect of a Shoulder Width Change

In general, the method to estimate the safety benefits involves the following steps:

1. Estimate the number of crashes by severity,
2. Multiply the estimates with corresponding CMFs, and
3. Finally, multiply the above result with corresponding crash costs to obtain the estimated safety benefits.

A significant challenge emerges when applying this method to ROR crashes, as their severity is highly dependent on roadside hazards. Because detailed information about these hazards is unavailable, it would be incorrect to model crash severity with conventional methods that rely on such data.

Therefore, alternate methodology is proposed. First, alternate severity models were developed based on exposure variables only (traffic volume, segment length and density of minor intersections). If one assumes that exposure is not related to roadway cross section, then the effect of exposure on severity is grasped through these models. The observed crash data reflect the effect of the roadside hazard while the model-based estimates combined with the crash data would reduce the random variability, resulting in a more accurate safety estimate. By applying this approach, INDOT can better assess the safety impact of cross-sectional design changes, such as shoulder widening, even when detailed roadside data are unavailable.

The process begins by identifying a roadway segment with an excessive number of crashes over the past 5 years, focusing on locations where cross-sectional improvements are being considered. Once a segment is selected, all observed crashes are classified into two categories: PDO and non-PDO crashes, with the latter encompassing those involving injuries or fatalities. This distinction is necessary to enable a severity-based analysis that aligns with safety performance objectives and cost estimation frameworks.

After classification, safety performance functions (SPFs) are used to estimate the expected number of crashes under existing conditions. These functions incorporate exposure variables, such as traffic volume and segment length, and are also used to estimate the dispersion parameter required for crash modeling. The Empirical Bayes (EB) method is then applied to combine the observed crash counts with the SPF-based estimates, producing a statistically robust expected annual crash frequency for the segment. This intermediate estimate reflects typical crash occurrence under current conditions and is further used to establish the proportion of PDO and non-PDO crashes.

In the next stage, the full ROR frequency model—previously developed as part of the overall safety analysis—is applied to obtain an estimate of the expected number of ROR crashes on the segment. This model incorporates additional roadway characteristics such as curvature and presence of rumble strips. This estimate is combined with the observed crashes using the EB method to obtain the best estimate of the expected ROR crashes.

To estimate the effect of shoulder widening, the appropriate CMF is applied to the EB-adjusted crash frequency. CMFs quantify the expected reduction in crashes associated with

the proposed design alternative. The adjusted total number of crashes is then allocated into PDO and non-PDO categories using the proportional distribution obtained previously. The resulting estimates are multiplied by the average crash costs for PDO and non-PDO crashes respectively to quantify the safety benefits.

An example illustrating this procedure is provided in the next section.

### 6.2 Example Safety Benefit Estimation

A critical component in the cost-benefits analysis of a project is to estimate safety benefits. This section illustrates the procedure used to quantify the safety benefits of widening shoulders arising from the expected change in run off road crashes. For a corridor that involves several segments each with differing geometry and traffic conditions, the safety benefits must be estimated individually for each segment.

A 1.72-mi segment with 12-ft wide lane, no shoulder or rumble strip, was selected for analysis. The other characteristics are shown in Table 6.1.

The analysis covers a five-year period from 2019 to 2023. The average AADT for the segment during the period of analysis is 3,415 vehicles per day.

#### 6.2.1 Crash Severity Distribution

The total number of ROR by severity is presented in Table 6.2.

The cost of crashes by severity annualized for 2025 are presented next:

TABLE 6.1  
Road Characteristics.

Year	AADT	Deflection Angle	No. of Curves	Int. per mile	ROR	ROR KA	ROR BC	ROR PDO
2019	3798	134.11	4.06	1.16	11	3	1	7
2020	3458	134.11	4.06	1.16	12	2	2	8
2021	2920	134.11	4.06	1.16	3	0	0	3
2022	3419	134.11	4.06	1.16	2	0	1	1
2023	3481	134.11	4.06	1.16	2	0	0	2

TABLE 6.2  
Crash Counts for 5 Years.

Crash Counts for 5 Years (2019–2023)		
Severity	PDO	KABC
Count	21	9

TABLE 6.3  
Cost of Crashes by Severity (\$1000).

Cost of Crashes by Severity (\$1000)		
Cost	PDO	KABC
	39.0	1,415.0

### 6.2.2 Safety Performance Functions Based on Exposure

Using three exposure variables, namely segment length and density of minor intersections, safety performance functions were developed for PDO crashes (Figure 6.1) and non-PDO crashes (KABC crashes, Figure 6.2) using an NB model.

The equations shown in Table 6.4 were derived from the above-mentioned NB models.

The expected number of crashes for the segment considered are calculated as follows:

$$a_{PDO} = 3.203 \cdot 10^{-2} \cdot (AADT)^{0.2582} \cdot (L)^{0.5169} \cdot (Int)^{0.0015}$$

$$a_{PDO} = 3.203 \cdot 10^{-2} \cdot (3415)^{0.2582} \cdot (1.723)^{0.5169} \cdot (1.160)^{0.0015} \quad (\text{Eq. 6.1})$$

$$a_{PDO} = 0.3474$$

$$a_{KABC} = 1.419 \cdot 10^{-2} \cdot (AADT)^{0.2495} \cdot (L)^{0.6120} \cdot (Int)^{0.0015}$$

$$a_{KABC} = 1.419 \cdot 10^{-2} \cdot (3415)^{0.2495} \cdot (1.723)^{0.6120} \cdot (1.160)^{0.0015} \quad (\text{Eq. 6.2})$$

$$a_{KABC} = 0.1510$$

Thus, the SPF estimated annual number of PDO crashes  $a_{PDO}$  is 0.3474 while the estimated annual number of injury crashes  $a_{KABC}$  is 0.151.

The EB method is used to combine SPF estimates of ROR crashes with observed crashes over 5 years. The calculations are shown below:

$$a_{EB} = \frac{C + \frac{1}{\alpha}}{Y + \frac{1}{\alpha a}} \quad (\text{Eq. 6.3})$$

$$a_{EB_{PDO}} = \frac{21 + \frac{1}{0.2221}}{5 + \frac{1}{0.2221 \cdot 0.3474}} = 1.4199 \quad (\text{Eq. 6.4})$$

$$a_{EB_{KABC}} = \frac{9 + \frac{1}{0.1245}}{5 + \frac{1}{0.1245 \cdot 0.1510}} = 0.2926 \quad (\text{Eq. 6.5})$$

Where,  
 $a_{EB}$  is the EB estimate,  
 $C$  is the number of target crashes in the preceding  $Y$  years,  
 $\alpha$  is the dispersion parameter value from the safety performance function,  
 $a$  is the safety performance function estimate of annual crashes.

Covariance Parameter Estimates					
Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr > Z
Intercept	RANDOM_ID	0.3071	0.0131	23.44	<.0001
Scale		0.2221	0.02323	9.56	<.0001

Solutions for Fixed Effects								
Effect	Estimate	Standard Error	DF	t Value	Pr >  t	Alpha	Lower	Upper
Intercept	-3.4411	0.1071	6790	-32.14	<.0001	0.05	-3.651	-3.2312
log_AADT	0.2582	0.01343	68518	19.23	<.0001	0.05	0.2319	0.2845
log_Miles	0.5169	0.0144	68518	35.88	<.0001	0.05	0.4886	0.5451
D_MinorInt	0.001466	0.000341	68518	4.31	<.0001	0.05	0.000799	0.002134

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
log_AADT	1	68518	369.93	<.0001
log_Miles	1	68518	1287.58	<.0001
D_MinorInt	1	68518	18.54	<.0001

Figure 6.1 PDO Model Results.

Covariance Parameter Estimates					
Cov Parm	Subject	Estimate	Standard Error	Z Value	Pr > Z
Intercept	RANDOM_ID	0.4673	0.02627	17.79	<.0001
Scale		0.1245	0.04418	2.82	0.0024

Solutions for Fixed Effects								
Effect	Estimate	Standard Error	DF	t Value	Pr >  t	Alpha	Lower	Upper
Intercept	-4.2554	0.1526	6790	-27.89	<.0001	0.05	-4.5545	-3.9563
log_AADT	0.2495	0.01911	68518	13.06	<.0001	0.05	0.212	0.2869
log_Miles	0.612	0.0217	68518	28.2	<.0001	0.05	0.5695	0.6546
D_MinorInt	0.001454	0.000557	68518	2.61	0.0091	0.05	0.000362	0.002547

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
log_AADT	1	68518	170.47	<.0001
log_Miles	1	68518	795.49	<.0001
D_MinorInt	1	68518	6.81	0.0091

Figure 6.2 KABC Model Results.

TABLE 6.4  
Safety Performance Functions Based on Exposure.

Severity	SPF	Dispersion ( $\alpha$ )
PDO	$3.203 \cdot 10^{-2} \cdot (AADT)^{0.2582} \cdot (L)^{0.5169} \cdot \exp\left[(Int)^{0.0015}\right]$	0.2221
Non-PDO	$1.419 \cdot 10^{-2} \cdot (AADT)^{0.2495} \cdot (L)^{0.6120} \cdot \exp\left[(Int)^{0.0015}\right]$	0.1245

TABLE 6.5  
Empirical Bayes Method for Crash Estimation.

Combined Estimate of Annual Crash Frequencies During 5 Years Using EB Method			
	PDO	KABC	Total
a (EB)	1.4199	0.2926	1.7126
Proportion	82.91%	17.09%	100%

The combined EB estimate of annual crash frequencies during the observed 5-year period is shown in Table 6.5.

From Table 6.5, it can be seen that PDO crashes are ~83% of the total crashes, whereas injury crashes represent ~17%.

### 6.2.3 Estimating Safety Benefit

The safety benefit estimation procedure can be summarized as follows:

1. Identify the existing condition and the proposed design alternative.
2. Estimate the annual crash frequency using the crash frequency model.
3. Combine the estimated annual crash frequency and the observed number of crashes over 5 years using EB method.
4. Using the appropriate crash modification factor, estimate the change in number of crashes (typically reduction of crashes).
5. Split the estimated crash reduction by severity using the previously obtained proportions.
6. Compute the annual benefits for each severity by multiplying the estimated reduction in crashes and the corresponding crash cost.
7. The sum of reduction in crash costs by severity is the desired total safety benefit.

The above-mentioned procedure is illustrated using the same example explained previously. The existing condition and proposed design alternatives are shown in Table 6.6.

TABLE 6.6  
Existing Conditions and Design Alternatives for a Segment.

	Shoulder Width	Lane Width
Existing Conditions	0	12
Design Alternative	4	12

The number of crashes observed over 5-year period is 30 (Table 6.2). Using Equation 4.2, we can calculate the expected number of crashes per year according to the model:

$$a = 0.036 \cdot AADT^{0.282} \cdot L^{0.640} \cdot \exp[-0.144 \cdot SW_{3,4} - 0.290 \cdot SW_{5,6} - 0.212 \cdot SW_{7+} + 0.001 \cdot DA + 0.018 \cdot Crv + 0.001 \cdot Int - 0.094 \cdot RS - 0.108 \cdot Y2020 + 0.114 \cdot LW_{<10} + 0.066 \cdot LW_{10,11} + 0.018 \cdot \sqrt{SW \cdot LW}] \quad (\text{Eq. 4.2})$$

$$a = 0.036 \cdot 3415^{0.282} \cdot 1.723^{0.640} \cdot \exp[0.001 \cdot 134.109 + 0.018 \cdot 4.061 + 0.001 \cdot 1.160 + 0.018 \cdot \sqrt{0 \cdot 12}]$$

$$a = 0.6673 \quad (\text{Eq. 6.6})$$

The model estimated annual crash frequency (Equation 6.6; Equation 3.1, and the observed number of crashes (Table 6.2) are combined using EB method to get the best estimate of annual crash frequency.

$$a_{EB} = \frac{C + \frac{1}{\alpha}}{Y + \frac{1}{\alpha a}}$$

$$a_{EB} = \frac{30 + \frac{1}{1.4134}}{5 + \frac{1}{1.4134 \cdot 0.6673}} = 5.0670 \quad (\text{Eq. 6.7})$$

The EB estimate for annual crash frequency is shown in Table 6.7. Using the crash modification factors table shown in Table 5.1, we select the appropriate CMF drawn from the intersection of existing condition of 12-ft-wide road with no shoulder (row) and proposed alternative design of 12-ft-wide lane with 4-ft-wide shoulder (column). The estimated CMF is 0.928.

Multiplying this factor with the EB estimate shown in Table 6.7, we get the estimate for annual crash frequency after the shoulders are widened to 4 ft.

$$a_{EB_{improved}} = 5.0670 \times 0.928 = 4.7022 \quad (\text{Eq. 6.8})$$

The expected reduction in annual crash frequency after the improvement is:

$$a_{EB} - a_{EB_{improved}} = 5.0670 - 4.7022 = 0.3648 \quad (\text{Eq. 6.9})$$

The reduction in annual crash frequency is split by severity using the crash severity proportions obtained at the end of Section 6.2.2 (Table 6.5). The results are shown in Table 6.8.

TABLE 6.7  
EB Method for Crash Estimation.

Combined Estimate of Annual Crash Frequencies During 5 Years Using EB Method	
a (EB)	5.0670

TABLE 6.8  
Estimated Annual Reduction in Crashes by Severity.

Reduction in Crashes by Severity		
Crashes	PDO 0.3025	KABC 0.0623

TABLE 6.9  
Estimated Annual Savings by Crash Severity.

Savings Per Reduction in Crashes by Severity (in \$1000)		
Savings	PDO \$11.80	KABC \$88.22

Multiplying the reduction in annual crash frequency by severity with its corresponding crash cost shown in Table 6.3, we obtain the estimated savings for each severity level.

The total annual savings for the proposed design alternative is \$100,013.00.

## 7. CLOSURE

### 7.1 Summary

Shoulder width plays a critical role in enhancing the safety of rural two-lane roads by offering drivers recovery space during unintentional lane departures. Wider shoulders reduce the risk and severity of ROR crashes, which constitute a major portion of fatal incidents on rural roadways. In Indiana, where more than 70% of the state-administered highway network consists of rural two-lane roads (many of which were built before current design standards), understanding the safety benefits of shoulder width is essential for guiding infrastructure improvements.

This study developed a crash frequency model using NB regression with random effects, analyzing more than 8,000 segments and 5,000 mi of rural roads across a 9-year period. The model controlled for traffic volume, roadway geometry, intersection density, and countermeasures like rumble strips. Results confirmed that shoulder width significantly affects ROR crash frequency. Increasing shoulder width up to 6 ft resulted in decrease in expected number of crashes. Excessively wide shoulders (7+ ft) showed reduced safety in comparison to 6-ft shoulders. This could be due to driver overconfidence and increased speeds. Presence of rumble strips further reduced crashes by approximately 9.1%, reinforcing their value as a complementary measure.

The safety effects were quantified through CMFs, which were derived for various combinations of shoulder and lane widths. These CMFs provide a practical tool for INDOT and other agencies to evaluate the benefits of proposed design alternatives.

To support implementation, the study introduced a methodology for estimating crash severity using SPFs and EB. This approach enables agencies to assess expected safety benefits even when detailed clear zone data is unavailable. The obtained CMFs are then used to quantify the safety benefits of widening shoulders.

## 7.2 Future Research

While the current research provides valuable insights into the relationship between shoulder width and crash frequency, there are still many opportunities for further research and improvement.

One promising area for future work involves extending the model to address different types of crashes beyond those targeted in the current study. Head-on, rear-end, and sideswipe crashes, among others, draw attention due to the influence of lane width. While increasing lane width may help mitigate certain crash types, it could also reduce the space available for shoulders, potentially increasing the risk of ROR crashes. Finding a balance between lane width and shoulder width is essential for a comprehensive safety analysis, ensuring that roadway design effectively addresses multiple crash risks while maintaining operational efficiency.

While the current analysis isolates shoulder width as a variable of interest, roadway safety is inherently multifaceted, with interventions such as raised pavement markers playing an essential role in guiding drivers and reducing crash risk. A future research direction could involve integrating these complementary countermeasures into the existing model. This integrated approach may reveal that the combination of these countermeasures produces a more substantial reduction in crashes than any single measure alone, thereby offering a more holistic perspective on road safety improvements.

Furthermore, the influence of roadway maintenance and the quality of shoulder materials is another area that deserves attention. Over time, degradation of road surfaces and shoulders may reduce the effectiveness of these safety features, and understanding this relationship could lead to improved maintenance strategies that sustain safety benefits in the long term.

The presence of roadside hazards significantly impacts a vehicle's ability to regain control after leaving the road. FHWA has established hazard ratings based on clear zone width, side slope steepness, and the presence of obstacles, ranging from fully recoverable zones (Rating 1) to nonrecoverable areas with a high likelihood of severe injuries (Rating 7). By incorporating clear zone ratings into safety models, the model can better assess whether expanding the shoulder width alone is sufficient or if additional roadside improvements are necessary to maximize safety benefits.

The rapid development of connected vehicle technologies also introduces new research opportunities. Modern vehicles are increasingly equipped with systems such as lane departure warning systems, which have the potential to reduce the likelihood of certain types of crashes. It is important to investigate how these technologies interact with traditional roadway design features, including shoulder width.

In summary, while the current research contributes important findings regarding the impact of shoulder width on crash frequency, many research possibilities remain open. Expanding the model to cover diverse crash types, assessing the joint effects of shoulder width and other safety countermeasures, exploring the integration of emerging vehicular technologies are all possible next steps.

## REFERENCES

- American Association of State Highway and Transportation Officials. (2018). *A policy on geometric design of highways and streets* (7th ed.). AASHTO.
- American Association of State Highway and Transportation Officials. (2022, September 2). *GSHA report highlights rural road safety issues*. AASHTO Journal. <https://aashtojournal.transportation.org/gsha-report-highlights-rural-road-safety-issues/>
- Ben-Bassat, T., & Shinar, D. (2011). Effect of shoulder width, guardrail and roadway geometry on driver perception and behavior. *Accident Analysis & Prevention*, 43(6), 2142–2152. <https://doi.org/10.1016/j.aap.2011.06.004>
- Benekohal, R. F., & Hashmi, A. M. (1992). Procedures for estimating accident reductions on two-lane highways. *Journal of Transportation Engineering*, 118(1), 111–129. [https://doi.org/10.1061/\(ASCE\)0733-947X\(1992\)118:1\(111\)](https://doi.org/10.1061/(ASCE)0733-947X(1992)118:1(111))
- Chen, E., & Tarko, A. P. (2014). Modeling safety of highway work zones with random parameters and random effects models. *Analytic Methods in Accident Research*, 1, 86–95. <https://doi.org/10.1016/j.amar.2013.10.003>
- Chen, J. Y., & Tian, X. P. (2012). Safety analysis of expressway's shoulder width. *Applied Mechanics and Materials*, 256–259, 1731–1736. <https://doi.org/10.4028/www.scientific.net/AMM.256-259.1731>
- Chen, S., Saeed, T. U., Alinizzi, M., Lavrenz, S., & Labi, S. (2019). Safety sensitivity to roadway characteristics: A comparison across highway classes. *Accident Analysis & Prevention*, 123, 39–50. <https://doi.org/10.1016/j.aap.2018.10.020>
- Ewan, L., Al-Kaisy, A., & Hossain, F. (2016). Safety effects of road geometry and roadside features on low-volume roads in Oregon. *Transportation Research Record*, 2580(1), 47–55. <https://doi.org/10.3141/2580-06>
- Federal Highway Administration. (1990, February 2). Technical advisory T 5040.29 paved shoulders. <https://www.fhwa.dot.gov/pavement/t504029.cfm>
- Federal Highway Administration. (2015). *Factors influencing operating speeds and safety on rural and suburban roads* (Federal Highway Administration Report No. FHWA-HRT-14-020). <https://www.fhwa.dot.gov/publications/research/safety/15030/001.cfm>
- Federal Highway Administration. (2018). *Rumble strips and rumble stripes*. <https://highways.dot.gov/safety/rwd/keep-vehicles-road/rumble-strips>
- Federal Highway Administration. (2023). *Roadway departure safety*. <https://highways.dot.gov/safety/RwD>
- Fitzpatrick, K., Dixon, K., & Avelar, R. (2016). Evaluating operational implications of reduced lane and shoulder widths on freeways. *Journal of Transportation Engineering*, 142(11). [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000884](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000884)
- Garber, N. J., & Ehrhart, A. A. (2000). Effect of speed, flow, and geometric characteristics on crash frequency for two-lane highways. *Transportation Research Record*, 1717(1), 76–83. <https://doi.org/10.3141/1717-10>
- Geedipally, S. R., Pratt, M. P., & Lord, D. (2019). Effects of geometry and pavement friction on horizontal curve crash frequency. *Journal of Transportation Safety & Security*, 11(2), 167–188. <https://doi.org/10.1080/19439962.2017.1365317>
- Gross, F., & Jovanis, P. P. (2007). Estimation of safety effectiveness of changes in shoulder width with case control and cohort methods. *Transportation Research Record*, 2019(1), 237–245. <https://doi.org/10.3141/2019-28>

- Gross, F., Jovanis, P. P., & Eccles, K. (2009). Safety effectiveness of lane and shoulder width combinations on rural, two-lane, undivided roads. *Transportation Research Record, 2103*(1), 42–49. <https://doi.org/10.3141/2103-06>
- Hadi, M. A., Aruldas, J., Chow, L.-F., & Wattleworth, J. A. (1995). Estimating safety effects of cross-section design for various highway types using negative binomial regression. *Transportation Research Record, 1500*, 169–177.
- Haghighi, N., Liu, X. C., Zhang, G., & Porter, R. J. (2018). Impact of roadway geometric features on crash severity on rural two-lane highways. *Accident Analysis & Prevention, 111*, 34–42. <https://doi.org/10.1016/j.aap.2017.11.014>
- Hallmark, S. L., Qiu, Y., Pawlovitch, M., & McDonald, T. J. (2013). Assessing the safety impacts of paved shoulders. *Journal of Transportation Safety & Security, 5*(2), 131–147. <https://doi.org/10.1080/19439962.2012.711438>
- Hall, T., & Tarko, A. P. (2019). Adequacy of negative binomial models for managing safety on rural local roads. *Accident Analysis & Prevention, 128*, 148–158. <https://doi.org/10.1016/j.aap.2019.03.001>
- Indiana Department of Transportation (2013). *Indiana design manual*. [https://www.in.gov/indot/design\\_manual/design\\_manual\\_2013.htm](https://www.in.gov/indot/design_manual/design_manual_2013.htm)
- Islam, M. S., Ivan, J. N., Lownes, N. E., Ammar, R. A., & Rajasekaran, S. (2014). Developing safety performance function for freeways by considering interactions between speed limit and geometric variables. *Transportation Research Record, 2435*(1), 72–81. <https://doi.org/10.3141/2435-09>
- Jiang, Y., Ma, Y., Li, S., & Zhao, G. (2013). Safety effects of geometric elements in design exceptions. In Y. Wang, K. Lennerts, G. Q. P. Shen, Y. Bai, X. Xue, C. Sun, Z. Gao, Y. Wu, & W. Xue (Eds.), *ICCREM 2013: Construction and operation in the context of sustainability* (pp. 725–740). American Society of Civil Engineers. <https://doi.org/10.1061/9780784413135.068>
- Karlaftis, M. G., & Golias, I. (2002). Effects of road geometry and traffic volumes on rural roadway accident rates. *Accident Analysis & Prevention, 34*(3), 357–365. [https://doi.org/10.1016/S0001-4575\(01\)00033-1](https://doi.org/10.1016/S0001-4575(01)00033-1)
- Khan, I. U., Motuba, D., & Vachal, K. (2024). Investigating factors affecting injury severity of single-vehicle run-off-road crashes. *Accident Analysis & Prevention, 208*, 107786. <https://doi.org/10.1016/j.aap.2024.107786>
- Khan, S. A., Yasmin, S., & Haque, M. M. (2023). Effects of design consistency measures and roadside hazard types on run-off-road crash severity: Application of random parameters hierarchical ordered probit model. *Analytic Methods in Accident Research, 40*, 100300. <https://doi.org/10.1016/j.amar.2023.100300>
- Labi, S. (2006). *Effects of geometric characteristics of rural two-lane roads on safety* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2005/02). Purdue University. <https://doi.org/10.5703/1288284313361>
- Labi, S. (2011). Efficacies of roadway safety improvements across functional subclasses of rural two-lane highways. *Journal of Safety Research, 42*(4), 231–239. <https://doi.org/10.1016/j.jsr.2011.01.008>
- Labi, S., Chen, S., Preckel, P. V., Qiao, Y., & Woldemariam, W. (2017). Rural two-lane highway shoulder and lane width policy evaluation using multiobjective optimization. *Transportmetrica A: Transport Science, 13*(7), 631–656. <https://doi.org/10.1080/23249935.2017.1315841>
- Lee, T., Cunningham, C., & Roupail, N. (2023). Movement-based intersection crash frequency modeling. *Journal of Transportation Safety & Security, 15*(5), 493–514. <https://doi.org/10.1080/19439962.2022.2092571>
- Llopis-Castelló, D., Findley, D. J., & García, A. (2021). Comparison of the highway safety manual predictive method with safety performance functions based on geometric design consistency. *Journal of Transportation Safety & Security, 13*(12), 1365–1386. <https://doi.org/10.1080/19439962.2020.1738612>
- Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A: Policy and Practice, 44*(5), 291–305. <https://doi.org/10.1016/j.tra.2010.02.001>
- Mecheri, S., Mars, F., & Lobjois, R. (2022). Driving around bends with or without shoulders: The influence of bend direction. *Transportation Research Part F: Traffic Psychology and Behaviour, 91*, 472–483. <https://doi.org/10.1016/j.trf.2022.10.019>
- Mecheri, S., Rosey, F., & Lobjois, R. (2017). The effects of lane width, shoulder width, and road cross-sectional reallocation on drivers' behavioral adaptations. *Accident Analysis & Prevention, 104*, 65–73. <https://doi.org/10.1016/j.aap.2017.04.019>
- Medina, A. M. F., & Tarko, A. P. (2005). Speed factors on two-lane rural highways in free-flow conditions. *Transportation Research Record, 1912*(1), 39–46. <https://doi.org/10.1177/0361198105191200105>
- National Highway Traffic Safety Administration. (2024). *Crash stats: Early estimate of motor vehicle traffic fatalities in 2023*. U.S. Department of Transportation. <https://crashstats.nhtsa.dot.gov/Api/Public/Publication/813561>
- Park, J., & Abdel-Aty, M. (2016). Safety effects of widening shoulders on rural multilane roads: Developing crash modification functions with multivariate adaptive regression splines. *Transportation Research Record, 2583*(1), 34–41. <https://doi.org/10.3141/2583-05>
- Patel, R. B., Council, F. M., & Griffith, M. S. (2007). Estimating safety benefits of shoulder rumble strips on two-lane rural highways in Minnesota: Empirical Bayes observational before-and-after study. *Transportation Research Record, 2019*(1), 205–211. <https://doi.org/10.3141/2019-24>
- Peng, Y., Geedipally, S. R., & Lord, D. (2012). Effect of roadside features on single-vehicle roadway departure crashes on rural two-lane roads. *Transportation Research Record, 2309*(1), 21–29. <https://doi.org/10.3141/2309-03>
- Pokorny, P., Jensen, J. K., Gross, F., & Pitera, K. (2020). Safety effects of traffic lane and shoulder widths on two-lane undivided rural roads: A matched case-control study from Norway. *Accident Analysis & Prevention, 144*, 105614. <https://doi.org/10.1016/j.aap.2020.105614>
- Rahman Shaon, M. R., & Qin, X. (2016). Use of mixed distribution generalized linear models to quantify safety effects of rural roadway features. *Transportation Research Record, 2583*(1), 134–141. <https://doi.org/10.3141/2583-17>
- Schneider, W. H., Savolainen, P. T., & Zimmerman, K. (2009). Driver injury severity resulting from single-vehicle crashes along horizontal curves on rural two-lane highways. *Transportation Research Record, 2102*(1), 85–92. <https://doi.org/10.3141/2102-11>
- Schrock, S. D., Parsons, R. L., & Zeng, H. (2011). Estimation of safety effectiveness of widening shoulders and adding passing lanes on rural two-lane roads. *Transportation Research Record, 2203*(1), 57–63. <https://doi.org/10.3141/2203-07>
- Souleyrette, R., McDonald, T., Hans, Z., Kamyab, A., Welch, T., & Storm, B. (2001). *Paved shoulders on primary highways in Iowa: An analysis of shoulder surfacing criteria, costs, and benefits*. Center for Transportation Research and Education. <https://www.intrans.iastate.edu/research/completed/paved-shoulders-on-primary-highways-in-iowa-an-analysis-of-shoulder-surfacing-criteria-costs-and-benefits/>
- Tarko, A. P. (2012). Use of crash surrogates and exceedance statistics to estimate road safety. *Accident Analysis & Prevention, 45*, 230–240. <https://doi.org/10.1016/j.aap.2011.07.008>
- Tarko, A. P., Dey, A., & Romero, M. A. (2015). *Performance measure that indicates geometry sufficiency of state highways: Volume I—Network*

- screening and project evaluation* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2015/06). Purdue University. <https://doi.org/10.5703/1288284315528>
- Tarko, A. P., Islam, M., & Thomaz, J. E. (2011). *Improving safety in high-speed work zones: A Super 70 study* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2011/09). Purdue University. <https://doi.org/10.5703/1288284314622>
- White, E. O. (2023). Unclear territory: Clear zones, roadside trees, and collaboration in state highway agencies. *Transportation Research Part D: Transport and Environment*, 118, 103650. <https://doi.org/10.1016/j.trd.2023.103650>
- Zegeer, C. V., Deen, R. C., & Mayes, J. G. (1981). Effect of lane and shoulder widths on accident reduction on rural, two-lane roads. *Transportation Research Record*, 806, 33–43.

## About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1 — evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at [docs.lib.purdue.edu/jtrp/](https://docs.lib.purdue.edu/jtrp/).

Further information about JTRP and its current research program is available at [engineering.purdue.edu/JTRP](https://engineering.purdue.edu/JTRP).

## About This Report

An open access version of this publication is available online. See the URL in the citation below.

Barahona, M., Bandaru, V. K., Romero, M., & Tarko, A. (2025). *Effective shoulder width on rural highway system related to roadway departure crashes* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2025/38). West Lafayette, IN: Purdue University. <https://doi.org/10.5703/1288284318601>