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Guardrail Evaluation for Hazards on Low-Volume Rural Roadways in Kansas Using RSAP

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16 Abstract

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

This study utilized Roadside Analysis Program Version 3 (RSAPv3) simulation because it implements previous crash statistics and could be readily updated with local data. With the help of KDOT staff, the research team synthesized traffic operation data and geometric features on rural roads in Kansas and carried out crash simulations using RSAPv3 to determine if the benefits of guardrail implementation exceeded the corresponding costs. The results were intended to help local engineers decide whether to implement guardrails in roadside locations with hazards. Meanwhile, the simulation also revealed significant contributing factors to rural roadside crashes. Survey results and simulation outcomes showed similar patterns. Based on project results, the benefit-cost ratios did not justify the implementation of new guardrails for bare culverts or bare embankments on rural roads in Kansas. However, W-beam guardrails were efficiently implemented on bridges with medium-hazard-level edges without bridge-approach guardrail. Likewise, for bridges with TL-2 bridge rails, study results did not justify implementing bridge-approach guardrail.

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Table of Contents

Abstract ... v
Acknowledgements ... vi
Table of Contents ... vii
List of Tables ... ix
List of Figures ... x
Chapter 1: Introduction ... 1
1.1 Background ... 1
1.2 Previous Research ... 3
1.2.1 Roadside Safety Issues ... 3
1.2.2 Benefit-Cost Analysis ... 5
1.2.3 Research on Guardrail Implementation ... 6
1.2.4 RSAP Application ... 14
1.3 Research Objectives ... 17
1.4 Report Organization ... 17
Chapter 2: Research Methodology ... 18
2.1 Crashes on the Kansas Rural Secondary System ... 18
2.1.1 Crash Dataset ... 18
2.1.2 Survey of Crashes with Guardrails ... 23
2.1.3 Crash Statistics ... 28
2.2 Introduction to RSAPv3 ... 30
2.2.1 Overview of RSAPv3 ... 30
2.2.2 Encroachment Probability Model ... 30
2.2.3 Crash Prediction Module ... 32
2.2.4 Severity Prediction Module ... 35
2.2.5 Benefit-Cost Module ... 37
2.3 Engineering Conditions for Kansas ... 37
2.3.1 Rural Roadway Conditions ... 38
2.3.2 Culvert Simulation ... 40
2.3.3 Embankment Simulation ... 44

2.3.4 Bridge Simulation 46
2.4 RSAPv3 Simulation 52
2.4.1 Input Parameters on RSAPv3 52
2.4.2 Implementing RSAPv3 Simulation 55
Chapter 3: Simulation Results and Analyses 63
3.1 Result and Analysis of Culvert Simulation 63
3.2 Result and Analysis of Embankment Simulation 66
3.3 Result and Analysis of Bridge Simulation 68
Chapter 4: Discussion and Significant Findings 73
4.1 Discussion of Results 73
4.2 Significant Findings 74
4.3 Contribution to Highway Safety 76
4.4 Limitations and Future Research 76
References 77
Appendix: Communication with Norm Bowers, Local Road Engineer, Kansas Association of Counties 80

List of Tables

Table 1.1: Traffic Fatality Rate, 2017 2

Table 1.2: Motor Vehicle Crash Fatalities, 2017 2

Table 1.3: Severity Index and Accident Cost 11

Table 2.1: Guardrail Crash Survey Results 23

Table 2.2: Fence Type 24

Table 2.3: Types of End Treatments 26

Table 2.4: Number of Crashes, AADT, and Posted Speed Limits 29

Table 2.5: Basic Encroachment Frequency, AADT, and Highway Type 32

Table 2.6: Comparison of Mechanistic and Statistical Methods 35

Table 2.7: Police-Reported Severity of Utility-Pole Crashes in Washington, 2002–2006 36

Table 2.8: Crash Costs and EFCCRs of Utility-Pole Crashes in Washington, 2002–2006 37

Table 2.9: Simulation Plan for Culverts 41

Table 2.10: Simulation Plan for Embankments 44

Table 2.11: Simulation Plan for Bridges 48

Table 2.12: Input Parameters for RSAPv3 53

Table 3.1: W-Beam Guardrail for Culvert on Three- or Four-Wheel-Track Gravel or Paved Roads 64

Table 3.2: W-Beam Guardrail for Culvert on Two-Wheel-Track Gravel Road 65

Table 3.3: W-Beam Guardrail for Embankment on Three- or Four-Wheel-Track Gravel or Paved Road 66

Table 3.4: Embankment Simulation for Three- or Four-Wheel-Track Gravel or Paved Road 67

Table 3.5: W-Beam Guardrail for Embankment on Two-Wheel-Track Gravel Road 68

Table 3.6: W-Beam Guardrail as Bridge Rail or Bridge-Approach Guardrails on Three- or Four-Wheel-Track Gravel or Paved Road 69

Table 3.7: B/C Ratio with Medium Bridge Edge as Existing Condition 70

Table 3.8: B/C Ratio with TL-2 Bridge Rail as Existing Condition 70

Table 3.9: W-Beam Guardrail as Bridge Rail or Bridge-Approach Guardrails on Two-Wheel-Track Gravel Road 72

List of Figures

Figure 1.1: Motor Vehicle Traffic Fatalities, 2008–2017 1
Figure 1.2: Depiction of Clear Zone 4
Figure 1.3: Blunt-End of Guardrail 7
Figure 1.4: An Example of a Vehicle Crash with a Guardrail Blunt-End 7
Figure 1.5: Turndown End of Guardrail 8
Figure 1.6: Breakaway Cable Terminal 8
Figure 1.7: Energy-Absorbing Terminal 9
Figure 1.8: Guardrail Length for Approaching Traffic 9
Figure 1.9: Guardrail Length for Opposite Traffic 10
Figure 1.10: Relationship between Severity Index and Impact Speed 11
Figure 1.11: RSAPv2 Approximation on Triangular Hazard 12
Figure 1.12: (a) Reinforced Concrete Box Culvert with Straight Wings; (b) Reinforced Concrete Box Culvert with Flared Wings; (c) Reinforced Concrete Pipe Culvert with Pipe/Headwall 13
Figure 1.13: Decision Matrix of Safety Treatment for Culverts 16
Figure 2.1: Ten-Year Crash Dataset Provided by KDOT 19
Figure 2.2: Table List in Crash Dataset 20
Figure 2.3: Kansas Motor Vehicle Accident Report Coding Manual 20
Figure 2.4: Accident Charts 21
Figure 2.5: GIS Shape File from the FHWA 21
Figure 2.6: County Map Files from KDOT 22
Figure 2.7: County Map (a) and GIS Map (b) 22
Figure 2.8: Low-Tension Cable Guardrail 23
Figure 2.9: Metal Fence 24
Figure 2.10: Wire Fence 24
Figure 2.11: Barbed Wire Fence 25
Figure 2.12: Irrigation System 25
Figure 2.13: Wood/Fiberglass Fence 25
Figure 2.14: Sign Frame 26

Figure 2.15: Energy-Absorbing Guardrail End in the Field 26
Figure 2.16: Breakaway Cable Terminal in the Field.. 27
Figure 2.17: Blunt-End in the Field 27
Figure 2.18: Turndown End in the Field.. 27
Figure 2.19: Cumulative Number of Culvert and Guardrail Crashes and AADT 28
Figure 2.20: RSAPv3 Crash Prediction Module Flowchart 33
Figure 2.21: Defining a Water Hazard.. 38
Figure 2.22: Rural Two-Wheel-Track Gravel Road 39
Figure 2.23: Rural Three-or Four-Wheel-Track Gravel or Paved Road.................................... 39
Figure 2.24: Cross Section Before and After Transition 40
Figure 2.25: Plan View of Culvert on Two-Wheel-Track Gravel Road.................................... 41
Figure 2.26: Plan View of Culvert on Three- or Four-Wheel-Track Gravel or Paved Road 42
Figure 2.27: Cross Section of Culvert 42
Figure 2.28: Culvert on Rural Road.. 43
Figure 2.29: Culvert with Zero Offset 43
Figure 2.30: Guardrail Shielding a Culvert 44
Figure 2.31: Plan View of Embankment on Two-Wheel-Track Gravel Road 45
Figure 2.32: Plan View of Embankment on Three- or Four-Wheel-Track Gravel or Paved Road 46
Figure 2.33: Cross Section of Embankment 46
Figure 2.34: Plan View of Bridge on Two-Wheel-Track Gravel Road..................................... 49
Figure 2.35: Plan View of Bridge on Three- or Four-Wheel-Track Gravel or Paved Road 50
Figure 2.36: Bridge Cross Section for Three- or Four-Wheel-Track Gravel or Paved Road...... 51
Figure 2.37: Bridge-approach guardrails to Bridge End.. 51
Figure 2.38: Bridge-approach guardrails to Bridge End.. 52
Figure 2.39: Costs of Fatal Crashes in Kansas for Fiscal Year 2017 54
Figure 2.40: RSAPv3 Project Interface 56
Figure 2.41: RSAPv3 Interface of Traffic Information 56
Figure 2.42: RSAPv3 Interface of Highway Characteristics... 57
Figure 2.43: RSAPv3 Interface of Highway Characteristics (User-Entered)............................. 58
Figure 2.44: RSAPv3 Interface of Alternatives (Alternative 1) 59

Figure 2.45: RSAPv3 Interface of Alternatives (Alternative 2) 59
Figure 2.46: RSAPv3 Interface of Alternatives (Alternative 3) 60
Figure 2.47: RSAPv3 Interface of Cross Section (Segment 1, 0–490 ft) 61
Figure 2.48: RSAPv3 Interface of Bridge Cross Section (Segment 3, 590–710 ft) 61
Figure 2.49: Interface of Results... 62

Chapter 1: Introduction

1.1 Background

According to the National Highway Traffic Safety Administration (NHTSA), rural crashes accounted for at least half of the total traffic fatalities from 2008 to 2017, as shown in Figure 1.1.

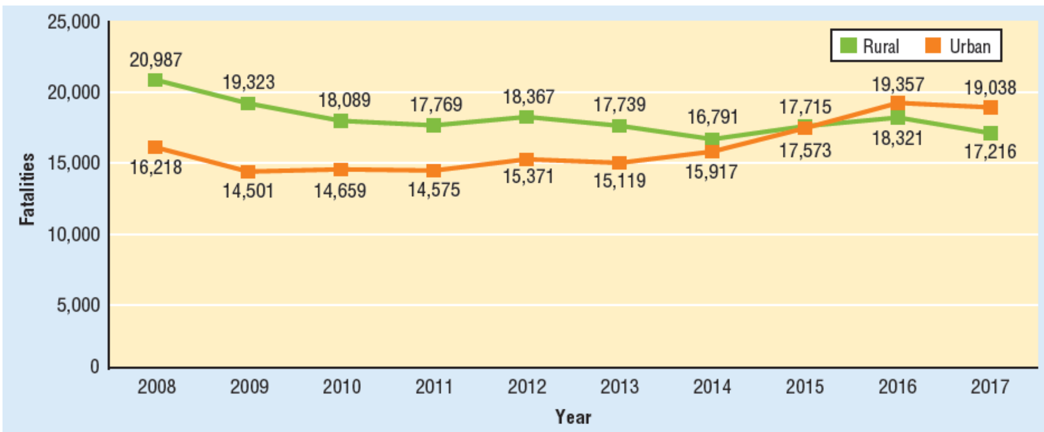


Figure 1.1: Motor Vehicle Traffic Fatalities, 2008–2017
Source: National Center for Statistics and Analysis (2019)

The American Community Survey from the United States Census Bureau revealed that only 19% of the U.S. population lived in rural areas in 2017, but of the 37,133 total traffic fatalities in that year, 17,216 fatalities (46%) occurred in rural areas. In addition, approximately 30% of the total vehicle miles traveled (VMT) were in rural areas (National Center for Statistics and Analysis, 2019). In rural areas of Kansas, the fatality rate per 100 million VMT was 2.07 in 2017, while the average fatality rate in the United States was 1.79, as shown in Table 1.1 and Table 1.2. The vehicle crash deaths in rural and urban areas, listed in these tables, show that single-vehicle crashes accounted for 55% of fatalities in rural crashes and 53% in urban crashes.

Table 1.1: Traffic Fatality Rate, 2017

Source: National Center for Statistics and Analysis (2019)

State	Fatality Rate Per 100 Million VMT	
	Rural	Urban
Kansas	**2.07**	0.85
U.S. Total	1.79	0.85

Table 1.2: Motor Vehicle Crash Fatalities, 2017

Source: IIHS (2019)

Crash Types	Rural		Urban		Total*	
	Deaths	Percent	Deaths	Percent	Deaths	Percent
Single-Vehicle Crashes	9,384	55%	10,099	53%	19,969	54%
Multiple-Vehicle Crashes	7,832	45%	8,939	47%	17,164	46%
Total	17,216	100%	19,038	100%	37,133	100%

*Total included other and/or unknowns

Single-vehicle crashes include crashes resulting from fallen rocks or debris on the road, rollover crashes within the road, crashes with animals, and roadside crashes, the most common crash type. Therefore, this research project focused on roadside crashes when considering improved traffic safety. KDOT typically implements new guardrails to shield roadside hazards on rural roads, but evidence has proven the limited effectiveness of this method, especially for rural roads in Kansas. This research was intended to fill that gap using crash simulation of guardrail implementation to shield culverts, embankments, and bridges to help local engineers determine optimal safety treatments.

Benefit-cost analyses were used to economically quantify the results and compare various implementations. With the help of KDOT staff, the research team synthesized traffic operation data and geometric features on rural roads in Kansas and carried out crash simulations using the Roadside Analysis Program Version 3 (RSAPv3) to determine if the benefits of guardrail implementation exceeded the corresponding costs. The research team also reviewed extensive literature related to roadside safety and concluded that the encroachment approach with RSAPv3 yielded the most efficient benefit-cost analysis because it utilizes real crash data to predict accident possibility and crash cost.

1.2 Previous Research

Benefit-cost analyses have become one of the primary methods to prioritize sometimes limited resources that a state highway agency may have and must use to improve the roadway network. Previous research of crash prediction models and benefit-cost analyses have been incorporated into current advanced software packages, thereby rapidly increasing the accuracy of prediction. This chapter reviews the development of roadside safety software packages. In addition, because guardrails are frequently used as effective prevention for severe loss in roadside crashes, numerous researchers have tried to determine how to optimize implementation benefits. This chapter also describes some previous research using RSAPv3, the main tool used in this study.

1.2.1 Roadside Safety Issues

The Federal Highway Administration (FHWA) has defined a roadway departure, or run-off-road (ROR) crash, as “a crash that occurs after a vehicle crosses an edge line or the centerline or otherwise leaves the traveled way.” Statistics provided by the FHWA show that roadway departures resulted in an average of 19,233 fatalities from 2015 to 2017, which accounted for 52% of all traffic fatalities in the United States (FHWA, 2019). Considering the significant damage attributed to roadside crashes, the American Association of State Highway and Transportation Officials (AASHTO, 2011) Roadside Design Guide (RDG), 4th edition, suggests six ways to reduce roadside obstacles. These measures include removing the obstacle, redesigning the obstacle for safe navigation, relocating the obstacle, reducing impact severity with appropriate breakaway devices, shielding the obstacle with a longitudinal barrier or crash cushion, and delineating the obstacle if the other measures are not applicable. The RDG also introduces the clear zone, an unobstructed, traversable area beyond the edge of the through-traveled way to help errant vehicles recover (AASHTO, 2011). The clear zone typically includes shoulders and other auxiliary systems, as shown in Figure 1.2.

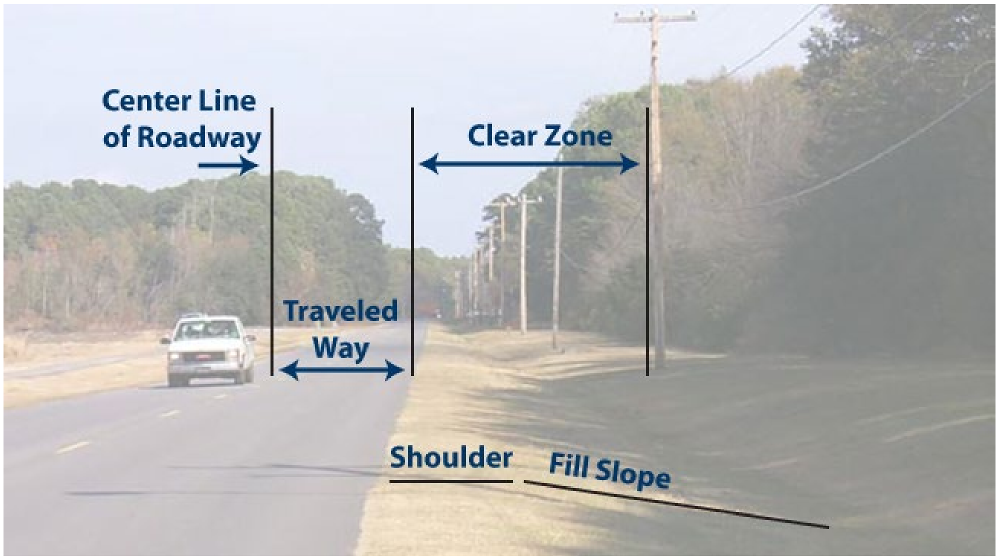


Figure 1.2: Depiction of Clear Zone
Source: Transportation Engineering Agency (n.d.)

Previous research has shown that widening lanes, medians, bridges, or shoulders, as well as relocating fixed objects farther from the roadway and flattening side slopes and medians could reduce the frequency and severity of ROR accidents (Lee & Mannering, 1999). Zegeer and Council (1995) further quantified the ratio of crash reduction on two-lane rural roads using the mentioned improvements, while Mak, Sicking, and Ross (1986) studied impact conditions for ROR crashes, as well as impact speed and angle distributions for various functional classes, thereby providing a basis for further study of severity prediction and encroachment prediction models. Research by Albuquerque, Sicking, and Stolle (2010) extracted typical crash data from the years 1997 to 1999 using previous studies and investigation to reconstruct departure and impact speeds, angles, and orientation. Bivariate normal distribution successfully fit to the impact speed and angle data, and the results were used to improve the encroachment prediction model, which was the foundation of mainstream benefit-cost analysis. Mak (1995) synthesized the previous research to predict crash possibility, providing an overview of roadside safety issues, such as design philosophy, cost-effectiveness analysis, and benefit-cost methodology. The researchers estimated unreported crashes and established a model based on the accident database and an encroachment probability model.

Although a guardrail is typically implemented to shield vehicles from dangerous hazards, the guardrail itself can become a roadside hazard, leading to severe crashes. Michie and Bronstad (1994) sought to justify the efficacy of guardrails for highway safety by estimating unreported crashes with guardrails to obtain actual fatal and injury ratios in guardrail crashes. Results showed that approximately 98% of all length-of-need impacts resulted in property-damage-only (PDO) crashes when guardrails were properly installed and maintained, with only 2% to 3% causing injuries or fatalities for vehicle occupants. Moreover, the primary causes of severe crashes with guardrails included improper installation of guardrails, non-crashworthy end-treatments, and collisions that occurred outside the practical design range of modern guardrail systems.

1.2.2 Benefit-Cost Analysis

Because funding is limited for roadside safety treatments, especially in rural areas, prioritization of limited resources is essential. Chapter 2 of the RDG introduces benefit-cost analysis to compare various designs (AASHTO, 2011). In the chapter, benefits are defined as the expected reduction in future costs of crashes associated with project improvements, while costs include expenses related to initial construction, maintenance, and repair. Benefits and costs must be annualized to compare treatments with each project life. Ray, Carrigan, Plaxico, Miaou, and Johnson (2012) established the equation of benefit-cost ratio as:

$$BCR_{i/j} = \frac{CC_i - CC_j}{DC_j - DC_i} \quad \textbf{Equation 1.1}$$

Where:

$BCR_{i/j}$ is the incremental benefit-cost ratio of Alternative *j* with respect to Alternative *i*,

CC_i, CC_j is the annualized crash cost for Alternatives *i* and *j*, and

DC_i, DC_j is the annualized project cost for Alternatives *i* and *j*.

According to RDG, data related to encroachments, roadside geometry, and crash costs are necessary to conduct a benefit-cost analysis (AASHTO, 2011).

A benefit-cost analysis can economically quantify a comparison of safety treatments, which comprises the core of traffic safety research and safety analysis software. An early research systematically reviewed benefit-cost methodology and developed a procedure that resulted in a computer program called ABC. Benefit was the product of accident prediction and corresponding crash costs, and the accident prediction model was based on a summation of all predicted encroachments and corresponding accident possibilities (Sicking & Ross, 1986). Encroachment characteristics were inferred from another study, which collected vehicle encroachment data from Canadian highways with similar speed range as most U.S. highways. Crash cost was obtained via severity index and distributions of PDO, injury, and fatal accidents and summated using estimated societal costs for each type of accident (Cooper, 1981).

1.2.3 Research on Guardrail Implementation

Previous guardrail research reviewed for this study focused on performance levels, end treatments, rational lengths, embankment and culvert evaluations, low-volume road applications, guardrail type comparisons, and evaluation methods for existing guardrails. Although guardrails are often used as a safety treatment to contain errant vehicles, they may cause impact injuries in the event of a vehicle crash. Lampela and Yang (1974) surveyed investigating officers at the scene of crashes to study the performance of W-beam guardrails in accidents in Michigan. Their research acquired angles of impact, speeds, results to the impacting vehicle, evidence of other objects or vehicles being impacted, locations of impact along the rail, the presence of curbs, and the types and spacing of guardrail posts. Accident severity, vehicle type, and vehicle impact areas were obtained from official traffic accident reports. Variables significantly related to injury rate and severity included impact speed, guardrail types and post spacing, and end treatments. Research results also indicated that rates of redirecting or stopping, as well as breaking through or hurdling guardrail, were related to guardrail type.

End treatments have also been shown to be an essential part of a guardrail's performance. Ivey, Bronstad, and Griffin (1993) investigated the relationship of guardrail end treatments and guardrail performance, usage, and cost to determine the most efficient type of end treatment. Another research reviewed performance of end treatment in some case (Glennon, 2012). Blunt-end treatments, as shown in Figure 1.3, have been used as guardrail end treatments on U.S. roadways since the 1950s, but in the mid-1960s, a blunt-end was recognized as a potential hazard in many vehicle crashes because it could strike an errant vehicle, as shown in Figure 1.4.

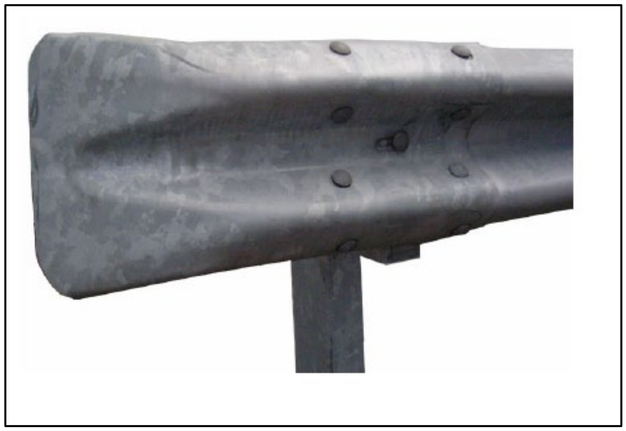


Figure 1.3: Blunt-End of Guardrail
Source: Glennon (2012)

Figure 1.4: An Example of a Vehicle Crash with a Guardrail Blunt-End
Source: Glennon (2012)

Turndown end treatments, in which the guardrail is bent and twisted 90 degrees and anchored flat on the ground (Figure 1.5), were widely implemented on guardrail systems during the late 1960s and are found on many roadways today.

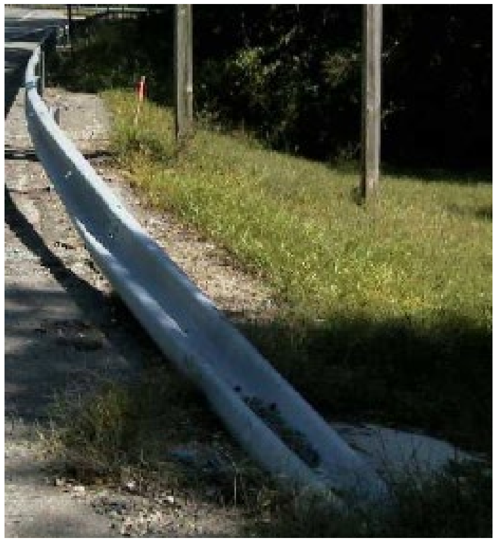


Figure 1.5: Turndown End of Guardrail
Source: Glennon (2012)

Although the turndown end was initially a favorable, economical solution, the treatment was shown in some cases to vault and roll vehicles and even channel vehicles into shielded hazards upon impact. To help reduce this crash occurrence, a breakaway cable terminal (BCT), shown in Figure 1.6, was developed to minimize striking and rolling tendencies of blunt-end and turndown end treatments. Another example of a BCT, the energy-absorbing terminal is Figure 1.7. Both treatments are common on many roadways.


Figure 1.6: Breakaway Cable Terminal

Figure 1.7: Energy-Absorbing Terminal
Source: Glennon (2012)

The economically optimal length of a guardrail reduces vehicles crashes where the vehicle runs off the roadway and optimizes construction costs. Previous research studies, which were based on the Roadside Design Guide (RDG) philosophy, explored appropriate guardrail lengths (Albuquerque, Stolle, Sicking, Faller, & Lechtenberg, 2014; Coon, Sicking, & Mak, 2006; Wolford & Sicking, 1996; Sicking & Wolford, 1996). Figures 1.8 and Figure 1.9 show required guardrail lengths for approaching and opposing traffic, respectively, in the current RDG.

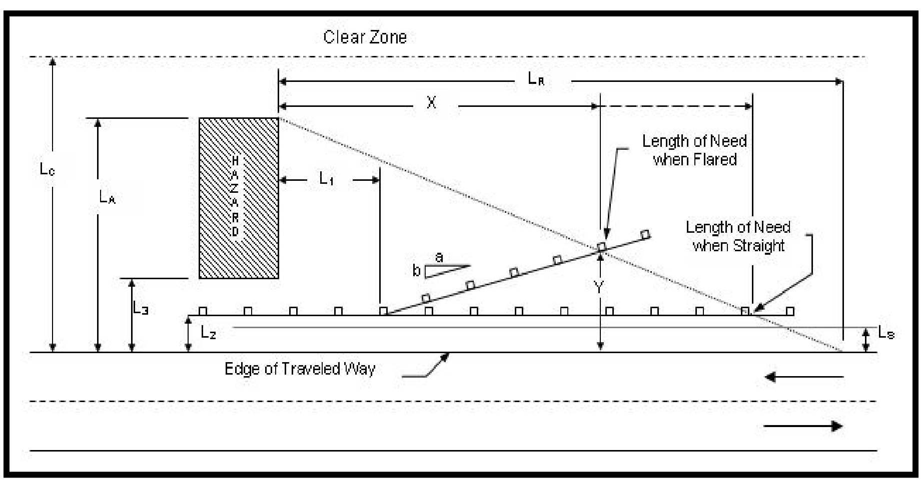


Figure 1.8: Guardrail Length for Approaching Traffic
Source: AASHTO (2011)

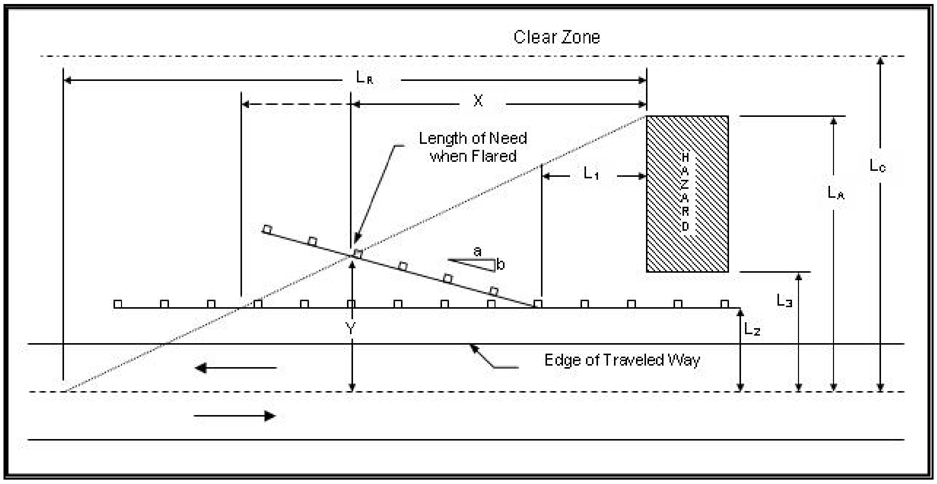


Figure 1.9: Guardrail Length for Opposite Traffic
Source: AASHTO (2011)

Traditionally, the required guardrail length is determined via the encroachment probability, which results in the straight line from the travelled way to the furthest extent of the hazard shielded by the guardrail. The safety concern was to reduce the number of vehicles that surpass the barrier and directly impact the hazard. These researchers, however, adopted encroachment data from Cooper (1981) to establish an encroachment model instead of the dataset used by RDG. The researchers asserted the validity of their choice based on the following considerations:

1. Data for RDG were collected on a snow-covered median, which is not a typical condition.
2. The speed limit was higher than current standard on US highway when the data for RDG were collected.
3. Cooper collected data under similar speed limits and with roadside conditions typical of most modern U.S. highways.

These research studies used benefit-cost analyses to evaluate the needed guardrail length which could significantly decrease from the RDG recommendation.

Since the main hazards covered in this research included embankments and culverts, previous research on the same hazards were reviewed. Wolford and Sicking (1997) studied guardrails for embankments and culverts using encroachment probability, benefit-cost analysis, and ABC software. Data from Cooper (1981) were used to establish the encroachment probability model, this was combined with analyzing crash data from Michigan and associated distribution of crash severity (fatal, injury, and PDO) with roadside hazards. With encroachment characteristics, they established a relationship between severity index and impact speed, as shown in Figure 1.10.

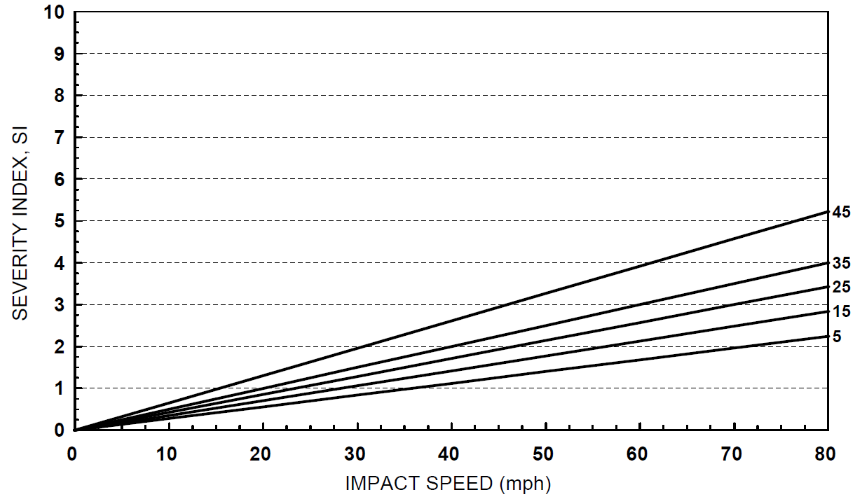


Figure 1.10: Relationship between Severity Index and Impact Speed
Source: Wolford and Sicking (1997)

As RDG recommends, the researchers connected severity index and societal costs with a distribution of crash severity (Table 1.3).

Table 1.3: Severity Index and Accident Cost
Source: AASHTO (2011)

Severity Index	Property Damage (1)	Property Damage (2)	Slight Injury	Moderate Injury	Severe Injury	Fatal Injury	Total	Probability of Injury	Accident Cost ($)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	$0
0.5	100.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	$625
1.0	66.7	23.7	7.3	2.3	0.0	0.0	100.0	9.6	$1,719
2.0	0.0	71.0	22.0	7.0	0.0	0.0	100.0	29.0	$3,919
3.0	0.0	43.0	34.0	21.0	1.0	1.0	100.0	57.0	$17,244
4.0	0.0	30.0	30.0	32.0	5.0	3.0	100.0	70.0	$46,063
5.0	0.0	15.0	22.0	45.0	10.0	8.0	100.0	85.0	$106,919
6.0	0.0	7.0	16.0	39.0	20.0	18.0	100.0	93.0	$225,694
7.0	0.0	2.0	10.0	28.0	30.0	30.0	100.0	98.0	$363,938
8.0	0.0	0.0	4.0	19.0	27.0	50.0	100.0	100.0	$556,525
9.0	0.0	0.0	0.0	7.0	18.0	75.0	100.0	100.0	$786,875
10.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0	$1,000,000

Crash severity was often overestimated due to lack of unreported, often minor, accidents. Therefore, Wolford and Sicking (1997) also estimated the magnitude of unreported crashes by tracking scratch marks and repair rates of guardrails. The costs of installation, repair, and maintenance were obtained from engineers at the Nebraska Department of Transportation.

Similar research on culverts evaluated safety treatments in terms of benefit-cost analysis and compared three common treatments: culvert extensions, guardrail installations, and grating. Local roads, rural arterials, and freeways were also investigated, and a parametric study was utilized to determine which variables influence crash cost most significantly. Variables with relatively limited impact on crash cost were eliminated from the simulation; the research proceeded with combinations of typical roadside characteristics. Results showed no optimal solution for all situations, although culvert extensions and grates were typically preferable (Albuquerque, Sicking, & Lechtenberg, 2009). The study used RSAPv2 simulation, which had difficulty modeling triangular hazards. Therefore, three rectangular hazards were combined to approximate a culvert extension, as shown in Figure 1.11. Additional details regarding simulations of this research are discussed in Section 1.2.4.

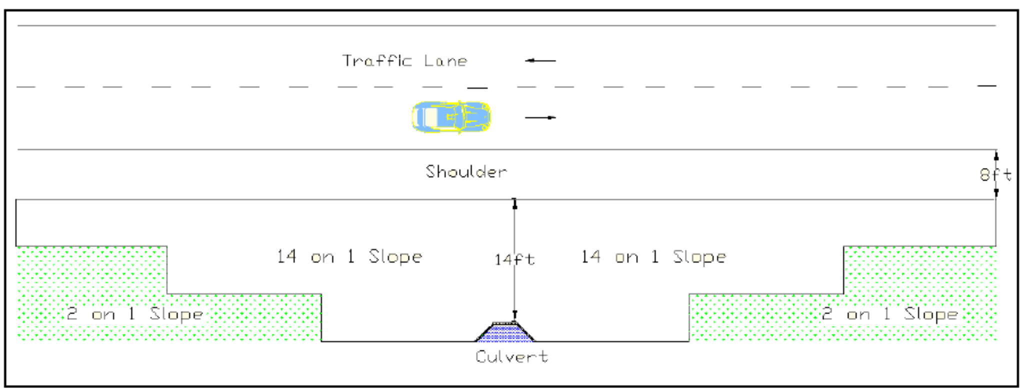


Figure 1.11: RSAPv2 Approximation on Triangular Hazard

Rys and Russell (1997) investigated guardrail performance on low-volume roads, focusing on reinforced concrete box culverts with straight wings, reinforced concrete box culverts with flared wings, and reinforced concrete pipe culverts with pipe/headwall, as shown in Figure 1.12.

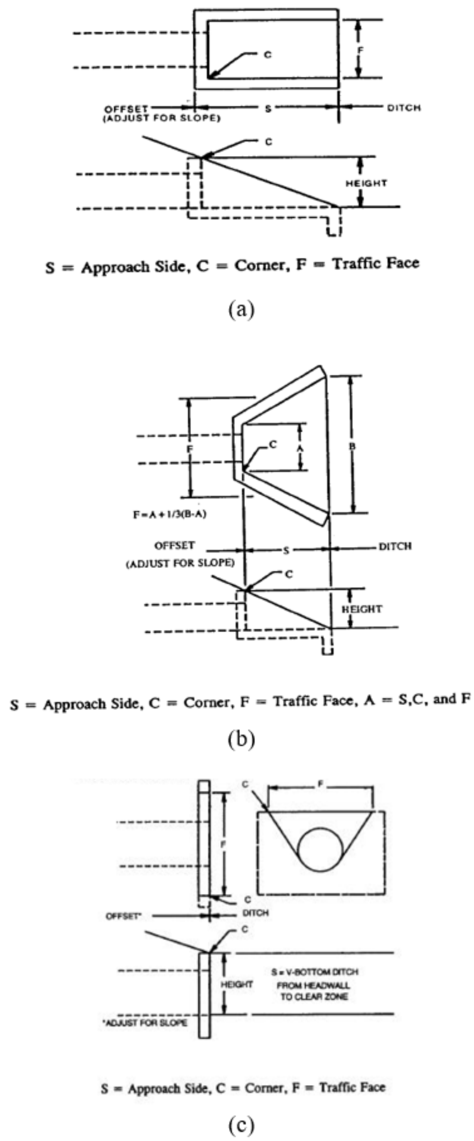


Figure 1.12: (a) Reinforced Concrete Box Culvert with Straight Wings; (b) Reinforced Concrete Box Culvert with Flared Wings; (c) Reinforced Concrete Pipe Culvert with Pipe/Headwall

The researchers used ROADSIDE program Version 5.0 to conduct cost-effectiveness analysis. Guardrail implementation was the only safety treatment considered, excluding the options of removing or relocating the hazard. They obtained crash costs and installation, repair, and maintenance expenditures from KDOT and then implemented simulation on ROADSIDE with a revised encroachment model to approximate field conditions. Research results provided a guardrail guideline for culverts and embankments on rural, low-volume roads. Annual average daily traffic (AADT), speed limit, offset of culvert, and slope of embankment were relevant variables for determining the guideline.

Safety evaluations of current guardrails are crucial for maintaining traffic safety. Therefore, Wiebelhaus, Lechtenberg, Sicking, Faller, and Rosenbaugh (2013) calibrated cost-effective treatments of existing guardrail systems using RSAPv2 simulations. A field survey of the barrier system along rural arterial highways in Kansas was carried out to record all system geometries, components, deviations from up-to-date practices, types of obstacles shielded by the guardrail, and roadway conditions. After conducting sensitivity analysis to determine significant variables to crash cost, the researchers developed a decision matrix for safety options for culverts depending on combinations of road curve, guardrail drop height, culvert length, culvert offset, and existing guardrail height. The safety treatments included doing nothing, removing the deficient system, or removing the deficient system and then installing a W-beam guardrail with a crashworthy end treatment.

1.2.4 RSAP Application

RSAP has been the primary software for roadside safety research since the publication of NCHRP Report 492, *Roadside Safety Analysis Program (RSAP) – Engineer's Manual* (Mak & Sicking, 2003), which introduced the second version of this software (RSAPv2) and utilized benefit-cost analysis to compare various roadside safety treatments. The most significant advantage of the newest RSAP version (RSAPv3) compared to its predecessors is that its prediction models rely heavily on previous crash datasets instead of predicting outcomes based only on physics equations. This project used RSAPv3 for simulation because it utilizes similar existing crashes according to input parameters to predict crash results. However, since RSAPv3 is relatively new and very few research studies have used it as an analysis tool, this section reviews both RSAPv2 and RSAPv3 applications. All reviewed RSAP research studies synthesized relevant parameters to approximate field conditions and conducted simulation based on a combination of related variables.

RSAP can simulate point hazard, line hazard, and area hazard; roadside trees are typically point or line hazards. Wiebelhaus et al. (2013) evaluated safety treatments for trees on low-volume rural roadways. A cost-effective recommendation was developed for the safety treatment of trees along roadways with AADT less than 500 vehicles per day and posted speed limits of at least 55 mph. Trees with diameters of 6 inches, 10 inches, and 12 inches or more were chosen for the analysis. A total of 120 scenarios were configured, including three tree diameters, four lateral offsets from the roadway, and 10 traffic volumes ranging from AADT 50 to 500 in increments of 50. Three safety treatments were considered: do nothing, removing the tree, or installing a crashworthy guardrail system. The researchers created a decision table to determine the optimal option based on the threshold of benefit-cost ratio associated with various combinations of parameters.

A series of studies explored safety treatments for culverts (Albuquerque et al., 2009; Albuquerque, Sicking, Faller, & Lechtenberg, 2011). First, the researchers conducted a sensitivity analysis using combinations of parameters set in normal ranges. The analysis utilized AADT, traffic growth factor, horizontal curvature, culvert size and offset, slope offset, slope steepness, slope depth, lane width, and lane numbers. Significant variables were selected after the sensitivity analysis was complete. The studies focused on four safety treatments: leaving the culvert unprotected or doing nothing; extending the culvert outside the clear zone; shielding the culvert with a guardrail; and placing safety grates over the culvert. A decision matrix for identifying the most appropriate safety treatment for roadside cross-drainage culverts was created, as shown in Figure 1.13. As shown in the figure, guardrail installation was not applicable for any highway scenario, and safety grates and culvert extensions were preferred.

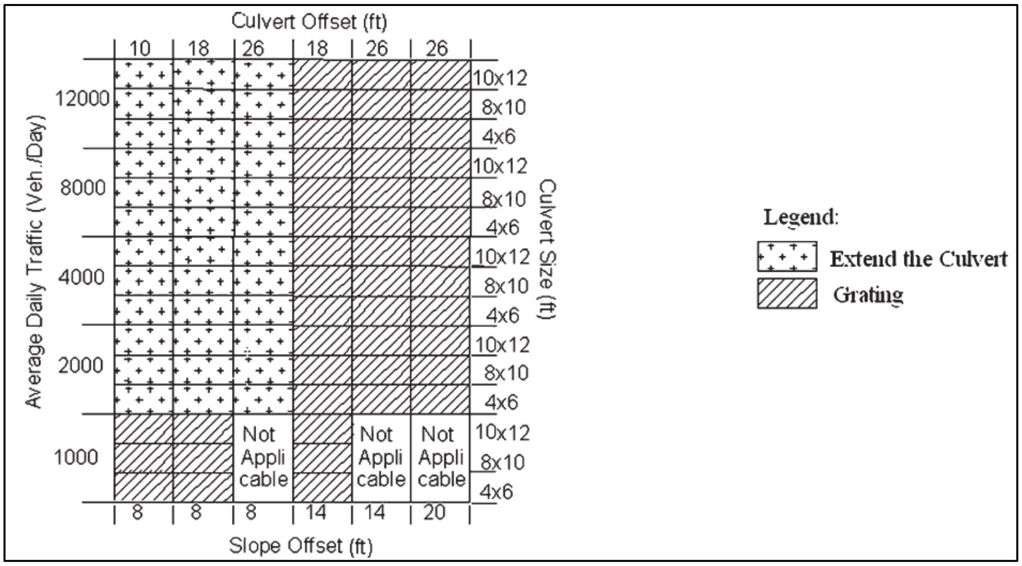


Figure 1.13: Decision Matrix of Safety Treatment for Culverts
Source: Albuquerque et al. (2011)

Embankments are another common hazard for roadside safety. Multiple research studies have utilized RSAPv2 to calibrate crash severity for various embankment geometries (Schrum, Albuquerque, Sicking, Faller, & Reid, 2014a, 2014b, 2014c; Schrum, Albuquerque, Sicking, Faller, & Reid, 2011). Prior to RSAPv3, severity index was commonly used to estimate crash cost; however, RSAPv2 often overestimated crash costs, but the results were difficult to validate. In order to obtain accurate estimates, they established relationships between real-world accident data and embankment geometry, associating the numbers of fatal and incapacitating accidents with the total mileage for each combination of slope and height and implementing benefit-cost analysis using RSAPv2. Research results showed improved accuracy with a revised severity index in RSAPv2. In RSAPv3, however, the severity index was not used, and the cost prediction model was established upon real crash data with estimated unreported crashes.

Schrum, Lechtenberg, Stolle, Faller, and Sicking (2012) also studied RSAP application on low-volume roads to develop recommendations for safety treatments of common features found on roadways with traffic volumes less than 500 vehicles per day (VPD) and posted speed limits of at least 55 mph. They conducted field investigations in Kansas and Nebraska to identify common roadside fixed objects and geometric features along very low-volume roadways. Culverts, trees, slopes, ditches, and bridges were considered. Benefit-cost analyses showed it was advantageous to remove substandard safety systems for most of the analyzed scenarios.

1.3 Research Objectives

The primary objective of the current research study was to evaluate the rationality of implementing new guardrails to shield three types of common hazards on Kansas rural roadways under various roadway operation data and geometric features. To accomplish this objective, previous crashes on Kansas rural roadways were evaluated, current Kansas roadway specifications for typical rural roadways were synthesized, and RSAPv3 was used to calibrate and develop simulations.

1.4 Report Organization

This report is comprised of four chapters. Chapter 1 included the background, previous research, and research objectives. Chapter 2 will describe a survey of previous roadside crashes in Kansas, the engineering principles underlying RSAPv3, specifications of Kansas rural roadways, and an overview of RSAPv3 simulation. Chapter 3 will explain the simulation results for three types of hazards, and Chapter 4 provides significant findings, contributions to highway safety, limitations of the research project, and recommendations for future studies.

Chapter 2: Research Methodology

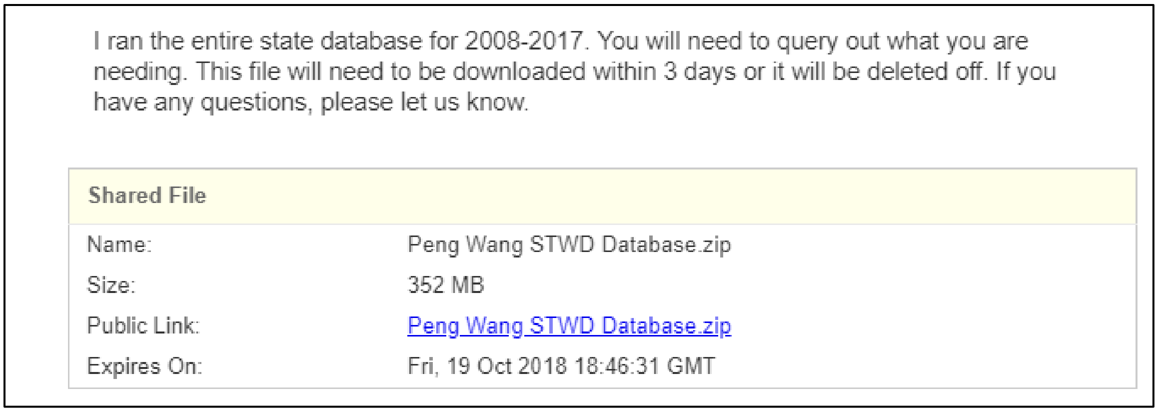
As mentioned, the objective of this research project was to use benefit-cost analysis to test the rationality of implementing new guardrails to shield roadside hazards on rural roadways in Kansas. During an initial teleconference, the research team and Kansas Department of Transportation (KDOT) staff established the empirical setting of the study which was to focus on the Kansas rural secondary system, which are rural major collector roads receiving federal-aid as secondary system (versus federal-aid primary state highway). The research team then requested a crash dataset from the KDOT Open Records Request Portal, which included 10,294 crashes with valid locations information. With help from the Geographic Information System (GIS) staff at KDOT, approximately 1,051 roadside crashes were identified that occurred on the rural secondary system from 2008 to 2017. The roadside features of guardrail crashes were investigated using Google Maps. Since culverts are difficult to determine in Google Maps, this study did not focus on this roadside feature. A benefit-cost analysis was the primary method used to compare the various safety treatments.

In order to obtain the most approximated crash simulation of typical hazards on Kansas rural roads, this study synthesized essential parameters, including crash and construction costs, from years of experiences by the project monitors. To focus the project scope, the research team (in conjunction with KDOT staff) determined to evaluate the rationality of implementing bridge rail, bridge-approach guardrails, guardrail shielding a culvert wingwall, or against an embankment across fill areas, and over crossroad pipes.

2.1 Crashes on the Kansas Rural Secondary System

2.1.1 Crash Dataset

This study investigated roadside crashes that occurred on the rural secondary system in order to identify common roadside features and basic crash patterns. Figure 2.1 shows the file link for the requested crash dataset.



I ran the entire state database for 2008-2017. You will need to query out what you are needing. This file will need to be downloaded within 3 days or it will be deleted off. If you have any questions, please let us know.

Shared File	
Name:	Peng Wang STWD Database.zip
Size:	352 MB
Public Link:	Peng Wang STWD Database.zip
Expires On:	Fri, 19 Oct 2018 18:46:31 GMT

Figure 2.1: Ten-Year Crash Dataset Provided by KDOT

The crash dataset contained 35 tables, or contributing causes, including ACCIDENTS, DRIVERS, OCCUPANTS, PEDESTRIANS, TRUCKS, VEHICLES, CC_DRIVER, CC_ENVIRONMENT, CC_ROADWAY, and CC_VEHICLE, as shown in Figure 2.2. Each table stored specific information about crashes. For example, the ACCIDENT table contained crash details such as crash location, intersection type (if applicable), light conditions, weather conditions, road surface type, road conditions, road character, road class, road maintenance information, date of crash, time of crash, day of crash, accident class, injury severity (fatal, injury, or PDO), and manner of collision. The DRIVERS table provided information such as traffic unit (potential of multiple vehicles in one case), state of license, license information, and alcohol and drug involvement. The OCCUPANTS table contained ACCIDENT_KEY, traffic unit, seat location, name, city, state, gender, and age of every occupant in the vehicle. This study utilized key information from different tables.

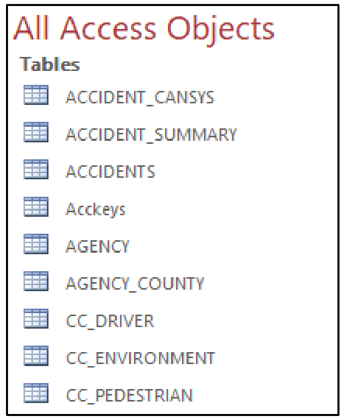
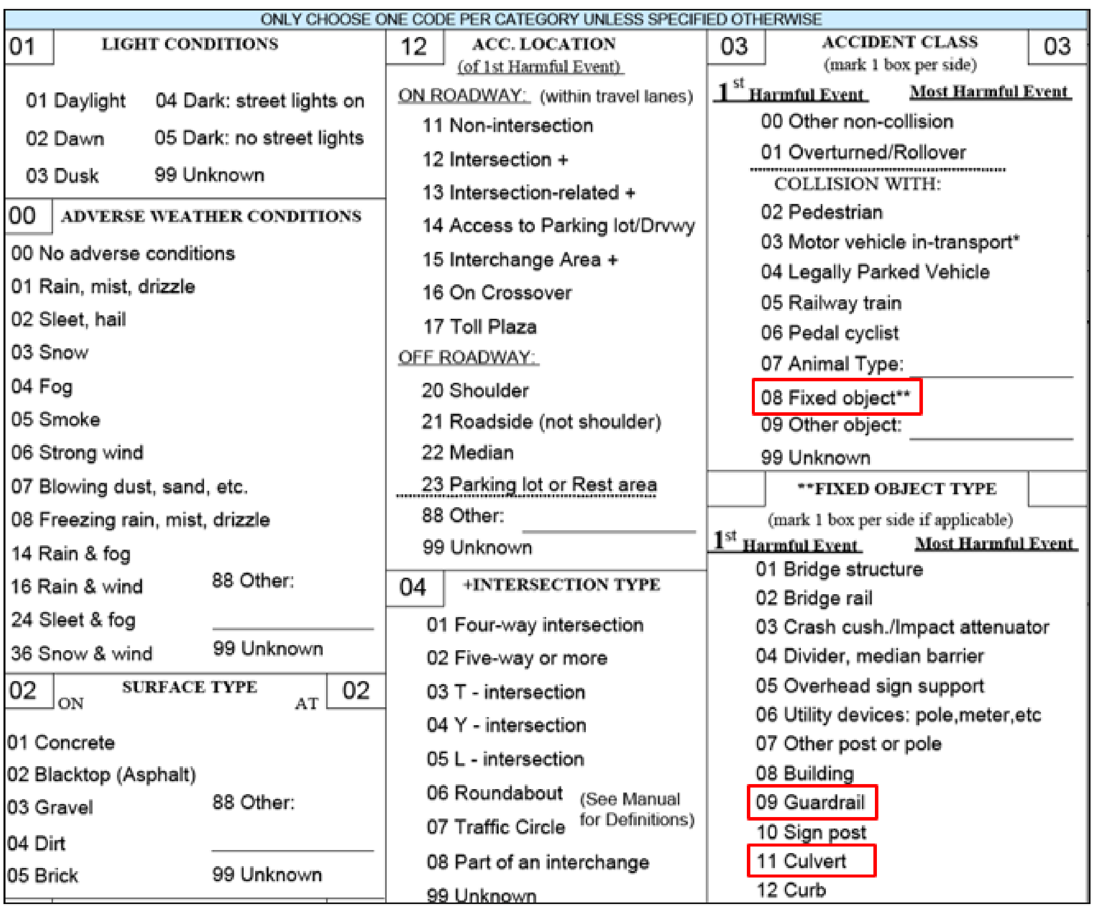


Figure 2.2: Table List in Crash Dataset

Using the Kansas Motor Vehicle Accident Report Coding Manual, fixed-object crashes with guardrails and culverts were extracted from the crash dataset, as indicated in Figures 2.3 and 2.4.



ONLY CHOOSE ONE CODE PER CATEGORY UNLESS SPECIFIED OTHERWISE

01 LIGHT CONDITIONS
01 Daylight
02 Dawn
03 Dusk
04 Dark: street lights on
05 Dark: no street lights
99 Unknown

00 ADVERSE WEATHER CONDITIONS
00 No adverse conditions
01 Rain, mist, drizzle
02 Sleet, hail
03 Snow
04 Fog
05 Smoke
06 Strong wind
07 Blowing dust, sand, etc.
08 Freezing rain, mist, drizzle
14 Rain & fog
16 Rain & wind
24 Sleet & fog
36 Snow & wind
88 Other:
99 Unknown

02 ON SURFACE TYPE AT 02
01 Concrete
02 Blacktop (Asphalt)
03 Gravel
04 Dirt
05 Brick
88 Other:
99 Unknown

12 ACC. LOCATION (of 1st Harmful Event)
ON ROADWAY: (within travel lanes)
11 Non-intersection
12 Intersection +
13 Intersection-related +
14 Access to Parking lot/Drvwy
15 Interchange Area +
16 On Crossover
17 Toll Plaza
OFF ROADWAY:
20 Shoulder
21 Roadside (not shoulder)
22 Median
23 Parking lot or Rest area
88 Other:
99 Unknown

04 +INTERSECTION TYPE
01 Four-way intersection
02 Five-way or more
03 T - intersection
04 Y - intersection
05 L - intersection
06 Roundabout
07 Traffic Circle
(See Manual for Definitions)
08 Part of an interchange
99 Unknown

03 ACCIDENT CLASS (mark 1 box per side) 03
1st Harmful Event Most Harmful Event
00 Other non-collision
01 Overturned/Rollover
COLLISION WITH:
02 Pedestrian
03 Motor vehicle in-transport*
04 Legally Parked Vehicle
05 Railway train
06 Pedal cyclist
07 Animal Type:
08 Fixed object**
09 Other object:
99 Unknown

**FIXED OBJECT TYPE
(mark 1 box per side if applicable)
1st Harmful Event Most Harmful Event
01 Bridge structure
02 Bridge rail
03 Crash cush./Impact attenuator
04 Divider, median barrier
05 Overhead sign support
06 Utility devices: pole,meter,etc
07 Other post or pole
08 Building
09 Guardrail
10 Sign post
11 Culvert
12 Curb

Figure 2.3: Kansas Motor Vehicle Accident Report Coding Manual

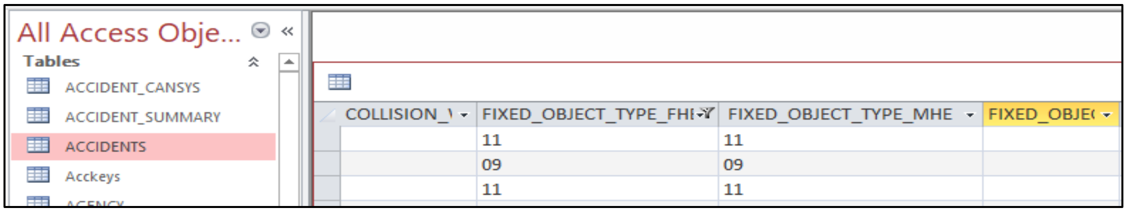


Figure 2.4: Accident Charts

A total of 11,031 crashes were filtered from the dataset, including 10,294 crashes with valid locations (latitude and longitude) that were loaded onto the GIS system. GIS shape files, including road system and corresponding AADT, were acquired from the FHWA website (Figure 2.5) to identify the locations of projected crashes.

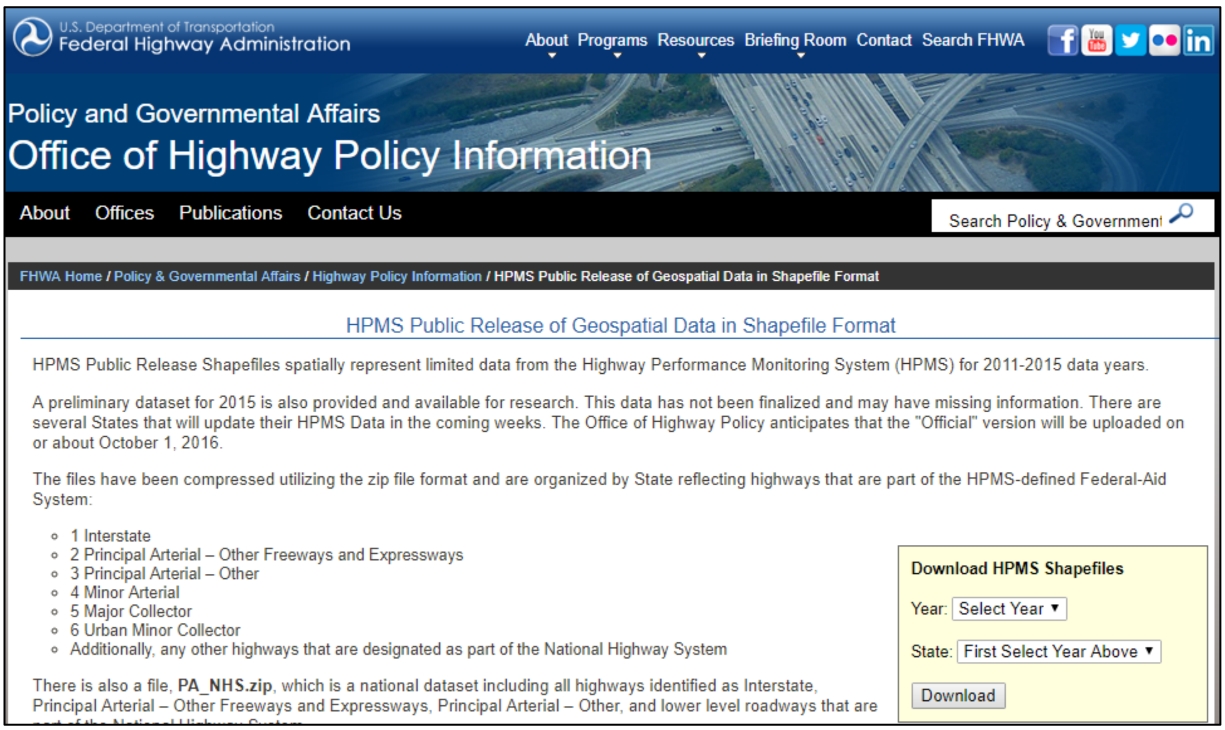
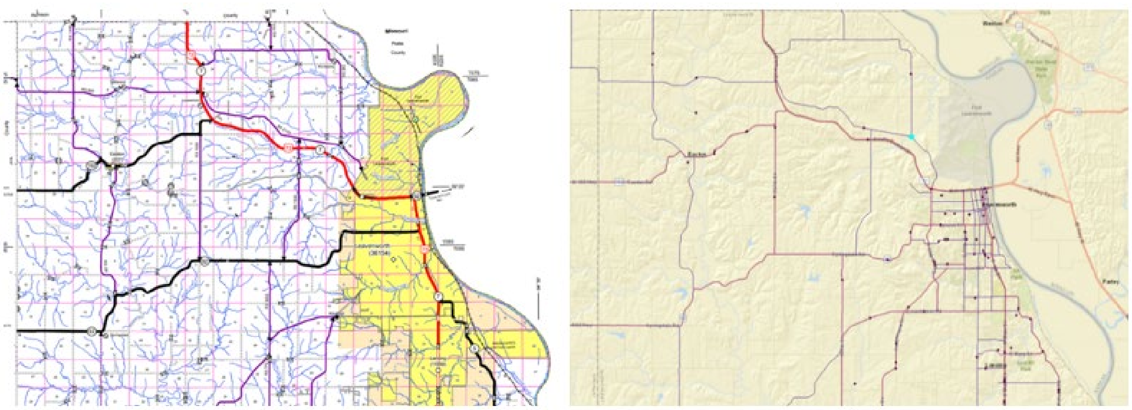


Figure 2.5: GIS Shape File from the FHWA

Additionally, Kansas county maps were obtained through KDOT's website (Figure 2.6) to determine which roads belong to the Kansas rural secondary system. As shown in Figure 2.7, the county maps were compared to GIS maps to identify crashes on specific road systems.

Figure 2.6: County Map Files from KDOT



(a) (b)

Figure 2.7: County Map (a) and GIS Map (b)

In Figure 2.7(a), the rural secondary system is highlighted in purple, and the blue point in Figure 2.7(b) shows a crash that occurred on that system. Following this comparison, 1,051 of 10,294 crashes occurred on the rural secondary system, including 288 guardrail crashes and 763 crashes involving culverts.

2.1.2 Survey of Crashes with Guardrails

Google Maps was then used to survey the 288 guardrail crashes. Approximately one-third of the crash locations contained guardrails (Table 2.1), and among those locations, nine crash sites contained low-tension cable guardrails (Figure 2.8).

Table 2.1: Guardrail Crash Survey Results

Locations	Number	Percentage
Guardrails Observed	99	34.38%
Fences Observed	55	19.09%
Nothing Nearby	134	46.53%
Total Locations	288	100.00%

Figure 2.8: Low-Tension Cable Guardrail

Of the 288 guardrail crashes, no guardrail was observed at 134 locations, and 55 crash locations only had fences nearby. Table 2.2 contains statistics for all the fence locations and what was observed by the researcher.

Table 2.2: Fence Type

Fence Type	Number	Percentage
Metal Fence	4	7.27%
Wire Fence	25	45.45%
Barbed Wire Fence	20	36.36%
Irrigation System	2	3.64%
Wood / Fiberglass Fence	2	3.64%
Sign	2	3.64%
Total Locations	55	100.00%

Objects that could be mistaken for guardrails were screen-captured by the research team for validation, as shown in Figures 2.9 through 2.14.

Figure 2.9: Metal Fence

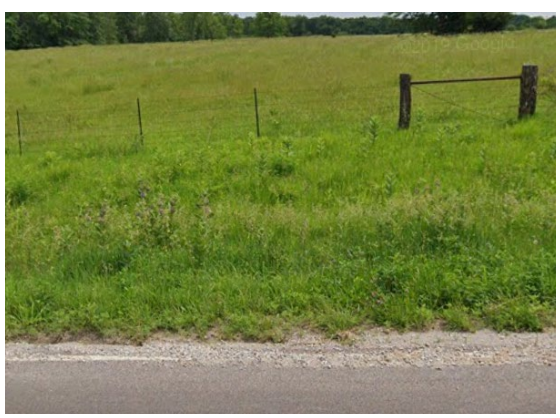


Figure 2.10: Wire Fence


Figure 2.11: Barbed Wire Fence


Figure 2.12: Irrigation System


Figure 2.13: Wood/Fiberglass Fence

Figure 2.14: Sign Frame

Moreover, for the 99 locations with guardrails nearby, 79 sites contained end treatments on the guardrails. Table 2.3 lists the types and statistics of observed end treatments. Various end treatments were photographically documented, as shown in Figures 2.15 through 2.18.

Table 2.3: Types of End Treatments

End-Treatment Type	Number	Percentage
Energy Absorbing End	8	10.13%
Breakaway Cable End	32	40.51%
Blunt End	35	44.30%
Turn Down End	4	5.06%
Totally Observed	79	100.00%

Figure 2.15: Energy-Absorbing Guardrail End in the Field

Figure 2.16: Breakaway Cable Terminal in the Field

Figure 2.17: Blunt-End in the Field

Figure 2.18: Turndown End in the Field

2.1.3 Crash Statistics

This section describes in-depth research of the dataset to capture basic patterns and contributing factors of roadside crashes on the Kansas rural secondary system. This study used GIS shape files, as described in Section 2.1.1, to correspond every roadside crash with a corresponding AADT using GIS. Of the 1,051 crashes involving guardrail or culvert, only five crashes occurred in locations with AADT ranging from 5,000 to 7,500 vehicles per day. AADTs of the rest of the crash locations were less than 4,700 vehicles per day. Therefore, in order to obtain a balanced sample, the entire dataset was truncated, and only crash locations with AADTs less than 4,700 vehicles per day were analyzed, resulting in 1,046 crashes. The AADTs were divided into a sequence from 100 to 4,700 vehicles per day, with increments of 100. The cumulative number of crashes for each sequence is shown in Figure 2.19.

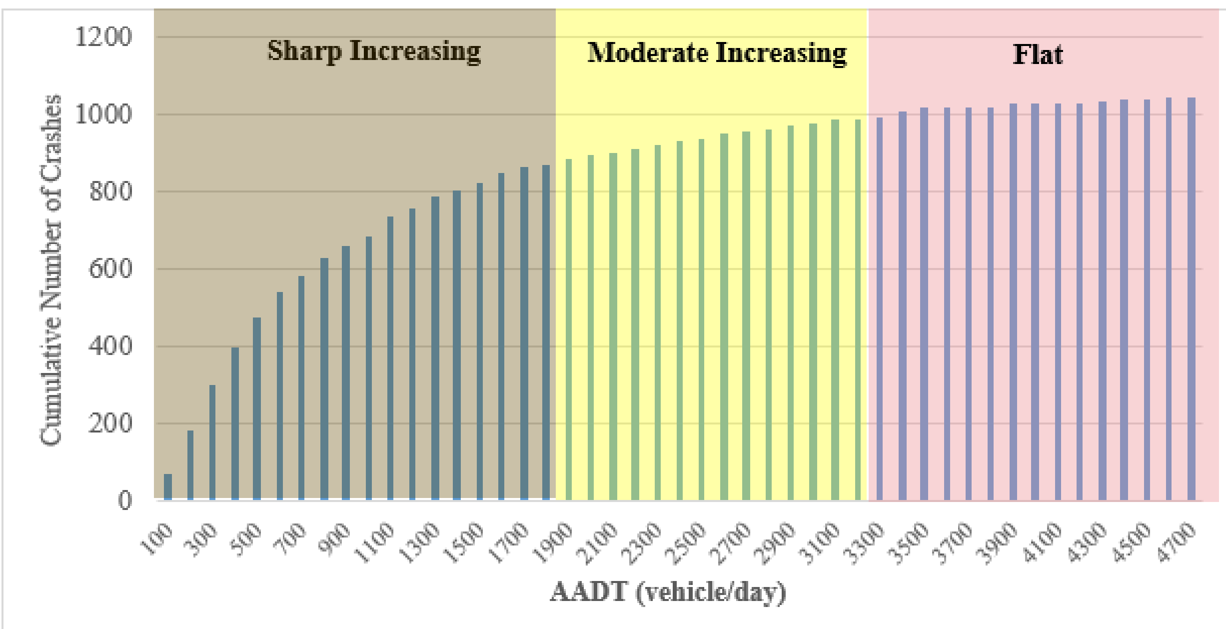


Figure 2.19: Cumulative Number of Culvert and Guardrail Crashes and AADT

As shown in Figure 2.19, the graph could be roughly divided into three sections of AADT. The first section includes 100–1,900 vehicles per day, with a sharp increasing trend. The second section ranges from 1,900 to 3,200 vehicles per day, with a moderate increasing trend, while the third section encompasses 3,300–4,700 vehicles per day, a nearly flat trend. Results showed that AADT was a contributing factor to roadside crashes, or crashes involving guardrails and culverts.

This study also investigated posted speed limit as another crash-contributing factor mentioned in previous research studies. Among the 1,046 analyzed crashes, 17 crashes did not have valid data pertaining to posted speed limit. Approximately 1,029 crashes were specifically studied for this factor. AADT and posted speed limit were exploited simultaneously to calibrate their effects on roadside crashes. Crashes were grouped according to posted speed limit, starting at 20 mph and ranging to 65 mph, with increments of 5 mph for each sequence. For a fixed posted speed limit, the number of crashes were divided into an AADT sequence, such as 0–500, 500–1,000, until 5,000 vehicles per day. The average AADT of crash locations for a certain posted speed limit was calculated via arithmetic mean. Table 2.4 shows the results of this analysis.

Table 2.4: Number of Crashes, AADT, and Posted Speed Limits

Posted Speed Limit (mph)	Average AADT	Total Number of Crashes	Number of Crashes in Each AADT Sequence									
			0–500	500–1000	1000–1500	1500–2000	2000–2500	2500–3000	3000–3500	3500–4000	4000–4500	4500–5000
20	1679	1				1						
25	1205	4	2				2					
30	**831**	**28**	12	6	5	3	1	1				
35	**1038**	**19**	8	4	3	1	1	1		1		
40	**1110**	**21**	5	9	2	2			3			
45	**1097**	**89**	29	21	22	5	3	4	1	1		3
50	**1153**	**50**	10	15	16	1	2	3	2			1
55	**926**	**801**	393	152	88	57	28	30	31	11	7	4
60	1640	4	1				3					
65	1694	12	4	1			3		4			

In the table, the relevant numbers in bold from 30 mph to 55 mph are significant because the sample size for each section was relatively sufficient. The number of crashes roughly increased with increasing posted speed limit, although the average AADT did not differ significantly, meaning the posted speed limit contributed more substantially to roadside crashes than AADT. Further discussion of this topic is beyond the scope of this research.

2.2 Introduction to RSAPv3

This section includes a succinct review of the RSAPv3 Engineer's Manual (Ray et al., 2012).

2.2.1 Overview of RSAPv3

RASPv3 was designed to perform benefit-cost analysis for alternatives of roadside safety treatments. As stated in Section 1.2.2, benefit is defined as a reduction in crash costs associated with project improvements, while cost includes construction, maintenance, and repair expenditures. When performing a benefit-cost analysis, RSAPv3 divides a crash into a series of conditional events, including the probability of encroachment, the probability of a crash given an encroachment, the severity of a crash, and the cost of the sequence. Based on this philosophy, RSAPv3 consisted of four modules: encroachment probability module, crash prediction module, severity prediction module, and benefit-cost analysis module.

The expected annual crash cost is calculated by a cumulative probability equation:

$$E(CC)_{N,M} = ADT \cdot L_N \cdot P(Encr) \cdot P(Cr|Encr) \cdot P(Sev|Cr) \cdot E(CC_s|Sev_s) \qquad \textbf{Equation 2.1}$$

Where:

$E(CC)_{N,M}$ = expected annual crash cost on segment N for Alternative M,

ADT = average daily traffic in vehicles/day,

L_N = length of segment N in miles,

$P(Encr)$ = the probability a vehicle will encroach on the segment,

$P(Cr|Encr)$ = the probability a crash will occur given that an encroachment has occurred,

$P(Sev_s|Cr)$ = the probability a certain severity will occur given that a crash has occurred, and

$E(CCs|Sev_s)$ = the expected cost of a severe crash in dollars.

2.2.2 Encroachment Probability Model

The encroachment probability model was implemented upon Cooper (1981) encroachment data which were collected on 59 road sections ranging from 60 km to 100 km in length in five geographically dispersed Canadian provinces. The collection team recorded tire tracks and objects struck by vehicles beyond the paved and gravel shoulders. Efforts were made to exclude improper encroachment records such as tire tracks generated by maintenance work, and inclement weather conditions were underrepresented due to limited time for data collection. Cooper's survey targeted three parameters for each detected encroachment, including maximum extent of lateral encroachment, longitudinal distance, and encroachment angle.

When using RSAPv3, the current study used the negative binomial regression model to predict roadside encroachment rate and frequency. Basic encroachment frequencies associated with AADT and highway type are listed in Table 2.5.

Base conditions for the encroachment module of RSAPv3 included a posted speed limit of 65 mph, flat ground, nearly straight segment, and lane widths of approximately 12 ft. RSAPv3 can adjust for variation from base conditions, such as multiple lanes, posted speed limit, access density, terrain type, vertical grade, horizontal curve, and lane width. RSAPv3 users also can add new encroachment data and adjustment factors, as well as new vehicle types.

Table 2.5: Basic Encroachment Frequency, AADT, and Highway Type
Source: RSAPv3 Engineer's Manual (Ray et al., 2012)

AADT (bi-directional)	Two-Lane Undivided (encr/mi/yr)	Four-Lane Divided (encr/mi/yr)	One-Way (encr/mi/yr)
1,000	1.2244	0.8473	0.4236
5,000	2.6514	3.5915	1.7958
10,000	1.8631	5.8435	2.9217
15,000	0.9819	7.1306	3.5653
20,000	1.3091	7.7344	3.8672
25,000	1.6364	7.865	3.9325
30,000	1.96.37	7.6779	3.8389
35,000	2.2909	7.2870	3.6435
40,000	2.6182	6.7749	3.3874
45,000	2.9455	7.6206	3.8103
50,000	3.2728	8.4673	4.2337
55,000	3.6000	9.314	4.657
60,000	3.9273	10.1608	5.0804
65,000	4.2546	11.0075	5.5038
70,000	4.5819	11.8542	5.9271
75,000	4.9091	12.7010	6.3505
80,000	5.2364	13.5477	6.7738
85,000	5.5637	14.3944	7.1972
90,000	5.8910	15.2412	7.6206
95,000	6.2182	16.0879	8.0439
100,000	6.5455	16.9346	8.4673

2.2.3 Crash Prediction Module

In order to determine the probability of a collision associated with a given encroachment, RSAPv3 constructs trajectories to reveal intersections with hazards. RSAPv3 identifies three types of hazards: point hazards, line hazards, and area hazards. Point and line hazards can be explicitly defined in the analysis by type and location, while area hazards are identified by terrain features and automatically handled by RSAPv3. Figure 2.20 shows an RSAPv3 flowchart for the crash prediction module.

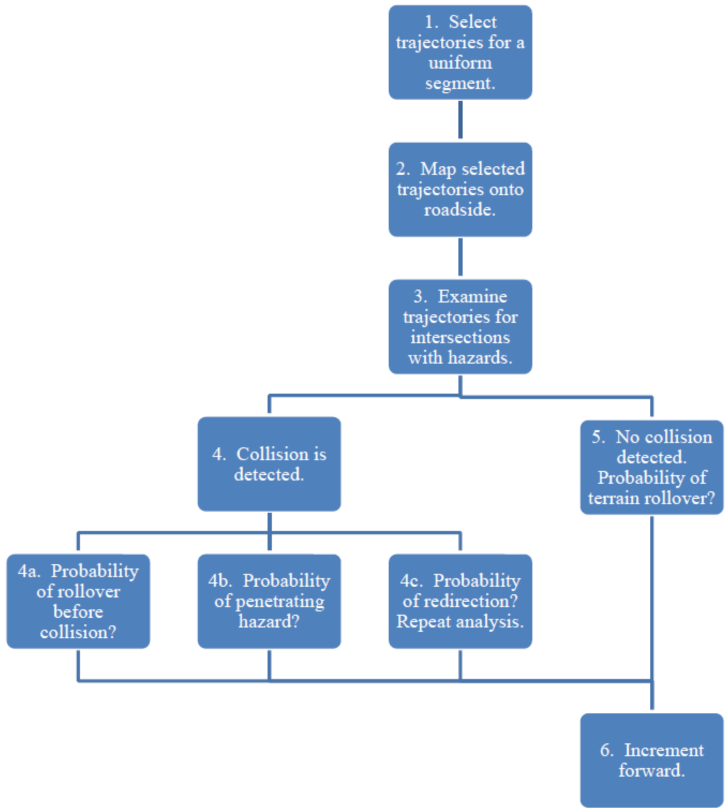


Figure 2.20: RSAPv3 Crash Prediction Module Flowchart
Source: RSAPv3 Engineer's Manual (Ray et al., 2012)

Because driver response, such as reacting to roadside features or maneuvering to avoid collision, significantly influences collision trajectory after encroachment, this trajectory cannot be reconstructed solely with data from non-crash-related research, such as research in Cooper (1981). Therefore, RSAPv3 established a trajectory look-up table to match crash routines with data found in NCHRP Project 17-22, *Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes*. NCHRP 17-22 assembled an ROR database of 890 crash cases from the FHWA rollover study, NCHRP Project 17-11, *Determination of Safe/Cost Effective Roadside Slopes and Associated Clear Distances*, and new cases. Although a crash-trajectory dataset is advantageous because it is based on real conditions, the disadvantage of this dataset is that all the trajectories from the source terminate at the point of impact. Due to the limited number of crashes and rare cases that occurred downstream far from initial impact, the research team extrapolated trajectory path beyond the collision point with the last known trajectory information (e.g., straight path, last known velocity vector, and braking rate), which was verified by the cumulative distribution chart.

RSAPv3 matched crash simulation with relevant cases in the trajectory database by comparing geometry features similarity. Four criteria were used in this procedure: roadside cross-section profile, horizontal curve radius, highway vertical grade, and posted speed limit. A composite score was computed based on the weighted average of the four criteria.

$$S_c = W_1 s_1 + W_2 s_2 + W_3 s_3 + W_4 s_4 \quad \textbf{Equation 2.2}$$

Where:

s_1 = score of roadside cross section,

s_2 = score of horizontal curvature,

s_3 = score of vertical grade,

s_4 = score of posted speed limit, and

W_j = a weight factor for each individual score, with default value:

$W_1 = 3, W_2 = 2, W_3 = 1, W_4 = 1$, which can be adjusted.

RSAPv3 uses side slope, horizontal curve radius, and highway grade to determine the probability of a terrain rollover along a trajectory path. A user can modify or add relevant data via the Encr Freq and Adj worksheet in RSAPv3.

$$P(R) = \frac{1}{L_{tot}} \sum_i^N P(R|slope)_i * \emptyset_{s_i,G} * \emptyset_{s_i,HC} * L_i \quad \textbf{Equation 2.3}$$

Where:

$P(R)$ = probability of a rollover for the trajectory,

$P(R|slope)_i$ = probability of a rollover based on the side slope at increment *i*,

$\emptyset_{s_i,G}$ = adjustment factor for vertical grade and side slope at increment *i*,

$\emptyset_{s_i,HC}$ = adjustment factor for horizontal curve radius and side slope at increment *i*,

L_i = length of current increment,

L_{tot} = total length of the trajectory path, and

N = total number of increments along the trajectory path during analysis.

RSAPv3 generally defines hazard penetration as bumping through a hazard, vaulting over a hazard, or rolling over the top of a hazard. Penetration outcomes for point hazards include vehicle penetration of a hazard, which is justified by comparing the kinetic energy of the collision with the strain energy of a hazard, or discontinuation of movement when a vehicle encounters a hazard. RSAPv3 matches various levels of severity to each type of a hazard. Line hazards have six possible outcomes of penetration: stop upon contact with a hazard (90-degree impact), redirection, redirection with a rollover on the impact side of a hazard, hazard penetration to cause structural failure of the barrier, rollover hazard on the other side, and vaulting on the other side. The RSAPv3 Severity worksheet contains analysis ratios of redirection, vaulting, and rollovers based on real crash data. Unlike previous roadside safety benefit-cost software that relied on mechanistic methods with structural penetration, RSAPv3 uses both mechanistic and statistical methods to perform benefit-cost analyses (Table 2.6).

Table 2.6: Comparison of Mechanistic and Statistical Methods

Source: RSAPv3 Engineer's Manual (Ray et al., 2012)

Mechanical		**Statistical**	
Strength	Weakness	Strength	Weakness
Based on physics	Capacity of barriers is seldom known a priori	Based on real-world data and therefore likely to be accurate	May not be data available for many types of barriers, especially new or special barriers
Useful for barriers with unknown field performance	Simple equations for prediction are not very accurate	Easy to compute and implement using RSAP	May not be able to determine impact conditions most associated with performance
Based on impact conditions and structural assessment	Complex simulations are not practical and are difficult to implement		
Simple equations are easy to implement			

2.2.4 Severity Prediction Module

The severity module implemented in RSAPv3 was based on police-reported crashes and then adjusted for unreported crashes and speed effects to develop a dimensionless severity measure that can be associated with impact speed of each simulated collision.

The value "equivalent fatal crash cost ration" (EFCCR) was the result of this analysis, which is an average dimensionless severity measure scaled to fatal crash costs.

Table 2.7: Police-Reported Severity of Utility-Pole Crashes in Washington, 2002–2006

Source: RSAPv3 Engineer's Manual (Ray et al., 2012)

Posted Speed Limit (mph)	Police-Reported Severity												
	K		A		B		C		PDO		Unknown		Total Cases
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
2002–2006 WSDOT HSIS													
25	0	0.00	3	5.45	12	21.82	4	7.27	33	60.00	3	5.45	55
30	1	1.39	1	1.39	11	15.28	11	15.28	35	48.61	13	18.06	72
35	1	0.40	9	3.63	42	16.94	57	22.98	115	46.37	24	9.68	248
40	4	3.70	3	2.78	22	20.37	20	18.52	51	47.22	8	7.41	108
45	1	0.95	4	3.81	23	21.90	25	23.81	40	38.10	12	11.43	105
50	6	1.77	15	4.42	75	22.12	57	16.81	161	47.49	25	7.37	339
55	4	1.87	10	4.67	55	25.70	37	17.29	98	45.79	10	4.67	214
60	1	1.56	1	1.56	9	14.06	16	25.00	31	48.44	6	9.38	64
65	1	33.33	0	0.00	0	0.00	1	33.33	1	33.33	0	0.00	3
70	0	0.00	0	0.00	0	0.00	1	33.33	2	66.67	0	0.00	3

Previous research has shown that police-reported crash data underrepresented low-severity crashes because a significant number of PDO crashes were not reported. Using estimated unreported crashes, total crash costs for respective posted speed limit were estimated, as shown in Table 2.8.

Table 2.8: Crash Costs and EFCCRs of Utility-Pole Crashes in Washington, 2002–2006

Source: RSAPv3 Engineer's Manual (Ray et al., 2012)

Posted Speed Limit (mph)	Police-Reported Severity						Unreported	Total Crash Cost	EFCCR
	K	A	B	C	PDO	Unknown			
	$2,600k	$180k	$36k	$19k	$2k	$2k	$1k		
	%	%	%	%	%	%	$		
Washington State HSIS (2002–2006)									
25	0.00	1.15	4.60	1.53	12.64	1.15	78.93	5,080	0.001954
30	0.44	0.44	4.80	4.80	15.29	5.68	68.56	15,888	0.006111
35	0.13	1.18	5.50	7.46	15.05	3.14	67.54	9,959	0.003830
40	1.52	1.14	8.37	7.61	19.39	3.04	58.93	47,098	0.018115
45	0.44	1.78	10.23	11.12	17.80	5.34	53.28	21,567	0.008295
50	1.14	2.85	14.27	10.85	30.64	4.76	35.49	43,086	0.016572
55	1.33	3.32	18.28	12.30	32.57	3.32	28.88	50,472	0.019412
60	1.55	1.55	13.98	24.85	48.14	9.32	0.62	54,076	0.020798
65	24.60	0.00	0.00	24.60	24.60	0.00	26.19	64,510	0.248116
70	0.00	0.00	0.00	57.07	42.93	0.00	0.00	12,413	0.004774

$$EFCCR_{25} = \frac{Total\ Crash\ Cost}{Fatal\ Crash\ Cost} = \frac{5{,}080}{2{,}600{,}000} = 0.001954$$ **Equation 2.4**

RSAPv3 research team developed a regression model to estimate the EFCCR as a function of posted speed:

$$EFCCR = \left[\frac{EFCCR_{65}}{65^3}\right] V_i^3.$$ **Equation 2.5**

2.2.5 Benefit-Cost Module

The benefit-cost module in RSAPv3 is based on the same principle described in Section 1.2.2. The user can input local project costs and fatal crash costs, which RSAPv3 transfers to a particular type of crash cost via EFCCR, as described in Section 2.2.4.

2.3 Engineering Conditions for Kansas

All of the geometric features of a hazard, including offset and slope (Figure 2.21), and traffic operation data are necessary to define a hazard in RSAPv3. This section details the engineering conditions specific to local roadways in Kansas.

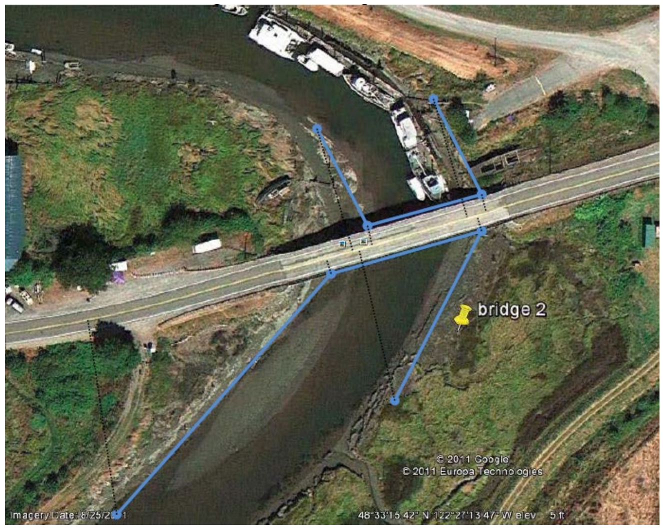


Figure 2.21: Defining a Water Hazard
Source: RSAPv3 User's Manual (Ray et al., 2012)

2.3.1 Rural Roadway Conditions

Rural roadways in Kansas are primarily comprised of two-wheel-track gravel roads (Figure 2.22) or three- to four-wheel-track gravel or paved roads (Figure 2.23). Roadway widths of two-wheel-track roads in this project were 18 ft, 20 ft, 22 ft, and 24 ft, with the 10 ft width wheel track in the center of the road defining the lane width. Any extra space on the roadway besides the lane width was considered the shoulder width, measured from the edge of the wheel track through the edge of the roadway. Shoulder widths for this study were 4 ft, 5 ft, 6 ft, and 7 ft for each road width in sequence. The AADT was especially low on these roads, usually 100 or 200 vehicles per day.

In three- or four-wheel-track gravel or paved roads, however, two lanes, each with widths of 12 ft, are defined by the wheel track. One lane is considered the primary direction, and the other lane is the opposing direction. Roadway widths of three- or four-wheel-track gravel or paved roads in this project were 24 ft, 26 ft, and 28 ft. After deducting the two-lane width from the road, shoulder widths were 0 ft, 1 ft, and 2 ft for each road width in sequence. The AADT for three- or four-wheel-track gravel or paved roads in this study were 100, 400, and 1,000 vehicles per day.

Figure 2.22: Rural Two-Wheel-Track Gravel Road
Source: N. Bowers (personal communication, 2019; see Appendix for correspondence)

Figure 2.23: Rural Three-or Four-Wheel-Track Gravel or Paved Road
Source: N. Bowers (personal communication, 2019)

For both types of rural roadways, the foreslope beside the road was 3:1 with a height of 2 ft, as shown in Figure 2.24.

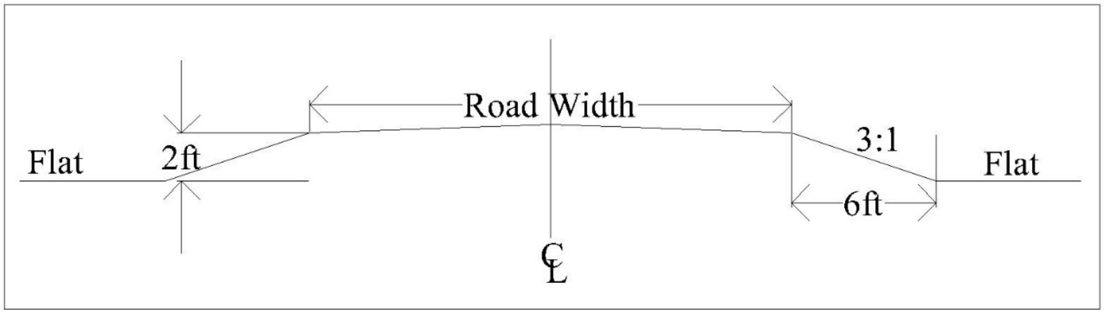


Figure 2.24: Cross Section Before and After Transition

2.3.2 Culvert Simulation

This study set up a culvert simulation, including use of a bare culvert and a culvert shielded with a guardrail, to determine whether new guardrails should be used to shield culverts based on benefit-cost analysis. Two-wheel-track gravel roads and three- or four-wheel-track gravel or paved roads were included in every simulation with parameters such as posted speed limit, AADT, lane width, shoulder width, and slope and height beside the road before and after transition. The simulated culvert, delineated by a water stream (Figure 2.28), consisted of a hubguard and a wingwall. Culvert simulation using RSAPv3 required a description of its geometric features, including boundaries (offset to the road, length, width, and height) and the slope of its wingwall. The guardrail length was provided by KDOT. Table 2.9 summarizes the culvert simulation plan.

A transition connected the culvert and roadway before and after the hazard; the length of the transition was 50 ft for each side, as shown in Figures 2.25 and 2.26. The foreslope from the transition through the culvert was 3:1, identical to the roadway, and the filling that covered the culvert extended 75 ft. Culvert width was estimated to be 20 ft, which was the worst-case scenario in the field according to engineering experience.

Table 2.9: Simulation Plan for Culverts

Parameters \ Road Types		Two-Wheel-Track Gravel Road	Three- or Four-Wheel-Track Gravel or Paved Road
Posted Speed Limit		45, 55 mph	
AADT		100 vehicles, 200 vehicles per day (all traffic primary-no opposing traffic)	100 vehicles, 400 vehicles and 1,000 vehicles per day
Lane Width		10 ft	Two 12 ft
Shoulder Width		4 ft, 5 ft, 6 ft, and 7 ft	0 ft, 1 ft, and 2 ft
Before & After Transition	**Slope**	3:1	
	Height	2 ft	
Culvert	**Offset**	0, 2, and 4 ft	
	Height	10 and 14 ft	
	Foreslope	3:1	
	Width	20 ft	
	Length	height * slope - offset	
	Guardrail	245 ft	

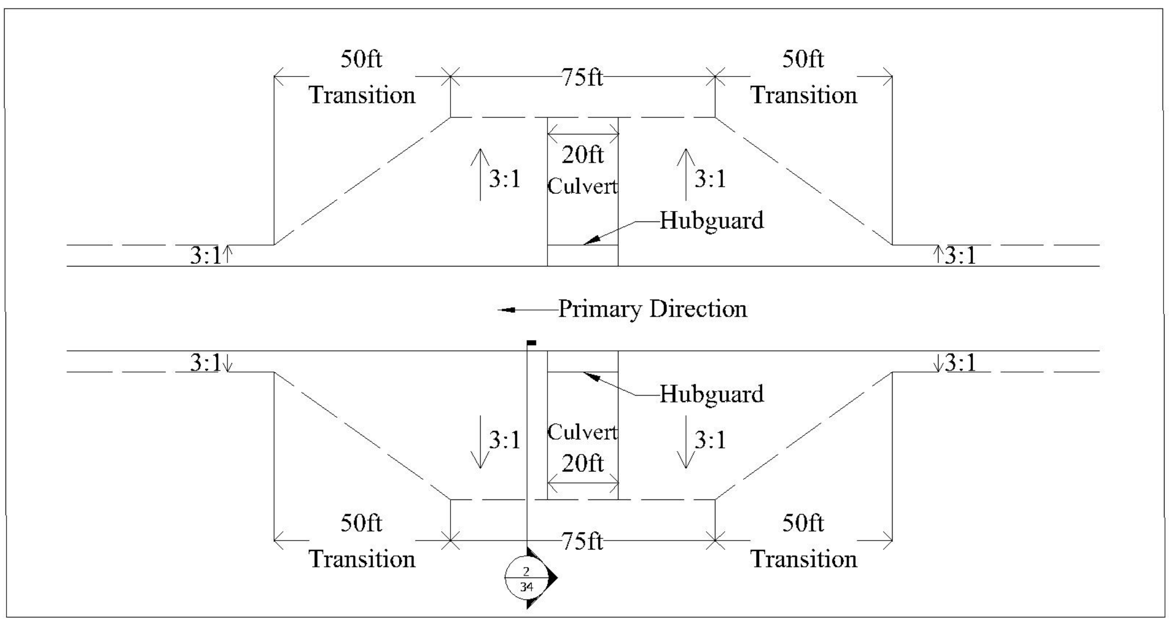


Figure 2.25: Plan View of Culvert on Two-Wheel-Track Gravel Road

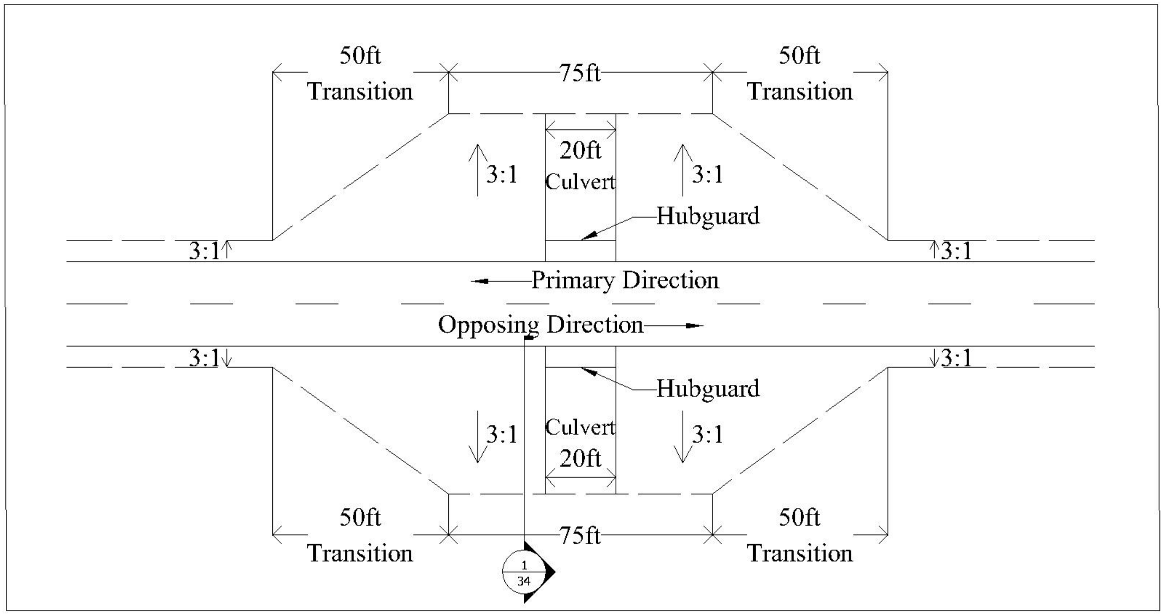


Figure 2.26: Plan View of Culvert on Three- or Four-Wheel-Track Gravel or Paved Road

The heights of the culvert rising from the flowing line of the channel to the roadway surface were 10 ft and 14 ft, as shown in Figure 2.27. The length of the stream delimited by the culvert was the distance that the foreslope extended minus the offset of the culvert, which was based on the culvert's slope and height. Since the slope was 3:1 and the height was *h*, the length of the stream was (*3h – offset*), as shown in Figure 2.27. The distances from the hubguard to the edge of the shoulder were 0 ft, 2 ft, and 4 ft, which were the offsets of the culvert to the edge of the shoulder, also shown in Figure 2.27.

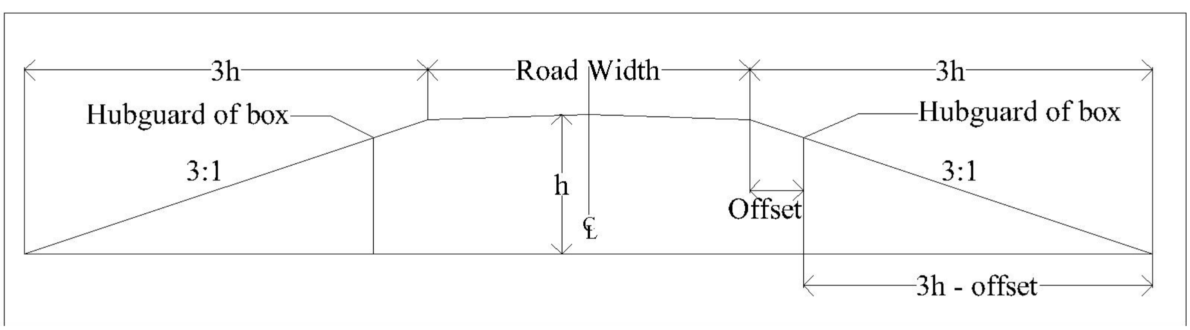


Figure 2.27: Cross Section of Culvert

The new guardrail-shielding culvert included 175 ft in front of the culvert and 35 ft for transition on each side. Therefore, the total length was (175 ft + 35 ft × 2) = 245 ft. The guardrail was established on the edge of the road with an end treatment according to KDOT. Figures 2.28, 2.29, and 2.30 show real culverts in the field. In Figure 2.28, the length of the wingwall was immaterial since it was vertical and aligned with the stream bank.

Figure 2.28: Culvert on Rural Road
Source: N. Bowers (personal communication, 2019)

Figure 2.29: Culvert with Zero Offset
Source: N. Bowers (personal communication, 2019)

Figure 2.30: Guardrail Shielding a Culvert
Source: N. Bowers (personal communication, 2019)

2.3.3 Embankment Simulation

This study set up an embankment simulation, using a bare embankment and an embankment with a new guardrail, to test the rationality of using new guardrails to shield an embankment across a fill area over pipe based on benefit-cost analysis. The simulated roads were identical to the roads in the culvert simulation, and the embankment parameters included height and foreslope. The simulated embankment began directly beside the road. Table 2.10 summarizes the embankment simulation plan.

Table 2.10: Simulation Plan for Embankments

Parameters \ Road Types		Two-Wheel-Track Gravel Road	Three- or Four-Wheel-Track Gravel or Paved Road
Posted Speed Limit		45, 55 mph	
AADT		100 vehicles, 200 vehicles per day (all traffic primary-no opposing traffic)	100 vehicles, 400 vehicles and 1,000 vehicles per day
Lane Width		10 ft	Two 12 ft
Right Shoulder Width		4 ft, 5 ft, 6 ft, and 7 ft	0 ft, 1 ft, and 2 ft
Before Transition	**Slope**	3:1	
	Height	2 ft	
Embankment	**Height**	6 ft, 12 ft, and 18 ft	
	Foreslope	2:1, 3:1, and 4:1	
	Guardrail	220 ft	

A transition connected the embankment and roadway before and after the embankment. The length of the transition was 50 ft for each side, as shown in Figures 2.31 and 2.32. The foreslopes beside the road, from the transition through the embankment, were 2:1, 3:1, and 4:1. The length of the filling that covered the embankment was 50 ft. The embankment heights were 6 ft, 12 ft, and 18 ft, as shown in Figure 2.33, and the embankment length was the extension distance of the foreslope, based on the slope and height of the embankment. The embankment length was (*Foreslope* * *h*).

The new guardrail-shielding embankment included 150 ft in front of the embankment and 35 ft for transition on each side. Therefore, the total length was (150 ft + 35 ft × 2) = 220 ft. A guardrail was also established on the edge of the road with an end treatment.

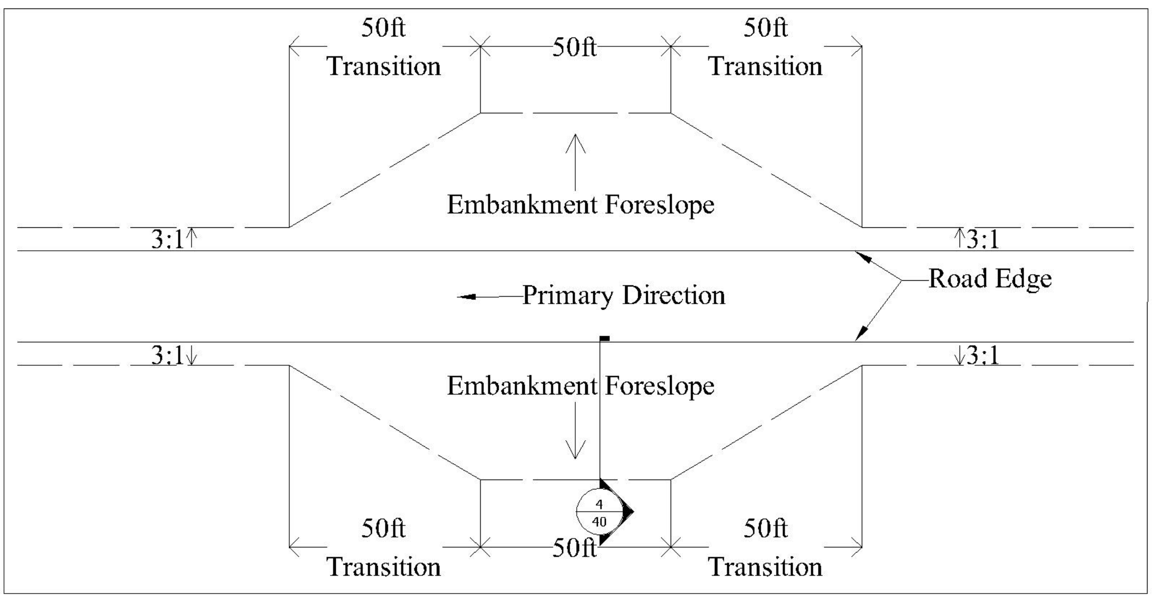


Figure 2.31: Plan View of Embankment on Two-Wheel-Track Gravel Road

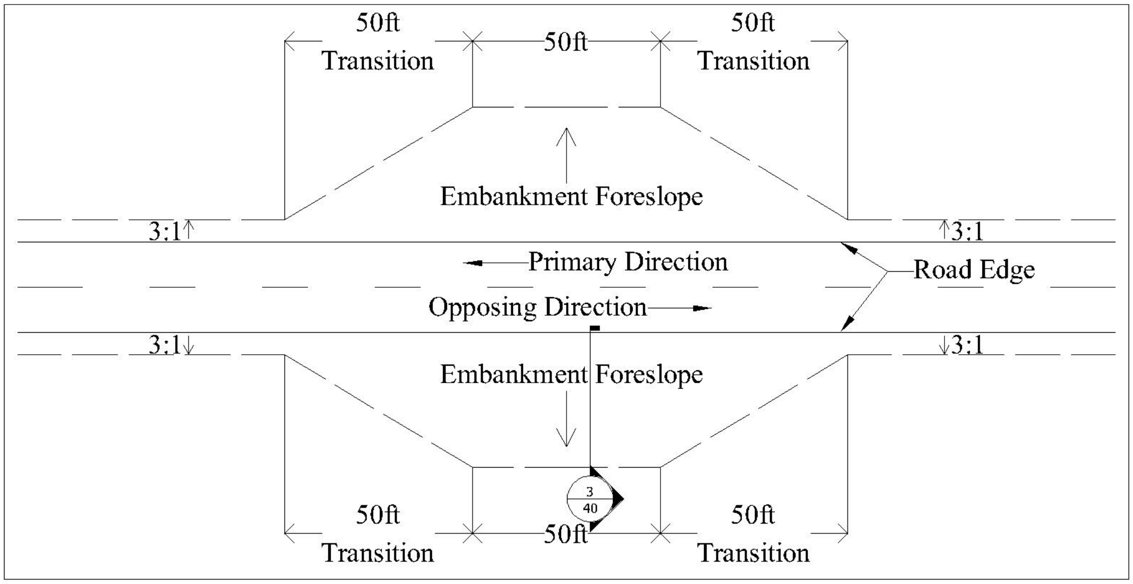


Figure 2.32: Plan View of Embankment on Three- or Four-Wheel-Track Gravel or Paved Road

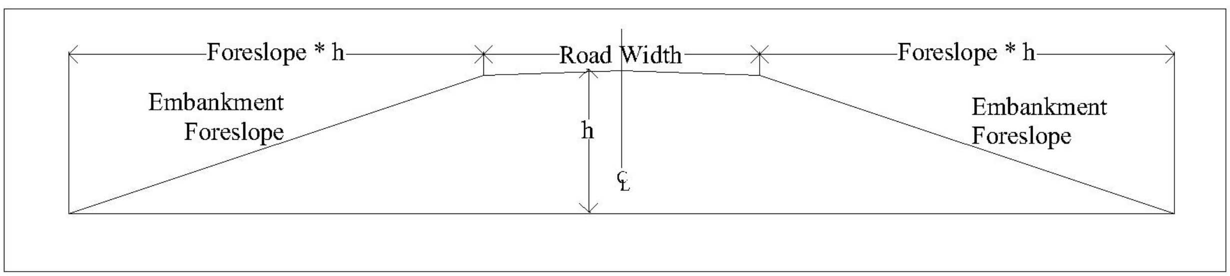


Figure 2.33: Cross Section of Embankment

2.3.4 Bridge Simulation

This study conducted two bridge simulations to test the rationality, based on benefit-cost analysis, of replacing bridge edges with W-beam guardrails or using new guardrails attached to bridge rails to deter errant vehicles. The first simulation had three alternatives: Alternative 1, the base condition, had bridge edge only, without bridge rail nor bridge-approach guardrails; Alternative 2 replaced the bridge edge with a W-beam guardrail; and Alternative 3 added bridge-approach guardrails. The second simulation used TL-2 rail as bridge rail, meaning that any transformation from other types of bridge rail to TL-2 required extra modification with bridge structure according to KDOT. Therefore, TL-2 bridge rail was implemented as the base condition, and the simulation was divided into two alternatives to avoid additional modification to the bridge structure. Alternative 1 used TL-2 bridge rail as the base condition, while Alternative 2 added bridge-approach guardrails to TL-2 bridge rail on each side.

The roadways were identical to previous simulations, but the bridge widths varied on different roadways. The bridge widths were 20 ft and 24 ft on two-wheel-track gravel roads, but on three- or four-wheel-track gravel or paved roads the bridge widths were 20 ft, 24 ft, 26 ft, and 28 ft. In fact, the width of the bridge could be wider than the width of the roadway. For example, the widest bridge on a three- or four-wheel-track gravel or paved road was 28 ft; considering when the shoulder width of the roadway was 0 ft, the roadway width was (12 ft × 2 + 0) = 24 ft. As previously advised, the guardrail should be implemented on the edge of the roadway for optimal performance, but since bridge-approach guardrails were attached to the bridge end, when the bridge was wider than the roadway, the guardrail was located on the slope beside the roadway. In practice, a transition is typically implemented to enlarge the width of roadway to match the bridge and keep bridge-approach guardrails on the edge of the roadway. For simplicity in this study, only the shoulder width was extended in the transition. Table 2.11 summarizes the bridge simulation plan.

The simulation also included scenarios in which the road was wider than the bridge and bridge-approach guardrails attached to the bridge end narrowed the road. No transition was used if the bridge was narrower than the road. Lanes were striped across the paved bridge, and the simulation was assumed to extend the lane across the bridge, leaving extra space as shoulder on the bridge. The transition length was 100 ft for each side of the bridge, and the length of the bridge was 120 ft, as illustrated in Table 2.11 and Figures 2.34 and 2.35. The average height from bridge surface to water surface was 12 ft, as shown in Figure 2.36.

Table 2.11: Simulation Plan for Bridges

<table>
<tr><th colspan="3">Road Types / Parameters</th><th>Two-Wheel-Track Gravel Road</th><th>Three- or Four-Wheel-Track Gravel or Paved Road</th></tr>
<tr><td colspan="3">Posted Speed Limit</td><td colspan="2">45, 55 mph</td></tr>
<tr><td colspan="3">AADT</td><td>100 vehicles, 200 vehicles per day (all traffic primary-no opposing traffic)</td><td>100 vehicles, 400 vehicles, and 1,000 vehicles per day</td></tr>
<tr><td colspan="3">Lane Width for Road</td><td>10 ft</td><td>Two 12 ft</td></tr>
<tr><td colspan="3">Shoulder Width for Road</td><td>4 ft, 5 ft, 6 ft, and 7 ft</td><td>0 ft, 1 ft, and 2 ft</td></tr>
<tr><td colspan="2" rowspan="2">Before & After Bridge</td><td>Slope</td><td colspan="2">3:1</td></tr>
<tr><td>Height</td><td colspan="2">2 ft</td></tr>
<tr><td colspan="3">Transition Before & After Bridge</td><td colspan="2">Expand the shoulder width to match the bridge width if the road width is less than the bridge width, transition length 100 ft</td></tr>
<tr><td rowspan="10">Bridge</td><td colspan="2">Width</td><td>20 ft and 24 ft</td><td>20 ft, 24 ft, 26 ft, and 28 ft</td></tr>
<tr><td colspan="2">Lane Width (Shoulder Width)</td><td>10 ft (5 ft) and 10 ft (7 ft)</td><td>10 ft (0), 12 ft (0), 12 ft (1 ft), and 12 ft (2 ft)</td></tr>
<tr><td colspan="2">Length</td><td colspan="2">120 ft</td></tr>
<tr><td colspan="2">Water Height from Bridge Surface</td><td colspan="2">12 ft (existing hazard for all alternatives)</td></tr>
<tr><td rowspan="3">Simulation 1</td><td>Alt 1</td><td colspan="2">Medium bridge edge without W-beam bridge-approach guardrails</td></tr>
<tr><td>Alt 2</td><td colspan="2">W-beam bridge rail without W-beam bridge-approach guardrails</td></tr>
<tr><td>Alt 3</td><td colspan="2">W-beam bridge rail with W-beam bridge-approach guardrails</td></tr>
<tr><td rowspan="2">Simulation 2</td><td>Alt 1</td><td colspan="2">TL-2 bridge rail without W-beam bridge-approach guardrails</td></tr>
<tr><td>Alt 2</td><td colspan="2">TL-2 bridge rail with W-beam bridge-approach guardrails</td></tr>
<tr><td colspan="2">Approaching Guardrail</td><td colspan="2">87.5 ft on each side of road, attached to bridge ends with end-treatments</td></tr>
</table>

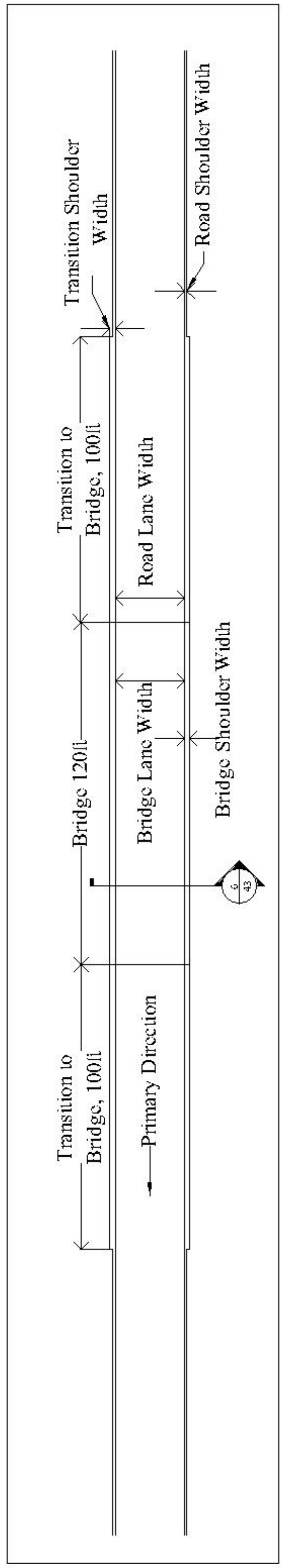


Figure 2.34: Plan View of Bridge on Two-Wheel-Track Gravel Road

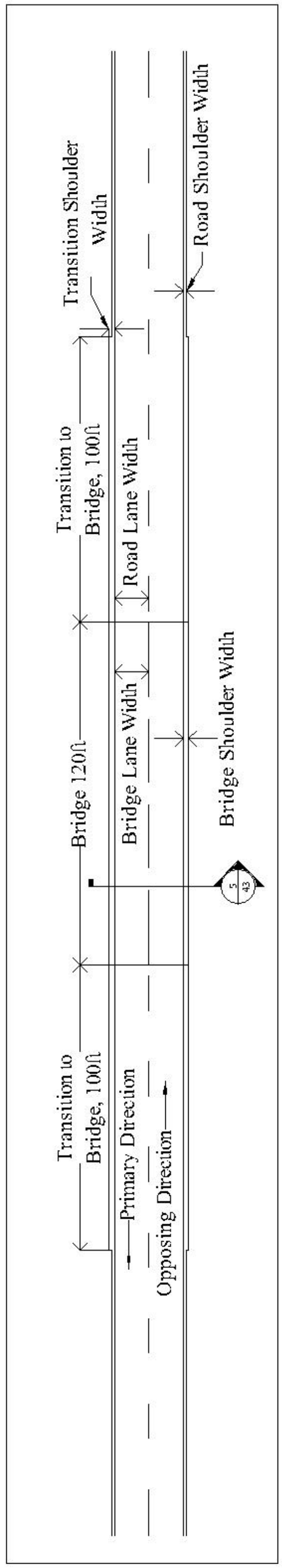


Figure 2.35: Plan View of Bridge on Three- or Four-Wheel-Track Gravel or Paved Road

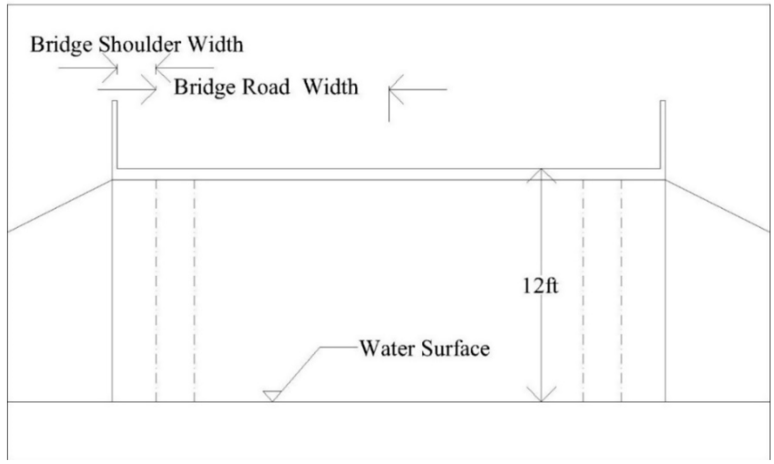


Figure 2.36: Bridge Cross Section for Three- or Four-Wheel-Track Gravel or Paved Road

Four bridge-approach guardrails were attached to the bridge end including end treatments on both sides of the bridge with lengths of 87.5 ft each. Figures 2.37 and 2.38 show bridge-approach guardrails found on Kansas roadways.


Figure 2.37: Bridge-approach guardrails to Bridge End
Source: N. Bowers (personal communication, 2019)

Figure 2.38: Bridge-approach guardrails to Bridge End
Source: N. Bowers (personal communication, 2019)

2.4 RSAPv3 Simulation

2.4.1 Input Parameters on RSAPv3

Input parameters for the simulations were divided into Project, Traffic, Highway, Alternative, and Cross-Section worksheets in RSAPv3. The data needed for each worksheet, as well as values and sources, are listed in Table 2.12. Common information shared by all the alternatives, such as project conditions, traffic data and highway features, were input into the first three worksheets, while specific features for each alternative were included in the Alternative and Cross-Section worksheets.

The Project worksheet used Kansas data to obtain estimated crash costs in accordance with local conditions. For example, guardrail life is typically 20 years in Kansas. For a crash occurring during the life of a guardrail, benefit-cost analysis was used to evaluate annual cost given design life and return of rate.

Table 2.12: Input Parameters for RSAPv3

Worksheet	Specific Data	Sources	
		KDOT	Other Sources
Project	Design Life	20 years	
	Construction Year		2019
	Rate of Return		4% (default)
	GDP Values during Life		N(default)
	Current Year by GDP		Y(default)
	GDP Deflector to Construction Year		1.07 (default)
	Base Year for Crash-Cost Data	2017	
	Value of Statistical Life	$4,733,650	
Traffic	AADT	Simulation Plan	
	Traffic Growth	0%	
	Vehicle Percentage (FHWA)		Previous simulation in Kansas
Highway	% of Traffic in Primary Direction		50% for two directions and 100% for one direction (default)
	% of Traffic Encroaching Right		50% (default)
	Highway Type	Simulation Plan	
	Flat, Rolling, or Mountainous		
	Posted Speed Limit		
	User Encroachment Adjustment		
	Access Density		
	Lanes Total		
	Lane Width		
	Median Shoulder Width		
	Median Width		
	Primary Road Curve		
	Primary Vertical Grade		
	Number of Primary Lanes		
	Rumble Strips		
	Right Shoulder Width		
Alternative	Hazard Type	Simulation Plan	
	Hazard Length		
	Hazard Offset		
	Hazard Width		
	Construction Cost	$80/ft for non-state highway; $3,000 for each end-treatment	
	Annual Maintenance Cost	$0	
Cross-Section	Slope Width	Simulation Plan	
	Slope		

As mentioned, RSAPv3 uses EFCCR, an average dimensionless severity measure scaled to fatal crash cost, to estimate various crash costs. Once the value of fatal crash costs, called the "Value of Statistical Life," was updated using Kansas data, the crash cost reflected local conditions. As shown in Figure 2.39, the fatal crash cost used in this study was $4,733,650 in fiscal year 2017. The rest of the data in this project utilized default values with KDOT approval as shown in Table 2.12.

Use : 1994 crash costs

January 2016 CPI = 236.916

Change in CPI = (236.916 - 146.2) / 146.2 = 62.049%

Updated crash cost rounded to nearest $50:

Cost per Fatality	$4,213,300
Cost per A Injury	$291,700
Cost per B Injury	$58,350
Cost per C Injury	$30,800
Cost per PDO	$3,250

The following were calculated using data obtained from the Bureau of Transportation Planning. This analysis combines type B and C injury accidents. For these calculations, we are assuming 50% of those injury crashes are type B (evident/moderate) and 50% are type C (possible).

Fatalities per fatal crash=	1.10
A Injuries per fatal crash=	0.26
B Injuries per fatal crash=	0.26
C Injuries per fatal crash=	0.26
Injuries per injury crash=	1.38

Cost per fatal crash: $4,733,650

Figure 2.39: Costs of Fatal Crashes in Kansas for Fiscal Year 2017

The Traffic worksheet contained AADT, traffic volume growth rate, and vehicle percentage. AADT information was previously described in the simulation plan, and the growth rate of traffic on Kansas rural roadways was 0%, according to KDOT. As for vehicle percentage, or the comprising percentage of each type of vehicle in traffic volume, percentages from previous simulations in Kansas were used since KDOT had no validated data on rural roads.

Most of the information included in the Highway worksheet was previously described in the simulation plan in Section 2.3. If the roadway contained two directions, a default value of 50% was used for traffic in the primary direction, meaning the division of traffic volume between primary and opposing directions was equal. Moreover, a value of 100% was used for traffic in the primary direction on two-wheel-track gravel roads, and the value for percentage of traffic encroaching right was set as a default value of 50%, meaning half of the total number of errant vehicles would advance to the right.

Geometric features of hazards in the Alternative worksheet were also described in Section 2.3. KDOT provided the costs of construction and maintenance. Likewise, the Cross-Section worksheet contained dimensions of cross sections associated with homogeneous sections of roads separated by users, as described in Section 2.3.

2.4.2 Implementing RSAPv3 Simulation

This section provides RSAPv3 simulation instructions using the complicated example of a bridge simulation on a three- or four-wheel-track gravel or paved road with bridge edge as a base condition.

As shown in the RSAPv3 interface in Figure 2.40, the RSAPv3 controls dialog box allows the user to navigate between worksheets, manipulate tasks or check results, and restore default settings and hazards. Useful resources, such as Manual or Help, are also accessible via the dialog box. Project information was input on the right side of the box. As shown in the figure, the rose-colored cells suggest editable default values, and the yellow cells represent specific data for this project, which must be filled. The Value of Statistical Life refers to the average cost of a fatal crash.

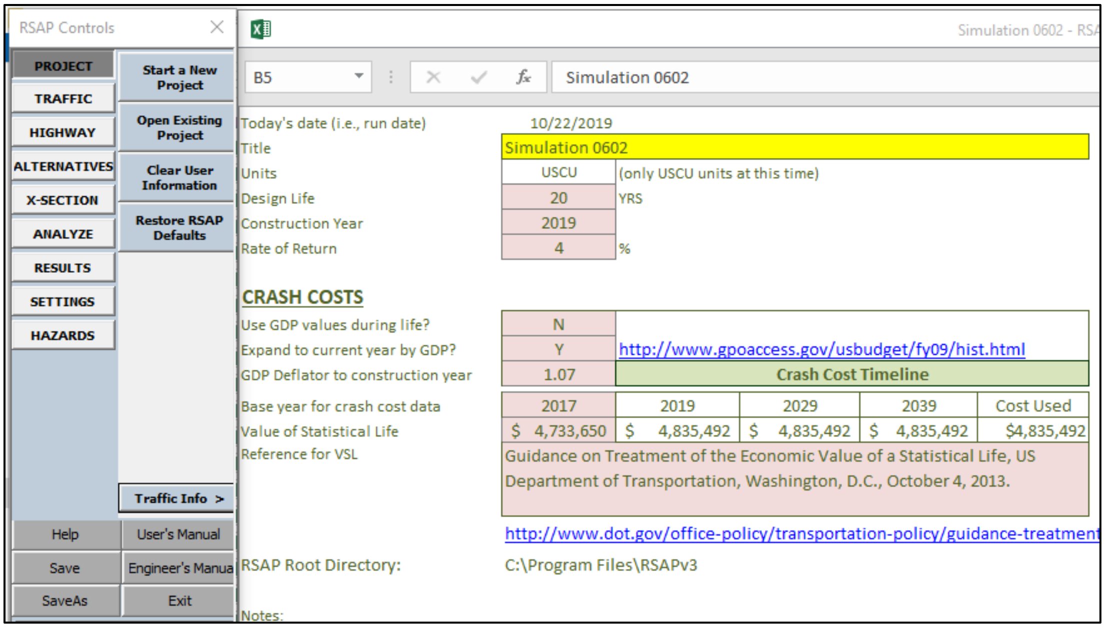


Figure 2.40: RSAPv3 Project Interface

After completing the data entry in all the Project worksheet fields, clicking on “Traffic” initiates the Traffic worksheet (Figure 2.41). Since traffic growth was 0% in the task, the default “Mid-Life” option was satisfactory. With the exception of crash cost adjustment, the rest of the values were described in Section 2.4.1. The default values were used in this task with no changes.

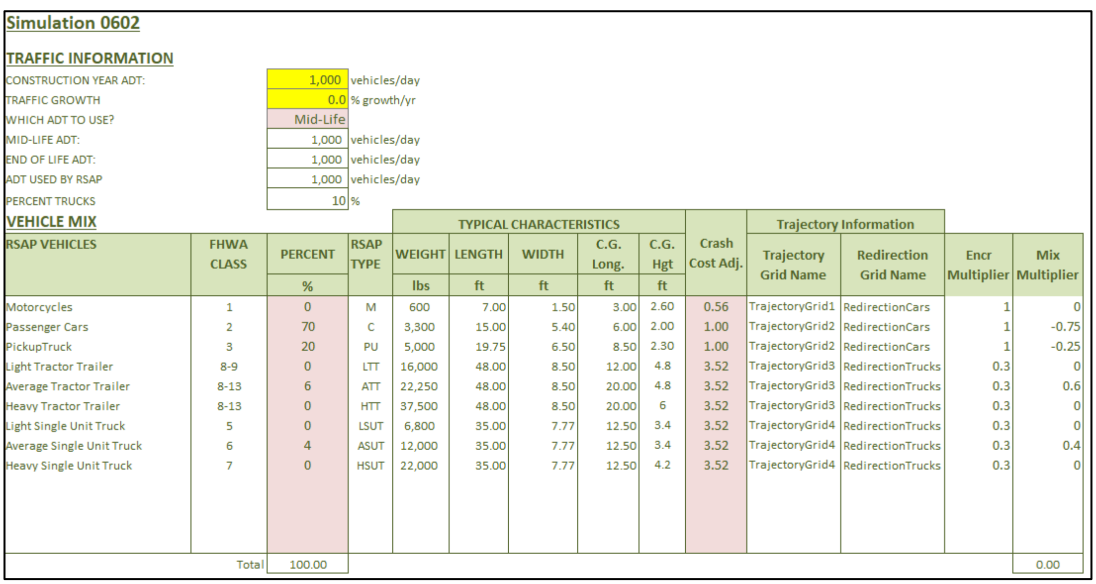


Figure 2.41: RSAPv3 Interface of Traffic Information

Figure 2.42 shows the interface of the Highway worksheet. The “U” value in the Highway Type cell denotes an undivided road, which applied to the two types of roadways in this study, and the “F” option in the Terrain cell means flat. This study used default value 1 in the cell for “User Encroachment Adjustment.” The information entered in the Highway worksheet was used to generate yearly encroachments based on results from the study by Cooper (1981). Expected encroachments are shown in the green table below the input cells in Figure 2.42.

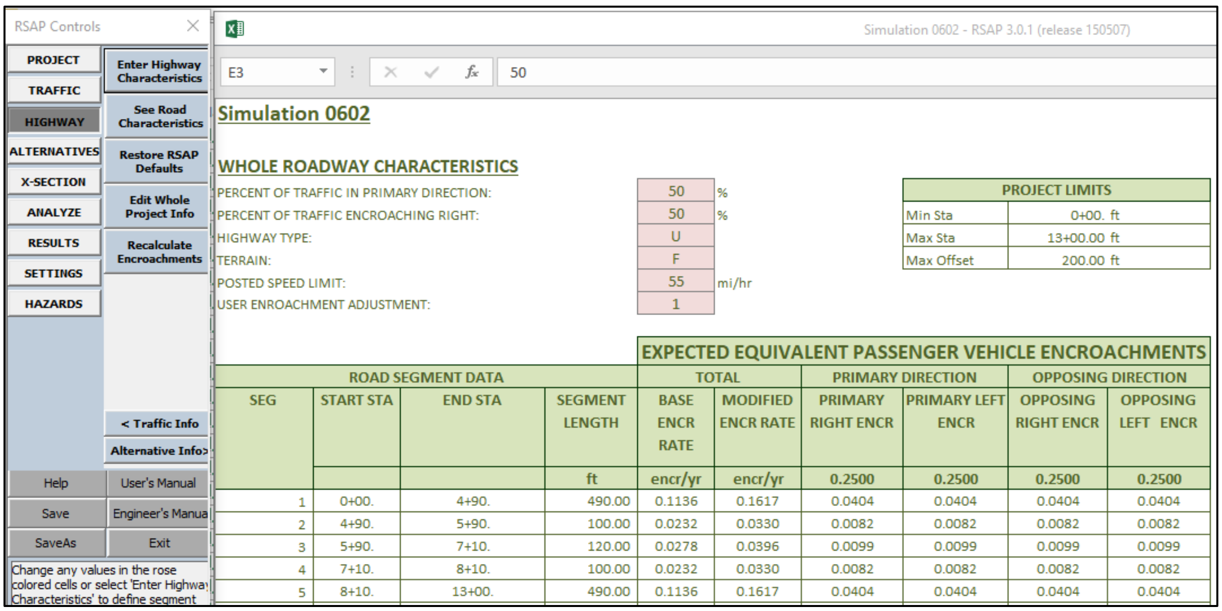


Figure 2.42: RSAPv3 Interface of Highway Characteristics

The roadway was divided into homogeneous sections based on geometric features, including lane number, lane width, shoulder width, grade, and curves. After completing data entry for the Highway worksheet, clicking on the “Enter Highway Characteristics” button in the dialog box opens the “User-Entered Characteristics” form, as shown in Figure 2.43. The right side of the box contains default characteristic values; only values that differ from default values need to be entered. In this study, the 120-ft bridge was located in the middle of the roadway, which started from 590 ft to 710 ft. In addition, the bridge width was 28 ft, the lane width was 12 ft for each direction, and the shoulder width of roadway was 1 ft, meaning the total width of the roadway was 26 ft. As discussed in Section 2.3.4, two transitions (100 ft each) were established on both sides of bridge if the bridge was wider than the roadway. Two transitions, 490–590 ft and 710–810 ft, were implemented with shoulder width equal to the bridge shoulder. After finishing the entry, one click on the "Segment Project" button saves the results and opens the next module.

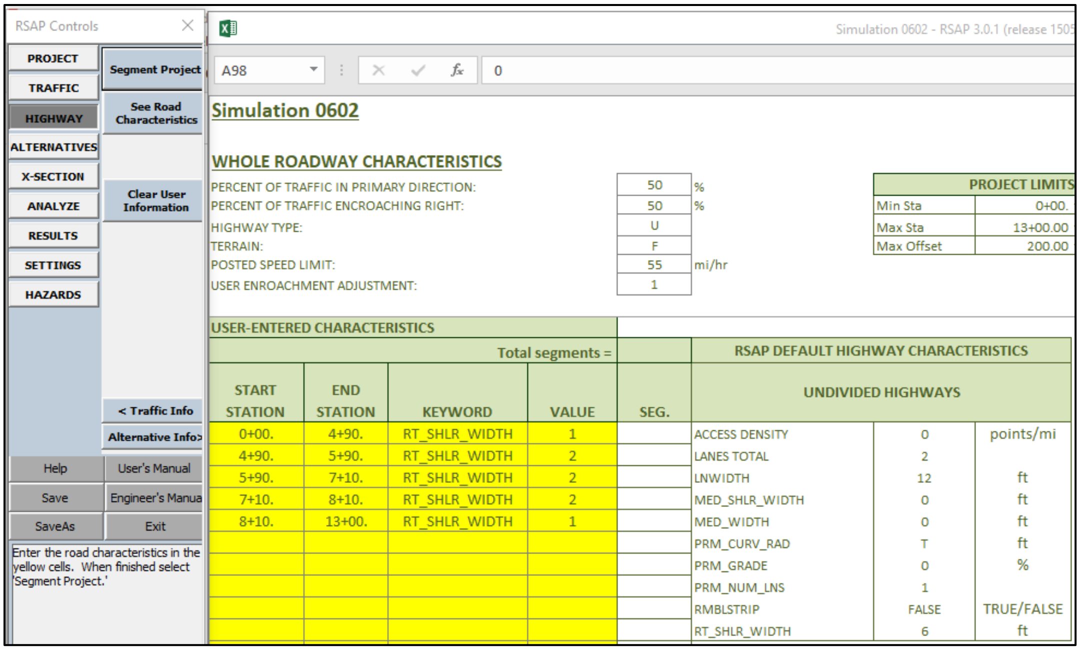
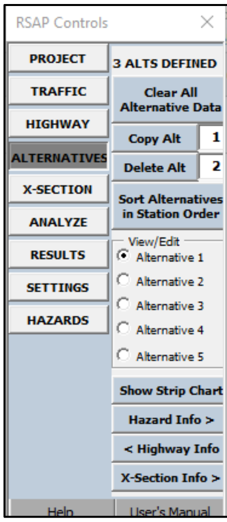


Figure 2.43: RSAPv3 Interface of Highway Characteristics (User-Entered)

As described in Section 2.3.4, three alternatives were used for the first bridge simulation. Figure 2.44 shows the first alternative, in which the initial offset is the distance from the baseline, or the left edge of travel in this simulation, and 200 ft is the maximum extension of the hazard. Therefore, the bridge edge was 14 ft from the baseline, which was half the width of the bridge. The water below the bridge was defined by three water lines on each side of the bridge (Figure 2.21, Section 2.3). The perpendicular line of water extended from the bridge edge (14 ft from the baseline) to the far end (200 ft from the baseline).



ROADSIDE FEATURES FOR ALTERNATIVE NUMBER:									1
ALTERNATIVE NAME		Bare Bridge Edge					DEFAULT X-SECTION		All 3:1
CONSTRUCTION COST		$ -			ANNUAL MAINTENANCE COST			$ -	
GENERAL HAZARD TYPE	SPECIFIC HAZARD TYPE	START STATION	START SIDE	START OFFSET	END STATION	END SIDE	END OFFSET	PARAMETER	VALUE
		STATIONS		ft	STATIONS		ft		
SpecialEdge	BridgeEdge_MedHaz	5+90.00	L	14.0	7+10.00	L	14.0		
SpecialEdge	BridgeEdge_MedHaz	5+90.00	R	14.0	7+10.00	R	14.0		
SpecialEdge	Water	5+90.00	L	14.0	7+10.00	L	14.0		
SpecialEdge	Water	5+90.00	R	14.0	7+10.00	R	14.0		
SpecialEdge	Water	5+90.00	L	14.0	5+90.00	L	200.0		
SpecialEdge	Water	5+90.00	R	14.0	5+90.00	R	200.0		
SpecialEdge	Water	7+10.00	L	14.0	7+10.00	L	200.0		
SpecialEdge	Water	7+10.00	R	14.0	7+10.00	R	200.0		

Figure 2.44: RSAPv3 Interface of Alternatives (Alternative 1)

In Alternative 2, the bridge edge was replaced with a W-beam guardrail. The cost for guardrail implementation was \$80/ft, so the total construction cost was \$80/ft × 120 ft × 2 = \$19,200, as shown in Figure 2.45.

ROADSIDE FEATURES FOR ALTERNATIVE NUMBER:									2
ALTERNATIVE NAME		W-beam Bridge Rail					DEFAULT X-SECTION		All 3:1
CONSTRUCTION COST		$ 19,200.00			ANNUAL MAINTENANCE COST			$ -	
GENERAL HAZARD TYPE	SPECIFIC HAZARD TYPE	START STATION	START SIDE	START OFFSET	END STATION	END SIDE	END OFFSET	PARAMETER	VALUE
		STATIONS		ft	STATIONS		ft		
Guardrails_SemiRigid	TL3WbeamGR	5+90.00	L	14.0	7+10.00	L	14.0	Width (in.)	12
Guardrails_SemiRigid	TL3WbeamGR	5+90.00	R	14.0	7+10.00	R	14.0	Width (in.)	12
SpecialEdge	Water	5+90.00	L	14.0	7+10.00	L	14.0		
SpecialEdge	Water	5+90.00	R	14.0	7+10.00	R	14.0		
SpecialEdge	Water	5+90.00	L	14.0	5+90.00	L	200.0		
SpecialEdge	Water	5+90.00	R	14.0	5+90.00	R	200.0		
SpecialEdge	Water	7+10.00	L	14.0	7+10.00	L	200.0		
SpecialEdge	Water	7+10.00	R	14.0	7+10.00	R	200.0		

Figure 2.45: RSAPv3 Interface of Alternatives (Alternative 2)

In Alternative 3, the W-beam bridge-approach guardrails were attached to the bridge end. The cost for each guardrail end treatment was \$3,000, so the total construction cost was \$80/ft × (120 × 2) ft + \$80/ft × (87.5 × 2) ft + \$3,000 × 4 = \$59,200, as shown in Figure 2.46.

ROADSIDE FEATURES FOR ALTERNATIVE NUMBER:									3
ALTERNATIVE NAME		W-beam Bridge Rail + Approaching GR			DEFAULT X-SECTION				All 3:1
CONSTRUCTION COST		$ 59,200.00			ANNUAL MAINTENANCE COST			$ -	
GENERAL HAZARD TYPE	SPECIFIC HAZARD TYPE	START STATION	START SIDE	START OFFSET	END STATION	END SIDE	END OFFSET	PARAMETER	VALUE
		STATIONS		ft	STATIONS		ft		
Guardrails_SemiRigid	TL3WbeamGR	5+90.00	L	14.0	7+10.00	L	14.0	Width (in.)	12
Guardrails_SemiRigid	TL3WbeamGR	5+90.00	R	14.0	7+10.00	R	14.0	Width (in.)	12
SpecialEdge	Water	5+90.00	L	14.0	7+10.00	L	14.0		
SpecialEdge	Water	5+90.00	R	14.0	7+10.00	R	14.0		
SpecialEdge	Water	5+90.00	L	14.0	5+90.00	L	200.0		
SpecialEdge	Water	5+90.00	R	14.0	5+90.00	R	200.0		
SpecialEdge	Water	7+10.00	L	14.0	7+10.00	L	200.0		
SpecialEdge	Water	7+10.00	R	14.0	7+10.00	R	200.0		
Guardrails_SemiRigid	TL3WbeamGR	5+02.50	L	14.0	5+90.00	L	14.0	Width (in.)	12
Guardrails_SemiRigid	TL3WbeamGR	5+02.50	R	14.0	5+90.00	R	14.0	Width (in.)	12
Guardrails_SemiRigid	TL3WbeamGR	7+10.00	L	14.0	7+97.50	L	14.0	Width (in.)	12
Guardrails_SemiRigid	TL3WbeamGR	7+10.00	R	14.0	7+97.50	R	14.0	Width (in.)	12
TerminalEnds	GenericEnd	7+97.50	L	14.0	NA	NA	NA		24
TerminalEnds	GenericEnd	7+97.50	R	14.0	NA	NA	NA		24
TerminalEnds	GenericEnd	5+02.50	L	14.0	NA	NA	NA		24
TerminalEnds	GenericEnd	5+02.50	R	14.0	NA	NA	NA		24

Figure 2.46: RSAPv3 Interface of Alternatives (Alternative 3)

In the Cross-Section worksheet, Segment 1 (0–490 ft) and Segment 2, the transition, (490–590 ft) were nearly identical except for the roadway shoulder width, which was input from the Highway worksheet. The 12-ft offset shown in Figure 2.47 was the lane width, or the distance from the lane edge to the baseline (left edge of travel). The 13-ft offset included the roadway shoulder width (1 ft). In addition, the 19-ft offset contained the slope length, which was 6 ft for the roadway. The elevation denoted the height (2 ft) from the bottom of the slope to the roadway surface. Details are explained in Section 2.3.1.

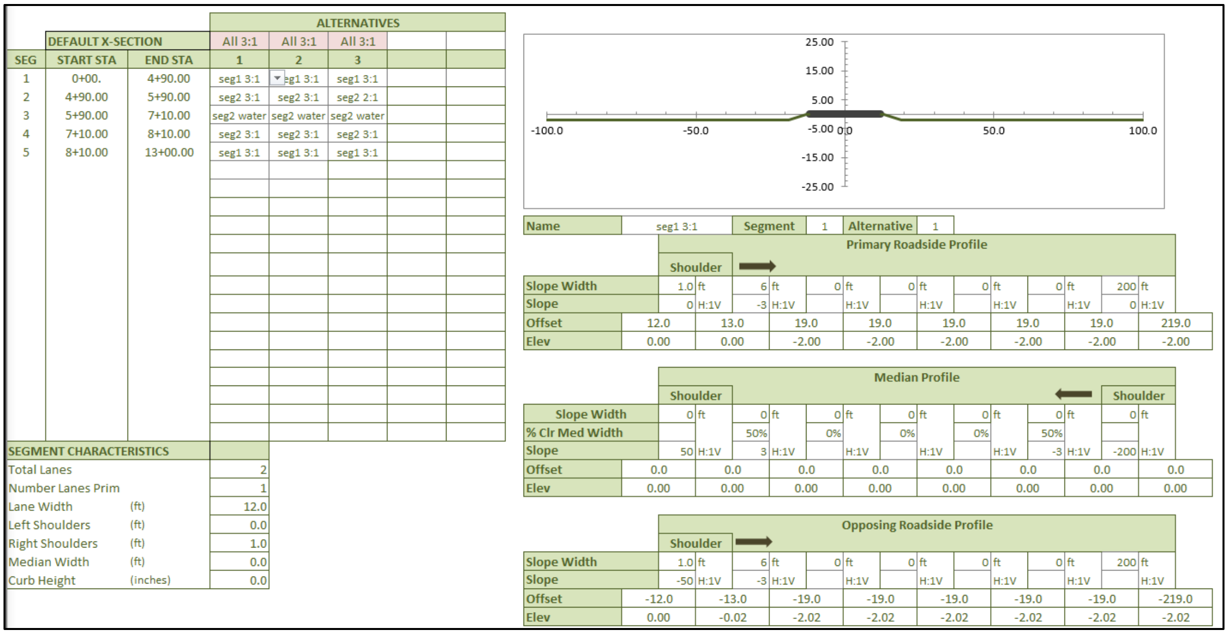


Figure 2.47: RSAPv3 Interface of Cross Section (Segment 1, 0–490 ft)

In the bridge cross section (Figure 2.48), the height from the water surface to the bridge surface was 12 ft. However, an error occurred when the shoulder width was displaced, which was read from Alternative Worksheet because RSAPv3 can only display the lane width and shoulder width from the first segment of the roadway. The RSAPv3 research team promised to fix this bug in the future.

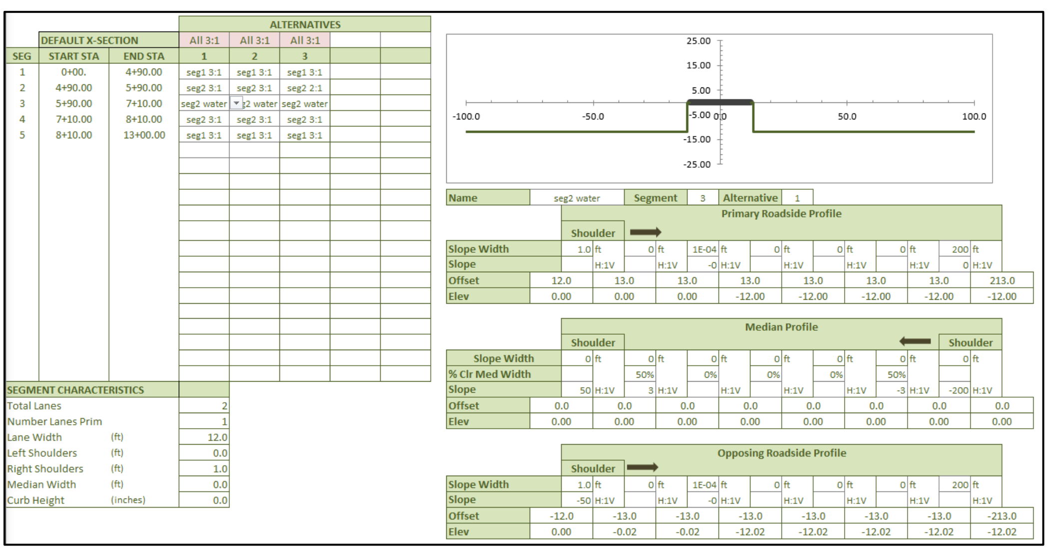
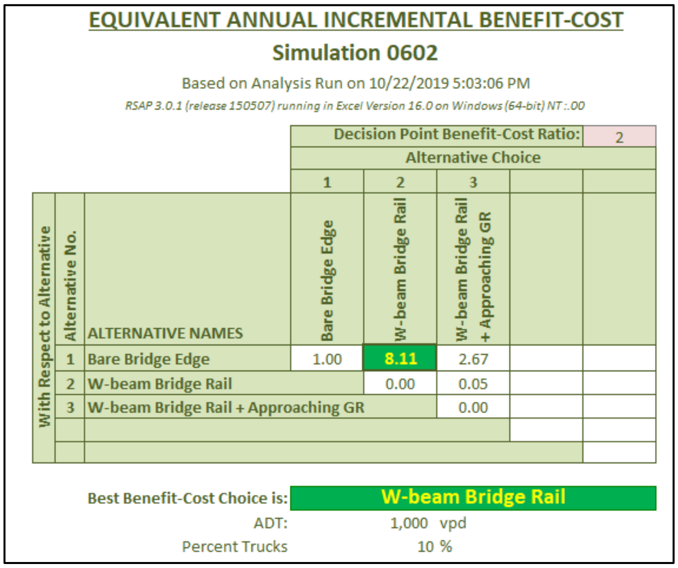


Figure 2.48: RSAPv3 Interface of Bridge Cross Section (Segment 3, 590–710 ft)

Simulation results are shown in Figure 2.49. When the threshold of benefit-cost ratio was set as 2.0, the ratio in green showed that Alternative 2 was the optimal implementation in terms of benefit-cost analysis.


EQUIVALENT ANNUAL INCREMENTAL BENEFIT-COST

Simulation 0602

Based on Analysis Run on 10/22/2019 5:03:06 PM

RSAP 3.0.1 (release 150507) running in Excel Version 16.0 on Windows (64-bit) NT :.00

Decision Point Benefit-Cost Ratio: 2

With Respect to Alternative	Alternative No.	ALTERNATIVE NAMES	Alternative Choice 1: Bare Bridge Edge	2: W-beam Bridge Rail	3: W-beam Bridge Rail + Approaching GR		
	1	Bare Bridge Edge	1.00	8.11	2.67		
	2	W-beam Bridge Rail		0.00	0.05		
	3	W-beam Bridge Rail + Approaching GR			0.00		

Best Benefit-Cost Choice is: W-beam Bridge Rail

ADT: 1,000 vpd

Percent Trucks 10 %

Figure 2.49: Interface of Results

Chapter 3: Simulation Results and Analyses

This study performed a total of 718 simulation runs. The average time required for each depended on the simulation complexity. For the same hazard size and offset, simulations for a two-wheel-track gravel road took much less time than a simulation for a three- or four-wheel-track gravel or paved road because AADT on three- or four-wheel-track gravel or paved roads was typically much higher than two-wheel-track gravel roads. In addition, two-way directions required more errant-track calculations. Therefore, this study utilized nine computers with approximately 18 hours of computing time per day. Computing time lasts for approximately three months, including initial communication with KDOT and simulation plan revisions. This chapter contains simulation results and analyses.

3.1 Result and Analysis of Culvert Simulation

The culvert simulation provided benefit-cost ratios with or without guardrails under various combinations of features. As synthesized in Sections 2.3 and 2.4, roadway geometric features, traffic data, and culvert profiles were essential for the culvert simulations, in which roadside slope was 3:1 on three- or four-wheel-track gravel or paved roads. The simulation contained two lanes, each with widths of 12 ft, and the culvert width was 20 ft. The three parameters were fixed and used for all culvert simulations on three- or four-wheel-track gravel or paved roads, as shown in Table 3.1. Values for shoulder width, AADT, and posted speed limit were combined in sequence on the left side of B/C (benefit-cost) ratio in Table 3.1. The B/C ratios under various combinations were easily retrieved in accordance with field conditions. The parameters contained in Table 3.1 were extracted from Table 2.9 in Section 2.3.2. A total of 108 simulations are presented in the table.

Table 3.1: W-Beam Guardrail for Culvert on Three- or Four-Wheel-Track Gravel or Paved Roads

Roadside slope=3:1, two lanes width = 12 ft, culvert width = 20 ft

Shoulder Width	AADT	Posted Speed Limit	B/C Ratio					
			Culvert Height = 10 ft			Culvert Height = 14 ft		
			offset 0 ft	offset 2 ft	offset 4 ft	offset 0 ft	offset 2 ft	offset 4 ft
0 ft	100	45	0.00	0.00	0.00	0.00	0.00	-0.01
		55	0.00	0.00	-0.01	0.01	0.00	0.00
	400	45	0.00	-0.01	-0.02	0.01	0.00	-0.01
		55	0.01	0.00	-0.01	0.02	0.01	0.00
	1000	45	0.00	0.01	-0.04	0.01	0.00	-0.02
		55	0.02	-0.01	-0.04	0.06	0.03	0.00
1 ft	100	45	0.01	0.01	0.00	0.01	0.01	0.01
		55	0.02	0.02	0.01	0.02	0.02	0.01
	400	45	0.05	0.04	0.02	0.06	0.04	0.02
		55	0.09	0.06	0.04	0.09	0.06	0.03
	1000	45	0.13	0.09	0.05	0.14	0.10	0.06
		55	0.22	0.16	0.09	**0.23**	0.15	0.08
2 ft	100	45	0.01	0.01	0.00	0.01	0.01	0.00
		55	0.02	0.01	0.01	0.02	0.01	0.01
	400	45	0.04	0.03	0.01	0.05	0.04	0.02
		55	0.08	0.05	0.03	0.08	0.05	0.02
	1000	45	0.11	0.07	0.02	0.13	0.09	0.05
		55	0.19	0.13	0.06	**0.20**	0.13	0.06

As shown in Table 3.1, when shoulder width was 0 ft, each B/C ratio was almost zero; positive non-zero ratios only appeared when shoulder width was 1 ft or 2 ft. Engineering experience has shown that guardrails typically protect roadside hazards when they are implemented far enough from traffic volume to avoid unnecessary minor crashes, as shown in Table 3.1.

The highlighted values in Table 3.1 allow several factors affecting B/C ratios to be inferred. When other parameters were fixed, B/C ratios decreased with increasing offset for the same culvert height. In other words, the farther away the hazard from the road, the less dangerous the hazard becomes, decreasing the frequency of subsequent crashes. In addition, the B/C ratios increased when AADT increased, and other parameters remained unchanged because traffic exposure increased, thereby increasing crash possibilities. Posted speed limit also significantly affected the B/C ratios; with other parameters fixed, the B/C ratio for a certain culvert was much higher at 55 mph than at 45 mph. Higher speeds decreased driver reaction time and increased crash severity.

Culvert size slightly influenced the B/C ratio, proven by the large culvert (culvert height as 14 ft) displaying a slightly higher B/C ratio than the small culvert (culvert height as 10 ft).

The results of culvert simulation on a two-wheel-track gravel road are shown in Table 3.2. As mentioned in Section 2.3.1, this roadway had only one direction and lane width was 10 ft. Shoulder width and AADT differed from the previous culvert simulation but posted speed limit and culvert profiles were identical to the previous simulation. The B/C ratios in Table 3.2 are almost all zeros because traffic exposure or AADT was too low for crashes to occur on this type of roadway and, although the lane was narrow, the shoulder was wide enough (at least 4 ft) to absorb most potential encroachments, providing a forgiving environment for errant vehicles. Moreover, these results could be applicable for guardrail performance, for which the inference could be made that proper space to contain errant vehicles on the road is a key factor in guardrail performance. In this case, guardrail implementation was not practical when AADT was low and roadway width was large enough to keep hazards far away from traffic.

Table 3.2: W-Beam Guardrail for Culvert on Two-Wheel-Track Gravel Road

Slope = 3:1, lane width = 10 ft, culvert width = 20 ft

Shoulder Width	AADT	Posted Speed Limit	B/C Ratio					
			Culvert Height = 10 ft			Culvert Height = 14 ft		
			offset 0 ft	offset 2 ft	offset 4 ft	offset 0 ft	offset 2 ft	offset 4 ft
4 ft	100	45	0.00	0.00	0.00	0.00	0.00	0.00
		55	0.00	0.00	0.00	0.00	0.00	0.00
	200	45	0.01	0.00	0.00	0.00	0.00	0.00
		55	0.01	0.00	0.00	0.01	0.00	0.00
5 ft	100	45	0.00	0.01	0.00	0.00	0.00	0.00
		55	0.00	0.00	0.00	0.00	0.00	0.00
	200	45	0.01	0.00	0.00	0.00	0.00	0.00
		55	0.01	0.00	0.00	0.01	0.00	0.00
6 ft	100	45	0.00	0.00	0.00	0.00	0.00	0.00
		55	0.00	0.00	0.00	0.00	0.00	0.00
	200	45	0.01	0.00	0.00	0.00	0.00	0.00
		55	0.01	0.00	0.00	0.00	0.00	-0.01
7 ft	100	45	0.00	0.00	0.00	0.00	0.00	0.00
		55	0.01	0.00	0.00	0.00	0.00	0.00
	200	45	0.01	0.00	0.00	0.00	0.00	0.00
		55	0.01	0.01	0.00	0.01	0.00	0.00

From the results shown in Tables 3.1 and 3.2, the general finding was made that new guardrails should not be implemented to shield culverts on Kansas rural roadways.

3.2 Result and Analysis of Embankment Simulation

The embankment simulation, which included one alternative with a bare embankment and another alternative with a guardrail to shield the hazard, intended to explore the benefit-cost ratios under various combinations of roadway geometric features and traffic operation data. The embankment simulation on three- or four-wheel-track gravel or paved roads was similar to the culvert simulation on the same type of roadway, except that the embankments had 2:1, 3:1, and 4:1 slopes, as shown under the B/C ratio column on the right side of Table 3.3. The table also displays the three embankment heights and shoulder widths, AADT, and posted speed limit.

Table 3.3: W-Beam Guardrail for Embankment on Three- or Four-Wheel-Track Gravel or Paved Road

Two-lane width = 12 ft

Shoulder Width	AADT	Posted Speed Limit	B/C Ratio								
			Embankment Height = 6 ft			Embankment Height = 12 ft			Embankment Height = 18 ft		
			slope 2:1	slope 3:1	slope 4:1	slope 2:1	slope 3:1	slope 4:1	slope 2:1	slope 3:1	slope 4:1
0 ft	100	45	-0.01	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02
		55	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	400	45	-0.09	-0.09	-0.09	-0.09	-0.10	-0.11	-0.09	-0.09	-0.09
		55	-0.12	-0.12	-0.13	-0.12	-0.12	-0.14	-0.12	-0.12	-0.12
	1000	45	-0.22	-0.22	-0.23	-0.06	-0.24	-0.29	-0.22	-0.22	-0.23
		55	-0.30	-0.30	-0.31	-0.30	-0.30	-0.34	-0.29	-0.29	-0.30
1 ft	100	45	-0.03	-0.03	-0.03	-0.03	-0.03	-0.04	-0.03	-0.03	-0.03
		55	-0.04	-0.04	-0.04	-0.04	-0.04	-0.05	-0.04	-0.04	-0.04
	400	45	-0.11	-0.12	-0.12	-0.12	-0.13	-0.17	-0.11	-0.12	-0.12
		55	-0.16	-0.16	-0.17	-0.16	-0.16	-0.19	-0.15	-0.15	-0.16
	1000	45	-0.28	-0.30	-0.30	-0.30	-0.33	-0.42	-0.28	-0.29	-0.30
		55	-0.38	-0.40	-0.41	-0.39	-0.39	-0.46	-0.38	-0.38	-0.39
2 ft	100	45	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.03	-0.03	-0.03
		55	-0.04	-0.04	-0.04	-0.04	-0.05	-0.05	-0.04	-0.04	-0.04
	400	45	-0.12	-0.12	-0.12	-0.12	-0.15	-0.17	-0.11	-0.12	-0.12
		55	-0.15	-0.16	-0.17	-0.16	-0.19	-0.19	-0.16	-0.16	-0.16
	1000	45	-0.29	-0.30	-0.31	-0.31	-0.38	-0.43	-0.28	-0.29	-0.30
		55	-0.38	-0.40	-0.41	-0.41	-0.46	-0.48	-0.39	-0.39	-0.40

All the B/C ratios were negative in Table 3.3, meaning that guardrail implementation to shield embankments is not justified in terms of a benefit-cost analysis. Additional crash patterns are shown in Table 3.4.

Table 3.4: Embankment Simulation for Three- or Four-Wheel-Track Gravel or Paved Road

Alternatives	Annualized Construction Cost	Expected Maintenance Cost	Expected Repair Cost	Expected Annual Crash Cost (with rollover)	Expected Annual Crash Cost (without rollover)
One: Bare Embankment	$0	$0	$0	$411	$0
Two: Guardrail Shielding Embankment	$1,737	$0	$33	$1,109	$797

The highlighted B/C ratio in Table 3.3 was: $\frac{\$1{,}109-\$411}{(\$0+\$0+\$0)-(\$1{,}737+\$0+\$33)} = -0.39$.

Table 3.4 shows all the costs related to the highlighted simulation in Table 3.3. Although the B/C ratio was -0.39, the alternative with a bare embankment still reported minimal crash costs (i.e., $411). In addition, all the crashes were rollover, meaning rollover was the only harm expected from bare embankments. Alternative 2 also reported crash costs related to rollover crashes: $1,109 (with rollover) - $797 (without rollover) = $312. However, rollover crash cost decreased by $\left(1-\frac{312}{411}\right) * 100\% = 24.09\%$ due to guardrail implementation. Other kinds of crashes occurred with new guardrails, though, with inferred crash costs of $797. The results in Table 3.4 confirm that the expected reduction of crash costs associated with rollover crashes was relatively lower than the reduction of crash costs associated with new guardrails.

Results of embankment simulation on a two-wheel-track gravel road are shown in Table 3.5. The roadway in this simulation had only one direction, and lane width was 10 ft. The shoulder width and AADT differed from the previous embankment simulation, but embankment profiles stayed the same.

All B/C ratios in Table 3.5 were negative and near zero. The minor crashes associated with the new guardrail overweighed the improvement in rollover crashes as shown in Table 3.4, causing all the B/C ratios to be negative because the traffic exposure or AADT was too low on two-wheel-track gravel roads for crashes to occur or because the shoulder was wide enough to offset the influence of errant encroachment. Results in Tables 3.3 and 3.5 prove that new guardrails are unnecessary to shield embankments on both types of Kansas rural roadways.

Table 3.5: W-Beam Guardrail for Embankment on Two-Wheel-Track Gravel Road

Lane width = 10 ft

Shoulder Width	AADT	Posted Speed Limit	B/C Ratio								
			Embankment Height = 6 ft			Embankment Height = 12 ft			Embankment Height = 18 ft		
			slope 2:1	slope 3:1	slope 4:1	slope 2:1	slope 3:1	slope 4:1	slope 2:1	slope 3:1	slope 4:1
4 ft	100	45	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01
		55	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	200	45	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.03	-0.03	-0.03
		55	-0.04	-0.04	-0.04	-0.04	-0.05	-0.04	-0.04	-0.04	-0.04
5 ft	100	45	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01
		55	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	200	45	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.03	-0.03	-0.03
		55	-0.04	-0.04	-0.04	-0.04	-0.05	-0.04	-0.04	-0.04	-0.04
6 ft	100	45	-0.02	-0.02	-0.02	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01
		55	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	200	45	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.03	-0.03	-0.03
		55	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
7 ft	100	45	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01
		55	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	200	45	-0.03	-0.03	-0.03	-0.03	-0.04	-0.04	-0.03	-0.04	-0.03
		55	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.05	-0.04

3.3 Result and Analysis of Bridge Simulation

As discussed in Section 2.3.4, the bridge simulations were the most complicated task in this project. To avoid extra complexity associated with the influence of TL-2 rails on bridge structures, one type of simulation utilized a medium bridge edge, and another type of simulation used a TL-2 bridge edge as the existing condition. Table 3.6 shows all the parameters and results of bridge simulations on three- or four-wheel-track gravel or paved roads. The height below the bridge to the surface of the water was 12 ft. “Shoulder Before and After Transition” in the table denotes the shoulder width of the roadway beyond the transition part, as described in Section 2.3.4. The lane was assumed to extend across the bridge, leaving the rest as shoulder. The first simulation had three alternatives for each combination, and the second simulation had two alternatives. The examples in the rectangle and the circle in the table illustrate the B/C ratios of bridge simulation.

Table 3.6: W-Beam Guardrail as Bridge Rail or Bridge-Approach Guardrails on Three- or Four-Wheel-Track Gravel or Paved Road

Two lanes with 12-ft width each; below bridge to water surface = 12 ft

Shoulder Before & After Transition	AADT	Posted Speed Limit	B/C Ratio											
			Existing Condition: Medium Bridge Edge								Existing Condition: TL-2 Bridge Rail			
			Bridge Width = 20 ft		Bridge Width = 24 ft		Bridge Width = 26 ft		Bridge Width = 28 ft		Bridge Width= 20 ft	Bridge Width= 24 ft	Bridge Width= 26 ft	Bridge Width= 28 ft
0 ft	100	45	1.17 0.37	-0.01	0.96 0.30	-0.02	0.65 0.22	0.01	0.61 0.20	0.00	-0.01	-0.01	0.01	0.01
		55	1.45 0.47	-0.01	1.17 0.37	-0.01	0.91 0.30	0.01	0.83 0.27	0.01	0.00	-0.01	0.01	0.01
	400	45	4.65 1.49	-0.04	3.82 1.20	-0.06	2.58 0.86	0.03	2.44 0.81	0.02	-0.03	-0.06	0.03	0.02
		55	5.75 1.85	-0.02	4.66 1.49	-0.03	3.59 1.19	0.03	3.30 1.08	0.02	-0.02	-0.03	0.04	0.03
	1000	45	11.48 3.68	-0.09	9.47 2.98	-0.15	6.34 2.11	0.07	6.01 1.99	0.05	-0.08	-0.15	0.08	0.05
		55	14.20 4.59	-0.05	11.53 3.70	-0.08	8.84 2.92	0.08	8.12 2.67	0.05	-0.04	-0.07	0.09	0.06
1 ft	100	45	1.17 0.37	-0.01	0.96 0.30	-0.02	0.65 0.22	0.01	0.62 0.20	0.00	-0.01	-0.01	0.01	0.01
		55	1.45 0.47	-0.01	1.17 0.37	-0.01	0.91 0.30	0.01	0.83 0.27	0.01	0.00	-0.01	0.01	0.01
	400	45	4.65 1.49	-0.04	3.83 1.20	-0.06	2.60 0.86	0.03	2.44 0.81	0.02	-0.03	-0.06	0.03	0.02
		55	5.75 1.85	-0.02	4.66 1.49	-0.03	3.61 1.19	0.03	3.30 1.08	0.02	-0.02	-0.03	0.04	0.03
	1000	45	11.48 3.18	-0.09	9.47 2.96	-0.19	6.39 2.13	0.08	6.01 1.99	0.05	-0.08	-0.15	0.09	0.05
		55	14.20 4.59	-0.05	11.53 3.67	-0.13	8.89 6.94	0.08	8.11 2.67	0.05	-0.04	-0.07	0.10	0.06
2 ft	100	45	1.17 0.37	-0.01	0.96 0.30	-0.02	0.65 0.22	0.01	0.62 0.20	0.01	-0.01	-0.01	0.01	0.01
		55	1.45 0.47	-0.01	1.17 0.37	-0.01	0.91 0.30	0.01	0.84 0.27	0.01	0.00	-0.01	0.01	0.01
	400	45	4.65 1.49	-0.04	3.82 1.19	-0.07	2.59 0.86	0.03	2.46 0.81	0.02	-0.03	-0.06	0.04	0.02
		55	5.75 1.85	-0.02	4.66 1.48	-0.05	3.61 1.19	0.03	3.32 1.09	0.02	-0.02	-0.03	0.04	0.03
	1000	45	11.48 3.68	-0.09	9.46 2.96	-0.20	6.38 2.13	0.08	6.06 2.01	0.05	-0.08	-0.15	0.09	0.05
		55	14.19 4.59	-0.05	11.53 3.67	-0.13	8.88 2.93	0.08	**8.17** **2.69**	**0.05**	**-0.04**	-0.08	0.09	0.06

Table 3.7 shows the results of a simulation that used a medium bridge edge as the existing condition on a three- or four-wheel-track gravel or paved road.

Table 3.7: B/C Ratio with Medium Bridge Edge as Existing Condition

8.17 **2.69**	**0.05**	Alt1. Medium Bridge Edge	Alt2. W-Beam Bridge Rail	Alt3. W-Beam Bridge Rail & Bridge-approach guardrails
Benefit (Crash Cost)		$ 15,129.00	$ 3,282.00	$ 3,127.00
Project Costs		$ -	$ 1,450.00	$ 4,466.00
Benefit-Cost Ratio		Alt2 to Alt1: ($15,129–$3,282)/($1,450–$0) = **8.17** Alt3 to Alt1: ($15,129–$3,127)/($4,466–$0) = **2.69** Alt3 to Alt2: ($3,282–$3,127)/($4,466–$1,450) = **0.05**		

The benefit-cost ratio of using a W-beam bridge rail without bridge-approach guardrails compared to using a medium bridge edge was $\frac{\$15{,}129-\$3{,}282}{\$1{,}450-\$0} = 8.17$. The benefit-cost ratio of using a W-beam bridge rail with bridge-approach guardrails compared to using a medium bridge edge was $\frac{\$15{,}129-\$3{,}127}{\$4{,}466-\$0} = 2.69$. Moreover, the benefit-cost ratio of Alternative 3 to Alternative 2 was $\frac{\$3{,}282-\$3{,}127}{\$4{,}466-\$1{,}450} = 0.05$. Table 3. 8 shows results of a simulation using a TL-2 bridge rail as the existing condition on a three- or four-wheel-track gravel or paved road.

Table 3.8: B/C Ratio with TL-2 Bridge Rail as Existing Condition

-0.04	Alt1. TL-2 Bridge Rail	Alt2. TL-2 Bridge Rail & Bridge-approach guardrails
Benefit (Crash Cost)	$ 6,484.00	$ 6,600.00
Cost (Construction and Repair Cost)	$ 3.00	$ 2,976.00
Benefit-Cost Ratio	Alt2 to Alt1: ($6,484-$6,600)/($2,976-$3) = **-0.04**	

The benefit-cost ratio of using a TL-2 bridge rail with bridge-approach guardrails compared to using a TL-2 bridge rail without bridge-approach guardrails was $\frac{\$6{,}484-\$6{,}600}{\$2{,}976-\$3} = -0.04$.

Overall, the B/C ratios increased with AADT and posted speed limit when other parameters were fixed, but the B/C ratios decreased with increasing bridge width, as in the culvert and embankment simulations. Moreover, the shoulder width before and after the transition had almost no influence on B/C ratios because the shoulder width on the bridge differed from the shoulder width of the roadway. The roadway lane width was 12 ft and extended across the bridge, so the shoulder width for one side of the bridge was 0 ft, 1 ft, and 2 ft when the bridge width was 24 ft, 26 ft, and 28 ft, respectively. While other parameters were fixed, B/C ratios of Alternative 2 to Alternative 1 using a medium bridge edge decreased with increasing bridge shoulder width in accordance with previous simulations.

If the threshold of B/C ratio was 2.0 and the AADT exceeded 400 vehicles per day, all the B/C ratios of Alternative 2 to Alternative 1 exceeded the threshold when a medium bridge edge was used as an existing condition. Therefore, W-beam bridge rails were recommended to replace medium bridge edges. Regarding W-beam bridge-approach guardrails, the results were reflected in the B/C ratios of Alternative 3 to Alternative 1 when a medium bridge edge was used as the existing condition and the B/C ratios of Alternative 2 to Alternative 1 when a TL-2 bridge rail was used as the existing condition. As shown in Table 3.6, none of the B/C ratios were larger than 1.0, and most values were almost zero. Therefore, under the given conditions, there was no practical justification for implementing bridge-approach guardrails on Kansas rural roadways.

Table 3.9 shows the results of bridge simulation on a two-wheel-track gravel road, with parameters adjusted to one-direction lanes. As shown in the table, none of the B/C ratios were larger than 1.0, meaning that benefit-cost analysis did not justify replacing medium bridge edges with W-beam guardrails, nor implementing W-beam bridge-approach guardrails.

Table 3.9: W-Beam Guardrail as Bridge Rail or Bridge-Approach Guardrails on Two-Wheel-Track Gravel Road

Lane width = 10 ft; below bridge to water surface = 12 ft

Shoulder Before & After Bridge	AADT	Posted Speed Limit	B/C Ratio					
			Existing Condition: Medium Bridge Edge				Existing Condition: TL-2 Bridge Rail	
			Bridge Width = 20 ft		Bridge Width = 24 ft		Bridge Width = 20 ft	Bridge Width = 24 ft
4 ft	100	45	0.30 0.09	0.00	0.30 0.10	0.00	0.00	0.00
		55	0.44 0.14	0.00	0.42 0.14	0.00	0.00	0.00
	200	45	0.60 0.19	-0.01	0.59 0.19	0.00	-0.01	0.00
		55	0.87 0.28	-0.01	0.84 0.28	0.00	-0.01	0.00
5 ft	100	45	0.30 0.09	-0.01	0.30 0.10	0.00	0.00	0.00
		55	0.44 0.14	0.00	0.42 0.14	0.00	0.00	0.00
	200	45	0.60 0.19	-0.01	0.59 0.19	0.00	-0.01	0.00
		55	0.87 0.28	-0.01	0.84 0.28	0.00	-0.01	-0.01
6 ft	100	45	0.30 0.09	-0.01	0.29 0.10	0.00	0.00	0.00
		55	0.44 0.14	-0.01	0.42 0.14	0.00	0.00	0.00
	200	45	0.60 0.19	-0.01	0.59 0.19	0.00	-0.01	0.00
		55	0.87 0.28	-0.01	0.84 0.28	0.00	-0.01	0.01
7 ft	100	45	0.30 0.09	-0.01	0.30 0.10	0.00	0.00	0.00
		55	0.44 0.14	0.00	0.42 0.14	0.00	0.00	0.00
	200	45	0.60 0.19	-0.01	0.59 0.19	0.00	-0.01	0.00
		55	0.87 0.28	-0.01	0.85 0.28	0.00	-0.01	0.01

Because the lane width was 10 ft, the shoulder widths on the bridge were 5 ft or 7 ft for each side, which was wide enough to contain most errant vehicles. Moreover, because the AADT was very low, the results in this case showed patterns similar to the previous simulations.

Chapter 4: Discussion and Significant Findings

4.1 Discussion of Results

Crashes that occur in rural areas caused almost 50% of the traffic fatalities in the United States in 2017, with Kansas having a higher fatality rate per 100 million VMT than the national average for rural areas in that same year. For all fatality crashes in rural areas, approximately 50% are single-vehicle, roadside crashes. This research study was performed for KDOT to investigate methods to reduce roadside crashes in rural areas and test the rationality of shielding roadside hazards with new guardrails. Benefit-cost analyses were implemented to economically quantify comparison results of various safety treatments. Benefit was defined as reduced crash costs associated with project improvements, while cost included design, construction, maintenance, and repair expenditures associated with project improvements. Analysis was annualized because crashes occurred in the life cycle of the project. This research project focused on bridge rails and bridge-approach guardrails, culverts with wingwalls, and embankments.

A 10-year crash dataset was used to capture the basic patterns of rural roadside crashes and field conditions in Kansas. A survey of crash locations revealed that nearly 50% of guardrail end-treatments were still blunt and turndown types. Descriptive statistics of crashes involving guardrails and culverts showed that crash frequency increased with increasing AADT. However, the trend decreased after a certain turning point of AADT. For rural roadways with high traffic volumes, the increasing trend was rather flat. However, results showed a steady increasing trend of crashes with increasing posted speed limits, while the average AADT for related crashes experienced almost no change. AADT and posted speed limit were confirmed as contributing factors to roadside crashes in the crash records of Kansas rural roadways.

RSAPv3 was used to carry out simulations in this research study because it utilizes real crash data to predict crashes and is easily updated with local data. KDOT provided data pertaining to costs related to fatal crashes in 2017 to use in the simulation, and traffic operation data and geometric features of rural roadways in Kansas were synthesized. Two-wheel-track gravel roads with one direction and three- or four-wheel-track gravel or paved roads with two directions were determined to be the most common types of rural roadways in Kansas. Geometric roadway parameters, such as foreslope, lane width, and total roadway width, as well as traffic operation data, such as AADT and posted speed limit, were established for the two types of roadways. Extra space on the roadway besides the lane width was used as the shoulder width in the simulation.

This study tested three hazards on the two types of rural roadways. For the culvert, the foreslope was the same as that of the roadway, and the offset of the culvert was the distance from the edge of the roadway to the hubguard. The culvert width, provided by KDOT, was relatively conservative to include the most severe situations in the field. Guardrail lengths were also provided by KDOT, and the simulated guardrail was implemented along the edge of the roadway in a straight line. The embankment simulation using RSAPv3 followed the same style as the culvert.

The bridge simulation included a TL-2 bridge rail, which requires modification of bridge structure if the bridge edge was the base condition. Therefore, the simulation was divided into two parts. Part one included three alternatives: using a medium bridge edge, replacing a medium bridge edge with a W-beam bridge rail, and implementing W-beam bridge-approach guardrails. Part two included two alternatives: using a TL-2 bridge rail as the base condition and implementing W-beam bridge-approach guardrails, thereby preventing bridge structure modifications and subsequent costs. Another key point in this simulation was that the bridge width potentially differed from the roadway width. When the bridge was narrow, the bridge-approach guardrails further narrowed the roadway, which was acceptable in this case, but when the bridge was wide, the bridge-approach guardrails were implemented on the slope beside the roadway, which was against common practice. Therefore, two transitions were set up before and after the bridge. Roadway shoulders in the transition were enlarged to make the roadway width equal to the bridge width. The bridge-approach guardrails were implemented in the transition along the edge of the road, as required by KDOT. Moreover, because a lane of the roadway should extend across the bridge, leaving extra space as a shoulder on the bridge, the width of the bridge shoulder differed from the shoulder width on the roadway.

4.2 Significant Findings

Culvert simulation results were displayed as the benefit-cost ratios of implementing new guardrails to shield bare culverts under various combinations of traffic operation data and roadside geometric features. For simulations on three- or four-wheel-track gravel or paved roads with no shoulders, nearly all the benefit-cost ratios were zero. Non-zero benefit-cost ratios only occurred when shoulder width was larger than zero, as determined in common practice that guardrails need sufficient space to prevent crashes efficiently. The contributing factors to benefit-cost ratios were observed when other parameters were fixed, including offset of culvert, AADT, posted speed limit, and culvert size. For the simulation on a two-wheel-track gravel road, almost all the results were zero due to wide shoulders that absorbed potential encroachment and low AADT, which was too low for crashes to occur. Since none of the ratios were larger than 1.00, the benefit-cost analysis did not justify the implementation of new guardrails to shield culverts on both types of roadways.

The pattern of embankment simulation differed from the culvert simulation. For simulations on three- or four-wheel-track gravel or paved roads, all benefit-cost ratios were negative, meaning that the harm caused by the guardrail exceeded the benefits. A case study proved this intuition. Only rollover crashes were expected on the bare embankment, while the guardrail caused more severe crashes. Simulation results from a two-wheel-track gravel road were also negative and near zero due to wide shoulders and low AADT. Therefore, benefit-cost analysis did not justify implementation of new guardrails to shield embankments on both types of roadways.

The bridge simulation included two parts. For Part one, which used a medium bridge edge as the base condition, the benefit-cost ratios of replacing a medium bridge edge with a W-beam bridge rail were larger than 2.00, with AADT larger than 400 vehicles per day, on three- or four-wheel-track gravel or paved roads. Some ratios were even higher than 10.00, which was significant as a threshold. Moreover, these ratios decreased with increasing shoulder width on the bridge, which was in accordance with previous simulations. Therefore, it was recommended to replace a medium bridge edge with a W-beam bridge rail on three-or four-wheel-track gravel or paved roads, given a specific threshold according to field conditions. However, the implementation of bridge-approach guardrails was not recommended. For part two, which used a TL-2 bridge rail as the base condition, the highest benefit-cost ratio was not significant, due to the wide shoulder on the bridge and low AADT. Benefit-cost analysis results showed that medium bridge edges do not need to be replaced with W-beam bridge rails, and bridge-approach guardrails are not cost-justified on two-wheel-track gravel roads.

4.3 Contribution to Highway Safety

The insight from this research project could save lives from roadside crashes in rural areas. The research team found significant benefit-cost ratios in the bridge simulation that replaced medium bridge edges with bridge rails. With feasible conditions, this implementation would save lives or mitigate injuries from roadside crashes, which is the most valuable principle of traffic engineers. One objective of this study was to allocate resources according to priorities in terms of benefit-cost analysis, thereby saving limited funding from unnecessary expenditures. Since benefit-cost ratios for shielding culverts and embankments and implementing bridge-approach guardrails to bridges were not significant, it is not rational to implement new guardrails for these hazards on rural roadways in Kansas. In addition, this study established a process of RSAPv3 application on local crash prediction. Updating this research project or implementing new projects on various types of hazards could follow the same procedure.

4.4 Limitations and Future Research

Although this study was conducted on the most advanced traffic safety software, there were still several limitations in this research. First, assumptions were made in the simulation to simplify the case, including geometric features and comparisons, which potentially affected the results. Second, RSAPv3 relies heavily on previous crash datasets, meaning accurate predictions depend on similarities between predicted crashes and the dataset, as well as the availability of sufficient data. If engineering conditions differ significantly from the crash dataset in RSAPv3, the results may be inaccurate. However, this issue could be solved by updating inside parameters of RSAPv3 with local crash datasets. A future study could continue the research on statistics of roadside crashes on rural roadways in Kansas, as partially explored in Section 2.1.3.

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Appendix: Communication with Norm Bowers, Local Road Engineer, Kansas Association of Counties

KTRAN Guardrail Study-Various simulations

Version May 7, 2019 Norm Bowers

Local Roads Only

Speed Limit: 45 & 55

Two Wheel Track Gravel Road: 10 ft. lane at center of road, all traffic primary-no opposing traffic. Road widths of 18, 20, 22 & 24. ADT 100 & 200

Three Wheel track road & blacktop road: Two 12 ft. lanes. Road Widths of 24, 26 & 28. ADT of 100, 400 & 1000

First Priority: Approach guardrail at bridge: When guardrail needs to be replaced. Compare no guardrail-medium hazard to new guardrail. Bridge widths on two track road of 20 and 24 ft. Bridge widths of three wheel path and blacktop road: 20, 24, 26 & 28. Use 120 ft. of bridge. We will need to get you average length of approach and exit guardrail.

Second Priority Culvert Wingwall: Distance from road edge to hubguard (opening): 0, 2, 4 New guardrail at edge of road, can't be down slope. Rise from flow line of channel to road: 10 ft. and 14 ft. Fill: Would be reasonable to assume 75 ft. at max fill and transition to standard 50 ft. each way. Guardrail required 175 ft. plus 35 ft. transitions total 245 ft. New guardrail at edge of road.

Third Priority Embankments across fill area over pipe: Fill Height 6, 12 & 18. Foreslopes 2:1, 3:1 & 4:1. Fill: Would be reasonable to assume 50 ft. at max fill and transition to standard 50 ft. each way. Guardrail required 150 ft. plus 35 ft. transitions total 220 ft. New guardrail at edge of road.

Discussion on KTRAN Guardrail Study-Various simulations

Based on Version May 17, 2019 Norm Bowers & May 22.

(1) Since there's extra space on the local roads (both two wheel track and three wheel track gravel ones), can we simulate it as shoulder? Or just use the whole space as road and no shoulder? After testing in RSAPv3, I found the result would be different even though the total width did not change.

Norm: For the two-wheel track road, this is really a Tod question as I have never used RSAP. For a typical section, use 3:1 foreslopes with a fill of 2 ft. See drawing I made-apologies for light scan, I am working from home.

Peng: Tod, can we get any suggestions on this question?

Tod Jun 03: For gravel roads, the wheel paths define the "travel way", so the "shoulder" starts at the edge of the wheel path.

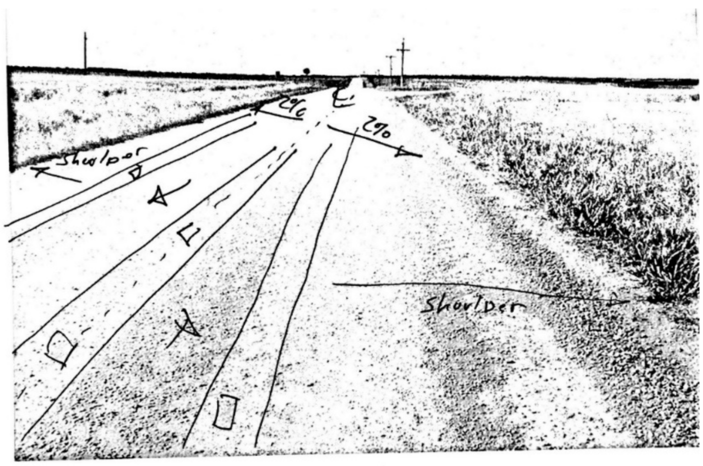
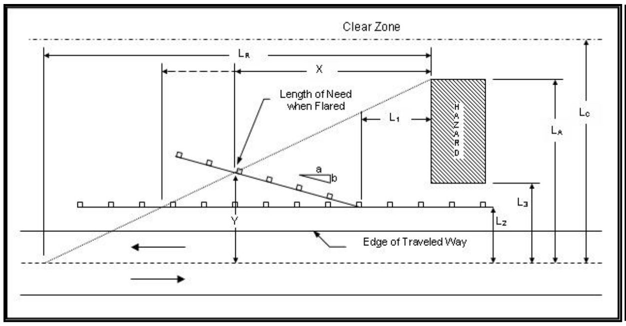
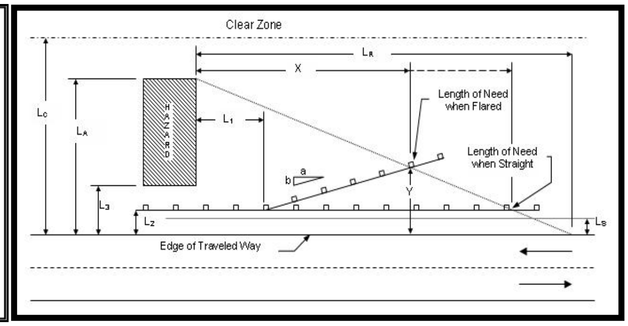


Figure 1 3 track road

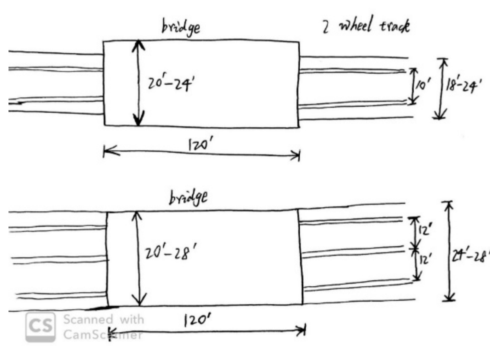
(2) For the local roads, if we try to implement guardrails to shield the hazard, do we need to make it on both sides of the hazard? Or just for the primary traffic. Norm: All the roads are local so not sure what you are asking I will address under the other scenarios.

Peng: Two pictures were added here to illustrate this question. Do we need to consider guardrails for both primary and opposing traffic on two-wheel and three-wheel track roads? Norm May 22: We always put guardrail on both sides of the road on bridges





(3) Sketch on scenario 1 (bridge). Is it correct? Norm: I think it is correct. This gets analyzed with and without guardrail at all four corners. We probably need to talk about severity factors to use with and without guardrail. Tod is supposed to give you average approach guardrail lengths. I suppose on the three-wheel track road the approach guardrail is needed worse than the departing guardrail, but I assume that is outside the scope of this project. Tod, what do you think?



(4) Sketch on scenario 2 (culvert).

- Distance of road edge to hub guard is 0, 2 and 4 ft. Can we use it as the offset of culvert to road edge? Norm: Yes, that is what it is, but to be clear on the three-track road the offset would be from the shoulder, if any.
- Is it right that the height of from culvert to road surface is 10 ft. and 14 ft.? Norm: Yes the vertical distance from flow line of the culvert to road surface: The length of the stream would be the distance that the foreslope would extend. The length of the foreslope then is based on the slope, so if we assume 3:1 the length as you describe it is 3 x 10 fill=30 ft. and 3 x 14 fill=42 ft. as measured from the edge of road.
- Would you please explain which section is for fill and transition? Is the sketch below right? Norm: Your sketch labels the guardrail as huguard, the width of fill is not as you

indicated- it is the road width plus the foreslopes. See attached sketch for transition of the fill from the normal road section.

- About the guardrail length (175 ft. plus 35 ft. transition total 245 ft.). Is it starting from middle of the culvert and both sides 245/2 = 122.5 ft.? Norm. Yes

  Peng: Thanks for providing the length of the guardrail. Is this the length for the existing guardrail, or for the new implemented one? Now we are considering one hazard under both protected and unprotected scenarios. For the protected one, we are using Roadside Design Guide to get the length of need. Norm May 22: The two scenarios are without guardrail and with new guardrail. The length I gave you was for a typical situation, I don't know how you would compute length of need without knowing a lot more about the geometry at a particular location.

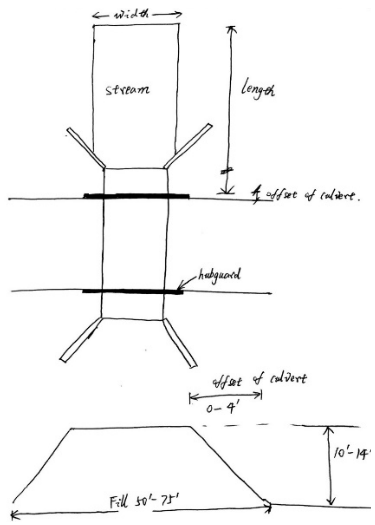
  Peng: Some of the guardrails on local roads have been through a long time of use. They might not be proper to shield the hazard anymore. We have calibrated the crash severity of such guardrails according the instruction of RSAPv3 manual. So, one option is to replace these outdated guardrails with new ones. Can we use the same length you have offered for the existing guardrail? (I mean use the length for the outdated guardrails which have already been implemented before hazards)

  Norm May 22: On all three of the scenarios, bridge, culvert or embankment, you need to forget about the existing guardrail. The two options are no guardrail or new guardrail. Is it cost effective to install new guardrail? If not, you don't install new guardrail.

  If the local agency is considering replacing an existing guardrail it is because it is so bad that it is not effective. So just forget about trying to evaluate existing guardrail it can be anyplace from not effective to worse than nothing.

- In RSAPv3, the culvert would be simulated as headwall plus stream, and the stream would play an important role as hazard. Can we get the size of wingwall and the stream (stream length and width)? Norm: The stream width is the width of the box, I think we are using worst case of 20 ft., kind of like you drew it. The length of the stream would be the distance that the foreslope would extend. The length of the foreslope then is based on the slope and the height, so if we assume 3:1 the length as you describe it is 3 x 10 fill=30 ft. and 3 x 14 fill=42 ft. as measured from the edge of road. I was just assuming straight wingwalls and vertical channel banks, so you need two sections at almost the same station to simulate a vertical wall. The length of the wingwall is immaterial since it is vertical and in the same location as the stream bank.

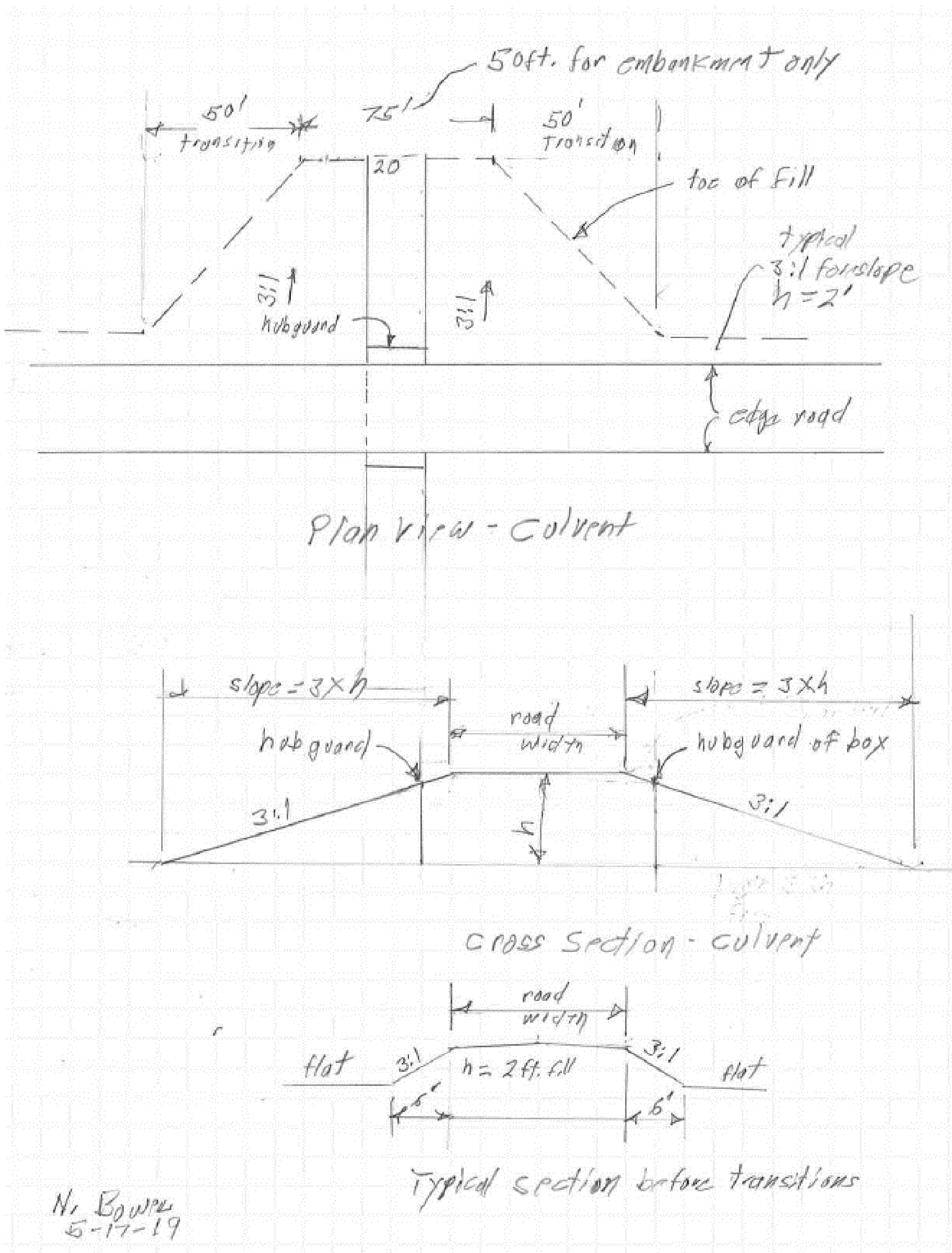
Peng: For the culvert, now we have height (10 ft. and 14 ft. from last email), what about the range of width of box and foreslopes? In this example, you have used width as 20 ft. and foreslpe 3:1. Can we get all the value range? Norm May 22: As noted above we use the worst case of 20 ft. width(span). The slope daylights to natural ground so for a 3:1 slope it would be 30 ft. for 10 ft. fill and 42 ft. for 14 ft fill as measured from the edge of the road. No range of slopes, just 3:1 for the culvert.



(5) Scenario 3 (embankment).

- The same question about fill and transition, as in scenario 2. Norm: See my sketch. Fill transitions from typical to maximum in 50 ft, with maximum fill for 50 ft. rather than 75 to represent a smaller channel.

(6) About implementation of new guardrail. Now we're following Roadside Design Guide. If the shy-line offset of guardrail were beyond the edge of the local roads, then we would assume it should be implemented on the edge. If it's within the edge, we would just use the distance recommended by Roadside Design Guide. Do you think if it is proper? Or should we implement new guardrail just on the edge without considering Roadside Design Guide. Norm: At the bridge, the guardrail has to attached to the bridge. For the culvert and embankment, the guardrail is placed at the edge of the road.


50ft. for embankment only
50'
transition
75'
50'
Transition
20
toe of fill
typical
3:1 foreslope
h = 2'
3:1
hubguard
3:1
edge road
Plan View - Culvert
slope = 3 X h
slope = 3 X h
road
width
hubguard
hubguard of box
3:1
3:1
h
Cross Section - Culvert
road
width
flat
3:1
h = 2 ft. fill
3:1
flat
6'
6'
Typical section before transitions
N. Bowen
5-17-19

K-TRAN

KANSAS TRANSPORTATION RESEARCH AND NEW-DEVELOPMENT PROGRAM

Kansas
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