RISK FACTORS ASSOCIATED WITH HIGH POTENTIAL FOR CRASHES ON LOW-VOLUME ROADS

by

Fahmid Hossain

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2016

DEDICATION

This thesis is dedicated to my mother, Perveen Nahar and my father, Md. Faruk Hossain who always have supported me and encouraged me to continue my higher study. This work is also dedicated to my friends and colleagues who have stood by me during this study.

ACKNOWDLEGEMENTS

I would like to acknowledge and thank you my advisor, Dr. Ahmed Al-Kaisy, for his dedication, support, and patience. Additionally, I would like to thank my committee members, Dr. Yiyi Wang and Dr. Natalie Villwock-Witte for their guidance and contributions. I also acknowledge Levi Ewan for his help and support during this study. Without the efforts of the acknowledged persons this work would not have been possible.

TABLE OF CONTENTS

TABLE OF CONTENTS - CONTINUED

LIST OF TABLES

Table Page

LIST OF TABLES - CONTINUED

Table Page

LIST OF TABLES - CONTINUED

Table Page

LIST OF FIGURES

Figure Page

LIST OF FIGURES - CONTINUED

Figure Page

LIST OF FIGURES - CONTINUED

ABSTRACT

A significant portion of the roadway mileage in the U.S. is comprised of the low volume roads. As these roads experience very low crash frequencies, the identification of hazardous locations based on crash history alone is difficult. However, these low-volume roads may be associated with higher level of risks and consequently higher crash rates due to substandard geometry on these roads. Therefore, an approach to identify hazardous locations on low volume roads which accounts for geometric and roadside features as well as crash history seemed to be necessary. For this purpose, roadway data from Oregon's low volume roads and 10-years of crash data on the selected sample were collected and analyzed to identify the roadway geometric and roadside features that contribute to the crash occurrence. Length of the horizontal and vertical curves under 100 feet, degree of curvature over 30 degrees, vertical grade over 5 percent, lane width narrower than 11 feet, shoulder width of 0 feet, and driveway density of 5 driveways/mile were found as the most restrictive features contributing to higher crash rate. Based on these analyses a quantitative tool was developed for assessing the level of risk on low volume roads. The developed risk index, which is a function of roadway geometry, roadside features, traffic exposure, and crash history, is proactive in nature, as it does not rely heavily on crash occurrence in assessing crash risks. Application of the crash risk index on the three corridors of Oregon showed that, the use of risk index provides new information about the level of hazard along highway segments compared to using crash history alone. Economic feasibility of some potential low-cost safety countermeasures was analyzed to identify which countermeasures would ensure the maximum return on investments. Installation of the rumble strips, object markers, safety edge, centerline and edge-line markings were found to be most cost effective with benefit/cost ratio over 8. The same procedure can be followed by other states, with similar road and traffic conditions, to identify the contributing factors of crashes and identify the most-effective countermeasures to improve the safety of the road.

CHAPTER ONE – INTRODUCTION

1.1. Low Volume Roads

Low volume roads are usually present in rural areas and they primarily consist of two-lane collectors and local roads. However, low volume roads are defined differently by different highway agencies, as the amount of volume that constitutes a low volume road is dependent on the agency. The Manual on Uniform Traffic Control Devices (MUTCD) states in Chapter 5A that “A low-volume road shall be a facility lying outside of built-up areas of cities, towns, and communities, and it shall have a traffic volume of less than 400 AADT (Annual Average Daily Traffic)” (*1*). Also Chapter 2 of the MUTCD establishes a cutoff between high and low volume roads of 1,000 AADT (*1*). One study at Iowa State University produced a similar cut off value of 400 vehicles per day (vpd) for definition of low volume roads (*2*). Another study by Gross et al. used 1,000 vpd for low volume roads and 400 vpd for very low volume roads (*3*). Therefore, the threshold value of AADT for defining low volume roads depends on the purpose or scope of the work by highway agencies.

Low volume roads comprise a significant portion of roadway mileage in the U.S. According to a Federal Highway Administration (FHWA) published report, the U.S. has over 4.8 million km (3 million mile) of two-lane roads and about 90 percent of these roads carry traffic volume that is less than 2,000 vpd, which are considered as low volume roads (*4*). Usually the rural roads with low volumes are constructed and maintained to lower standards compared to higher volume roads. Presence of narrow lanes, lack of shoulders, presence of sharp curves, and presence of more roadside objects are usually encountered on low volume roads, which usually contribute to the higher crash risk and severity.

The National Highway Traffic Safety Administration (NHTSA) and the U.S. Department of Transportation (USDOT) provide the fatality rates per 100-million VMT by road classification (*5*, *6*), which is shown in Table 1.1. Evidence of higher crash rate on low-volume roads can be seen from this table. The rural roads that usually experience lower volume are rural collectors and local roads. The fatality rate for these two classes of road are higher than any other classes which suggests higher crash severity on these roads.

Table 1.1. National fatality rate (per 100-Million VMT) by road classification (2013 data)

	Class	**Fatalities**	**VMT (Billions)**	**Rate**
Urban	Total	14,987	2,046.41	0.73
	Interstate	2,088	505.31	0.41
	Other Arterial	8,550	1,068.93	0.80
	Collector	1,101	188.55	0.58
	Local	3,231	283.63	1.14
Rural	Total	17,696	941.91	1.88
	Interstate	1,992	234.30	0.85
	Other Arterial	7,388	358.76	2.06
	Collector	4,744	221.22	2.14
	Local	3,469	127.62	2.72

1.2. Challenge of Assessing Risk on Low Volume Roads

Identification of high crash locations along the roadway has become one of the utmost priorities for highway agencies in the past few years. The more frequent crashes on the roadways with higher traffic volume make it easier for direct identification of these locations using crash history; whereas on local roads with low volumes and low crash frequencies, the identification of hazardous locations based on crash history alone is difficult. Traditional methods for identifying candidate locations for safety improvements has inherent bias in favor of well-travelled roadways that experience higher crash frequencies. However, low-volume roads may be associated with high level of risks mainly due to their substandard roadway geometry and roadside features. Therefore, an approach to identifying hazardous locations on low volume roads which accounts for geometric and roadside features as well as crash history seems to be necessary. In order to identify the hazardous locations on low-volume roads it is necessary to identify the geometric, traffic, and other features that may increase the risk of crash occurrence. Identification of these features may result a low-volume road as hazardous location due to substandard design, whereas the low crash frequency may not identify that road as hazardous.

1.3. Study Objective

The primary objective of this study is to identify the roadway geometric and roadside features that contribute to the crash occurrence on low-volume roads by examining their effects. For examining the risk effects associated with each geometric and roadside feature, an extensive analyses of road data and safety data are required. Moreover, regression and correlation analyses seem to be necessary to explore the relationship of crash rate and severity with the geometric features for this purpose.

Another objective of this study is to develop a quantitative tool for assessing the level of risk on low volume roads, as for low volume roads, the use of crash history alone for identifying hazardous location is not practical. This proactive tool does not depend only on the crash history and this tool can be easily used at the network level to identify the hot spots that require further investigations. For this purpose, developments of a crash risk index using roadway geometry, roadside features, traffic exposure, and crash history appears to be crucial in assessing the crash risk on low volume roads.

The last objective of this study is to analyze the economic feasibility of different safety countermeasures on low volume roads by investigating roadway and crash data from the state of Oregon. As the state and federal resources that are dedicated to safety improvements have become limited in recent years, it is necessary to properly identify the countermeasures and the location where these countermeasures can be implemented, which would ensure the maximum return on investments. Performing a benefit-cost analysis of different countermeasures consistent with the guidelines of the Highway Safety Manual (HSM) for this purpose seems to be essential.

1.4. Thesis Organization

This thesis consists of seven chapters including the introduction. The next chapter discusses the literature review focusing on the safety features of low-volume roads, existing approaches of risk index development, and previously found economic feasible countermeasures. Chapter three describes the data collection procedures as well as selection of the study sample from Oregon’s low-volume roads. Chapter four characterizes the roadway geometric and roadside features in order to understand their influence on crash risk. The results found from regression and correlation analyses are also interpreted in this chapter. The next chapter portrays the risk index development procedures in order to quantify the crash risk based on roadway and traffic characteristics. Moreover, application of the developed risk index to three low-volume corridors in Oregon is illustrated in this chapter. Chapter six describes the economic feasibility investigation in order to determine low-cost safety treatments that can improve the safety condition of low-volume roads. This thesis ends with a summary of findings found from the analyses, limitations of the study, and recommendations to improve the study.

CHAPTER TWO – LITERATURE REVIEW

Identification of different roadway and roadside features that contribute to crash risk requires study of previous literature to better understand the impacts of these features. Moreover, exploring the existing approaches seems to be necessary in order to develop a proactive tool to identify the risk factors. Therefore, previous studies and researches regarding these areas have been reviewed. This chapter reviews the previous safety studies based on three different realms:

i. Impacts of different roadway geometry and roadside features on crash occurrence,
ii. Development of a tool or framework that prioritize the sites according to the crash risks, and
iii. Investigation of safety countermeasures and their economic feasibility.

2.1. Studies Related to Safety Effects of Different Roadway Factors and Features

One study in Texas investigated the effects of roadside features on single vehicle crashes on rural two lane roads (*7*). Field data from four districts in Texas which included 245 miles of two-lane rural roads were sampled to collect shoulder width, side slope rating, driveway density, and lateral clearance for analysis using traffic data and six years of crash history. Two models were developed for analysis: a negative binomial model of crash frequency and a multinomial logit model of crash severity. Results showed that shoulder width, lateral clearance, and side slope condition had a significant effect on road departure crashes. Crash frequency and severity increased when lateral clearance or shoulder width decreased or when a steeper side slope was present.

Cenek et al. investigated the road geometry, road surface condition, carriageway characteristics, and crash data information to develop a statistical crash prediction model for application to rural New Zealand state highways (*8*). A total length of 13,670 lane-miles of roadway were used which included all paved roadways in New Zealand. Six years of crash data were used to perform the regression model analysis which showed that horizontal curvature and skid resistance had significant effects on crash rates.

A study was conducted by Schrum et al. in Kansas and Nebraska to identify the common fixed objects and geometric features that presented safety issues to drivers (*9*). The field study included 21 miles of low-volume roads of Marshall County in Kansas and 55 miles of low volume roads of Saunders and Butler counties in Nebraska. Features identified by this effort included culverts, bridges, driveways, trees, ditches, slopes, utility poles, and public broadcast service routing stations. Infrequent obstacles, including road and advertising signs, mailboxes, tree stumps, bushes, rock walls, boulders, and water bodies were also identified as presenting issues.

One study in Iowa was performed to examine the crashes that occurred on low volume roads and to identify the major contributing factors by descriptive statistics and crash modeling (*10*). Seven years of crash data (from 2001 to 2007) from rural low volume roads (≤ 400 AADT) of Iowa were used for this study. From the analysis, crashes on rolling and hilly terrain were found to be more frequent than on flat terrain and also crash frequency found to be higher during night. Fixed object crashes occurred at higher frequency on low volume roads compared to higher volume roads. Moreover, crashes occurred frequently on the location of bridges, railroad crossing, driveways, T intersections, and Y intersections.

Garber and Kassebaum conducted a study in Virginia to identify the contributing factors of crashes on two-lane highways (*11*). Four years of crash data (from 2001 to 2004) from 143 five-to-ten miles segments of roads were used in this study. In addition to the crash data, researchers compiled the speed data, traffic data, and other roadway features (e.g. grades, curvatures, crossing zones, passing zones). Fault-tree analysis and generalized linear models were used to identify crash causal factors. Run-off-road (ROR) crashes were found to be predominant type of crash and the significant causal factors for ROR crashes were horizontal curvature and traffic volume. Lane width, traffic volume, presence of turn lane were found to be causal factors for rear end crashes; and curvature, operating speed, grade were found as casual factors for head on crashes.

Gross et al. examined the safety effectiveness of lane and shoulder widths and how these two are inter-related for a given fixed pavement width on rural two-lane roads (*12*). Geometric and traffic data from more than 52,000 miles of roadway in Pennsylvania and Washington state and 5 years of crash data were used for this study. For wider pavement width the crash risks were found to be lower; similar results were obtained for wider lanes (while holding shoulder width constant) and for wider shoulders (while holding lane width constant). For a fixed pavement width, the trade-offs between lane and shoulder widths were not in favor of one versus the other.

Another study by Cafiso et al. investigated the safety of the low volume roads in Italy and developed a safety index for measuring the safety performance of road segments (*13*). From the analysis presence of access points located within horizontal curves, vertical crests, missing or misplaced delineation and worn pavement markings were found as risky factors. Lane width less than 9 feet and greater than 14.7 feet, shoulder width less than 1 foot and sight distance less than 165 feet were also cited as safety concerns.

One study by Prato et al. analyzed the risk factors associated with crash severity on low volume rural roads in Denmark (*14*). For this study roads with AADT < 2000 vpd were selected as low volume roads and 5 years of crash data (from 2007 to 2011) were used. From the analysis it was found that drivers in crashes were 30 percent, 50 percent and 60 percent more likely to sustain light, severe, and fatal injuries when the speed limit was above 80 km/h. Under adverse driving condition (e.g. on unpaved roads and slippery roads) the crash severity was found to be less. Unpaved roads were associated with a 14% decrease in fatalities, whereas slippery roads were associated with a 17% decrease in severe injuries. However, the poor visibility due to reduced sight distance were found to increase the fatalities by 20%.

The Australian transportation agency (Austroads) explored the relationships between crash risk and different geometry and roadside features (*15*). Researchers developed a crash risk ratio which were defined as the relative change in crash rate attributable to differences in geometric standards, intersection configuration or traffic conditions. It was found that total pavement width had a large effect on crash risk for rural two-lane roads, with 5.5 meter total pavement width being 2.7 times more likely to experience a crash than a 10 meter pavement width. Similarly, sight distance deficiencies increased the risk ratio to 1.4 when the deficiency was more than 40 percent of the design value. Also smaller radii curves, steeper vertical grades were found to have higher crash risks.

One study in Indiana investigated the safety effects of geometric and other roadway features of rural two-lane roads by analyzing the data and developing crash reduction factors (*16*). This study analyzed the data from the entire Indiana state-owned highway system as well as samples from county-owned roads and the traffic volume for these two lane roads varied from 200 vehicles per day to 23,300 vehicles per day with an average of 3,754 vehicles per day. Results showed that the longer road sections and traffic volumes were associated with higher number of crashes. The increasing lane width and shoulder width were found to decrease the frequency of crashes. For rural major collectors and minor arterials, roads with higher pavement friction were found to experience lower crash rates and for the principal arterials, roads with poor pavement condition experiences more crashes.

Findley et al. developed a spatial relationship between adjacent horizontal curves and horizontal curve safety using crash modification factors (*17*). This study evaluated data from two two-lane rural roads of North Carolina which contain 246 and 174 curves respectively. Five years of crash data (from 2005 to 2009) were studied which include 4,505 reported crashes. The results showed that the distance to adjacent curves was significant in estimating crashes, with curves more distant from one another having more predicted crashes.

Knapp and Robinson evaluated the speed impacts of dynamic curve warning signs on low volume roads of Minnesota (*18*). For this study roads with at least 100 vehicle per day were considered as low volume roads; three study sites from Meeker County and McLeod County in Minnesota were selected. As a part of this study researchers identified a critical radius for crashes at horizontal curves. It was found that higher fatal and injury crash rates (3.86 crashes per million vehicle-miles traveled) are associated with curves of a radius 800 feet or less.

Schneider, et al. examined the severity of crashes at horizontal and vertical curves on rural two lane roads (*19*). Five years of crash data (from 1997 to 2001) for rural two-lane roads in Texas were used for the analysis. The analysis showed that driver injuries were more likely to be severe on curves with a radius between 500 and 2,800 feet. The combination of horizontal and vertical curves increased the fatal crashes by 560 percent on curves with a radius of 500 to 2,800 ft.

2.2. Studies Related to Development of Crash Risk Index or Safety Index

Martinez et al. developed a crash risk index to identify the hazardous sections of the roadway (*20*). For this study six roads (total length of 215 km) from central Asturias, a region in Spain, were analyzed. The risk index was computed using the total number of injury crashes in a segment of a road over a five year period, as well as using traffic (AADT) and the length of the segment being examined as follow:

$$R = \frac{10^8 . U}{AADT . 365 . section\ length}$$

Where, R = Risk factor

U = Total number of injury crashes over 5 years

AADT = Annual Average Daily Traffic

Segments with risk were identified as those which met one of two criteria: $U \geq N$ or $R \geq P$. Where, $N = \text{Integer}(\mu + 2\sigma)$ where μ is the mean and σ the standard deviation of the maximum number of accidents for all sections with similar characteristics. And $P = \text{Integer}(\mu' + 2\sigma')$ where μ' is the mean and σ' the standard deviation of the risk index of all sections with similar characteristics.

One study in South Dakota developed a quantitative assessment method for local low-volume roads (<400 vehicles per day) safety by developing a rural road safety index (*21*). Safety issues present along 500 foot segments were identified and graded from 1 (needs treatment) to 4 (no treatment needed). The index was calculated by subtracting the sum of "deduct" points (the grading of a feature). The index ranked the road network according to the safety issues present along it and the lowest index value then became the top rated segment to address via countermeasures. This approach is quite attractive as the approach of assigning values to certain features can be adapted for use with existing databases.

Pardillo-Mayora et al. developed a roadside hazardous index for tow lane rural roads of Spain (*22*). For this study roadside data, traffic data and crash data from a sample of 1432 km of Spanish two lane rural roads were used. Four indicators were adopted to characterize the roadside features: side-slope, non-traversable obstacles offset from the roadway edge, safety barrier installation, and highway alignment. Cluster analyses were applied to group the combinations of these four indicators into categories with homogeneous effects on road departure crash frequency and severity. Based on this, a 5-level roadside hazardousness index was developed, which is summarized as follows:

- ✓ Index 1: 0 – 4.5 fatalities/100 departure crashes and 0 – 31.9 severe injuries/100 departure crashes.
- ✓ Index 2: 4.6 – 5.4 fatalities/100 departure crashes and 32.0 – 34.3 severe injuries/100 departure crashes.
- ✓ Index 3: 5.5 – 5.7 fatalities/100 departure crashes and 34.5 – 37.2 severe injuries/100 departure crashes.
- ✓ Index 4: 5.8 – 6.8 fatalities/100 departure crashes and 37.3 – 37.9 severe injuries/100 departure crashes.
- ✓ Index 5: 6.9 – 12.9+ fatalities/100 departure crashes and 38.0 – 40.2+ severe injuries/100 departure crashes.

Cafiso et al. investigated the safety of the low volume roads in Italy and developed a safety index for measuring the safety performance of road segments (*13*). A safety index was developed that combined an exposure factor, an accident frequency factor and an accident severity factor. Exposure was calculated as the length of a segment times AADT. The accident frequency factor was the road safety index value times the geometric design accident frequency factor; both of these values were established by safety experts. The accident severity factor was a function of the 85th percentile speed divided by base operating speed for the segment times a roadside severity factor. When all calculations were combined, the result was the severity index. This index was then sorted in descending order to rank segments from worst to best.

Waiby, et al. discussed the development of a proactive road safety assessment tool in New Zealand (*23*). Historical traffic and crash data were used to produce color coded maps of the level of personal and collective risk on a road segment. Star ratings were then assigned to segments based on an assessment of the road's engineering for safety.

One study at Brazil developed a proactive method for evaluating the safety of rural two lane roads by estimating a potential safety index (*24*). This method assigned weights and scores to 34 road features based on field inspections. The approach developed consisted of the following steps:

- ✓ Identify the features impacting safety.
- ✓ Select features that compose the Potential Safety index (PSI).
- ✓ Estimate the weights of the selected PSI features. Estimation of the PSI weights was made by considering Brazilian experience and through use of the knowledge of a panel of road safety professionals.
- ✓ Calculate the PSI for 1 km road sections (also incorporating a safety score from field inspections).

Montella discussed the safety assessment methodology for the existing roads in Italy (*25*). For the purpose of this study the researcher developed a safety improvement index (PFI). The PFI was a function of exposure, estimated increase in injury crashes due to an issue and the proportion of crashes affected by the issue. The PFI was calculated by multiplying the AADT for a segment (raised to an exponent of AADT from an accident prediction model) times the sum of relative risk values for features along the segment. A higher PFI value indicated a greater opportunity to make safety improvements.

Another study in Italy discussed the procedure for ranking unsignalized rural intersections to implement the safety improvements (*26*). The researchers developed a safety index that could be used with or without crash data and the index itself consisted of the exposure of road users to hazards and the probability of being involved in a crash. Exposure was determined by multiplying the major and minor leg AADT's (vehicles per day/1,000). Crash probability was determined by summing different safety scores for features (developed by experts with experience in road safety engineering and consisting of a score from 0 (no problems) to 1 (high level problem) multiplied by an estimated change in crash risk (again developed by experts). The result of these two figures when multiplied together was a safety index value which, when arranged in descending order, provided a ranking of sites from worst to best.

Evans, et al. in discussing the implementation of Wyoming's rural road safety program, touched upon how high risk rural locations were identified (*27*). This identification process consisted of five steps:

- ✓ Crash data analysis: Crash data from a 19 year period were used to identify road segments with a proportionally higher number of crashes during the time period compared to other segments.
- ✓ Level I field evaluation: Based on these identified segments, a field evaluation was performed to assign an initial rating score from 0 (worst) to 10 (best).
- ✓ Combined ranking to identify potential high risk locations: This score was combined with the initial ranking from the crash data analysis to identify the prioritized list of high risk locations.

- ✓ Level II field evaluation: These locations received a Level II field evaluation to identify safety improvement alternatives.
- ✓ Benefit/cost analysis: A benefit/cost analysis was performed to evaluate the potential countermeasures selected to address safety and identify those that would most effectively reduce crashes at the lowest cost.

deLeur and Sayed developed a road safety risk index in Canada using a four step approach (*28*). These steps are:

- ✓ Identification of the factors to be considered in the index.
- ✓ Formulation of the guidelines for the index; which include the consideration of exposure, probability and consequence.
- ✓ Development of the procedures to obtain the risk index values, including quantifying the components of risk.
- ✓ Calculation of risk index by multiplying the risk exposure, probability and consequence scores together. The exposure score was a function of traffic volumes on a corridor and at the point of a feature. The probability score was produced by assigning a score for each feature being evaluated on the segment from 0 to 3 (3 representing a high crash probability). And the consequence score was a function of speed limits at the point of concern and on the overall segment being evaluated.

A systemic approach was discussed by Isebrands to improve the rural road safety (*29*). The approach presented has been employed by Minnesota counties, which consists of four steps. First, targeted crash types and risk factors were identified by examining statewide (or countywide) trends. The second step screened and prioritized candidate locations by identifying those where the targeted crash types and risk factors were present on the network. The Minnesota approach assigned a star to the segment or site when certain conditions that met the criteria of concern were present. The greater the number of stars assigned, the more at risk the segment or site was. Following these two primary steps, the remaining steps involved selection of low cost countermeasures and prioritizing projects. Prioritization required a decision-making process to determine which countermeasures and projects should be pursued.

2.3. Studies Related to Investigation of Safety Countermeasures

Potts et al. conducted research for the Missouri Department of Transportation to evaluate the safety effectiveness of the Smooth Roads Initiative or SRI (*30*). The evaluation of SRI was conducted using crash data for three years before (from 2002 to 2004) and three years after (from 2007 to 2009) the implementation of SRI improvements. The improvements included in the program are: wider & high visibility lane lines, wider edge lines with rumble strips, centerline rumble strips, barrier-mounted delineators and emergency reference marker signs. The striping and delineation program resulted in an overall reduction of 16 percent in fatal and disabling injury crashes and 11 percent in fatal and all injury crashes. This program resulted a reduction of 12 to 76 percent in daytime fatal and all injury crashes and 23 to 56 percent in nighttime fatal and disabling injury crashes. The SRI program provided an overall benefit-cost ratio of 11.2.

Mclnerney and Smith investigated the safety effectiveness of different countermeasures at the road network in Malaysia as a part of the International Road

Assessment Program (*31*). The study assessed the crash risk of different roads and assigned star ratings based on safety performance. For benefit-cost analysis, the researchers estimated the reduction in the number of fatalities and total serious injuries as a result of implementing a certain countermeasure and then calculated the annual benefit by using a factor and Gross Domestic Product per capita. Then the benefit-cost ratio (B/C) was calculated by comparing the economic costs and benefits. The B/C for pedestrian crossing, shoulder widening, traffic calming, regulate roadside commercial activity, and roadside safety- hazard removal were found to be 19, 12, 26, 13, and 7 respectively.

A study by Meuleners et al. investigated the safety effectiveness of sealed shoulder and audible edge line (shoulder rumble strip) in Western Australia (*32*). For this study Albany Highway was selected as treatment site, which is located in the south-west of Western Australia and 410 km in length. 5 years of crash data before the treatment and after the treatment for 13 sites on Albany Highway were used for analysis. Two types of costs were used for economic analysis: the treatment costs and the resulting cost savings from reduction in road crashes. The treatment was reported to reduce all-severity crashes by 58 percent and casualty crashes by 80 percent. The benefit-cost ratio of the treatment was found to be 40.3 for all selected sites.

Srinivasan et al. investigated the safety effectiveness of improved curve delineations for two states: Washington and Connecticut (*33*). Geometric, traffic, and crash data were obtained from 89 treated curves in Connecticut and 139 treated curves in Washington for the study and all of the curves were on two-lane rural roads. The improved curve delineation varied by site, but included individual treatments or combinations of chevrons, horizontal arrows, advanced warning signs, post mounted delineators, and new fluorescent sheeting. The study reported an 18 percent reduction in injury & fatal crashes, 27.5 percent reduction in dark conditions crashes, and 25.4 percent reduction in dark condition lane departure crashes. The reductions were found to be more prominent at locations with higher traffic volumes, sharper curves and more roadside hazards. The study also reported a benefit-cost ratio of 8:1 for improving curve delineation.

One study by FHWA investigated the safety evaluation of the safety edge treatment (*34*). Three types of roadway segments were analyzed from three participating states: Georgia, Indiana, and New York. The selected roadway segments were: rural multilane roadways with paved shoulder of width ≤ 4 ft., rural two-lane roadways with paved shoulder of width ≤ 4 ft., and rural two-lane roadway with no paved shoulder. The study found that for two-lane highways with paved shoulder, the application of safety edge treatment had minimum benefit-cost ratio which varied between 3.8 and 43.6 for Georgia and between 3.9 and 30.6 for Indiana. For two-lane highways with unpaved shoulder, the benefit-cost ratio ranged from 3.7 to 62.8 for Georgia and from 2.8 to 12.8 for Indiana.

A study by Neuman et al. investigated the safety effectiveness of raised pavement markers in 184 high accident locations including narrow bridges, curves, and intersection approaches (*35*). The evaluation of raised pavement marker was conducted using crash data for one year before and one year after the implementation. The results indicated a total 9 percent reduction in all crashes and 15 percent reduction in injury crashes. The benefit-cost ratio of the raised pavement marker was found to be 6.5:1.

Another study investigated the safety evaluation of centerline and shoulder rumble strips as a part of FHWA evaluation of low-cost safety improvements (*36*). Two-lane rural roads from three states were selected for this study: Kentucky, Missouri, and Pennsylvania. An Empirical Bayes (EB) before-after analysis was conducted to account for potential selection bias and regression to the mean. The Crash Modification Factor (CMF) for head-on crashes, run-off-road crashes, and sideswipe-opposite-direction crashes were found 0.632, 0.742 and 0.767 respectively. The combined CMF for these three types of crash was found 0.733. For all types of crashes, the combined CMFs were found 0.80 and 0.771 for all severities and for fatal + injury respectively. Benefit-to-cost ratio for all types of crashes varied between 28.2 and 67.7 depending on the treatment cost and service life assumptions.

One study conducted by Ayala and Turochy investigate the economic feasibility of paved shoulder installation on high-priority segments of two-lane rural highways in Alabama (*37*). An analysis of expected benefits and actual improvement costs was performed to derive the benefit-cost ratio. For this research high priority segments were identified based on two criteria: crash rate and severity. The economic benefits associated with the installation of paved shoulders at these locations were calculated based on a range of crash reduction factors. The study reported benefit-cost ratios ranging from 0.09:1 to 2.39:1 for the segments identified based on crash rate and from 1.32:1 to 8.90:1 for the segments identified based on severity.

CHAPTER THREE – STUDY DESIGN

This chapter illustrates the selection of low-volume roads and description of the study sample that are used for the study. Also the procedures and methods used for data collection are discussed in this chapter.

3.1. Selection of Low Volume Roads

As discussed in chapter one, the low volume roads are defined differently by different highway agencies according to their purpose of study. The AADT that are typically selected for defining the low volume roads varies from 400 vpd or less to 1000 vpd or less. For the purpose of this study, low volume roads are defined as those rural roads with AADT of 1000 vpd or less. These roads usually consist of "secondary" two-lane highways serving less developed rural areas and are generally classified as class II two-lane highways per the Highway Capacity Manual (HCM) classification.

3.2. Study Sample

For the purpose of the study, low volume roads from the rural parts of Oregon were selected as the study sample. The state-owned low volume roads were used for the analysis as the required data were available for these routes, and were not as readily available for roads at the county level.

Low volume road characteristics in Oregon differ by location. In this regard, roads in the western region are completely different from those in the eastern region due to their geographical locations. The Western region consists of rainier and mountainous terrain with hilly and winding roads, whereas the Eastern region has drier (desert), flatter and straighter roads. Therefore, the road sample was selected from these two distinct parts of Oregon. All state owned roads with AADT less than or equal to 1,000 vpd were queried using online GIS data, and then random selections were made from that query to arrive at approximately 800 miles of total road sample.

The selected sample is comprised of a total of 831.75 miles of road (435.55 miles western, 396.20 miles eastern). Figure 3.1 shows the low volume road sample.

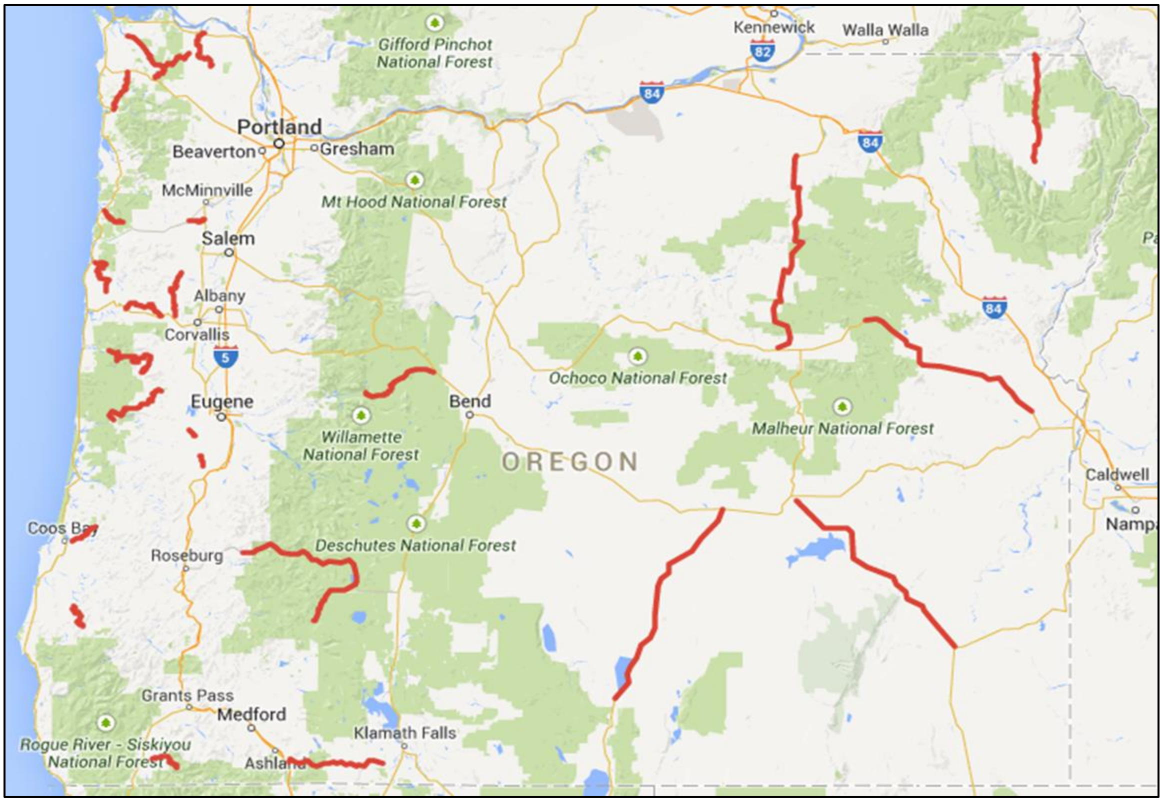

Figure 3.1. Selected study sample (Source: Google maps)

A total of twenty-eight Oregon state-owned highways comprised the selected 831.75 miles of road. The details about these highways are shown in Table 3.1.

Table 3.1. Highways included in the study sample

Segment No.	HWY No.	Begin MP	End MP	Length (mile)
1	102	9.50	41.70	32.20
2	103	0.00	7.60	7.60
3	046	0.05	18.00	17.95
4	130	0.00	9.25	9.25
5	181	1.00	22.95	21.95
6	180	0.00	19.15	19.15
7	027	11.10	38.60	27.50
8	229	0.05	31.35	31.30
9	200	25.40	32.05	6.65
10	200	37.90	42.05	4.15
11	015	56.10	91.25	35.15
12	138	27.20	83.05	55.85
13	233	0.05	23.75	23.70
14	241	3.90	19.10	15.20
15	242	2.50	17.80	15.30
17	110	0.50	11.85	11.35
18	102	46.20	54.20	8.00
19	153	0.00	5.80	5.80
20	191	10.95	30.65	19.70
21	201	0.00	9.45	9.45
22	038	3.75	19.30	15.55
23	021	6.50	49.30	42.80
24	028	23.70	120.10	96.40
25	005	191.30	270.50	79.20
26	049	0.05	90.00	89.95
27	442	3.70	91.55	87.85
28	011	0.00	42.80	42.80

From the selected sample, a subsample of 680.85 miles (323.7 miles western, 357.15 miles eastern) was used in the road segment analysis. The subsample was compiled by removing intersection areas from the original sample as intersection specific crash risk considerations should involve different characteristics. Intersection areas were considered to be the 0.05-mile segment which contained the intersection and two 0.05 mile segments, one from each side of the intersection-containing segment. The selected subsection comprised all 55 mph posted speed limit road segments.

3.3. Data Collection & Methods

Roadway data of the selected sample size were collected by using the Oregon Department of Transportation (ODOT) online databases and video logs system. Characteristics of roadway geometrics & roadside features were compiled for the sample with 0.05-mile resolution. The 0.05-mile resolution was selected because that increment allowed for video log data to be comprehensive without missing characteristics of interest between video log images. The roadway geometrics and roadside features for which data were collected are shown in Table 3.2.

Table 3.2. Roadway geometrics and roadside features

- Lane type & width
- Shoulder type & width
- Percent grade
- Driveway density
- Side slope rating
- Fixed object near the roadway
- Guardrail presence
- Horizontal curve presence
- Degree of curvature
- Length of horizontal curve
- Spiral curve presence
- Vertical curve presence & type
- Length of vertical curve

The most recently available ten years of crash data (from 2004 to 2013) were gathered from the ODOT online databases for the sample. The crash data was consisted of only police reported crashes, as the data were gathered from ODOT online database. The same 10 years of AADT data were also collected. The information for each crash as shown in Table 3.3 were collected and combined with the geometric data for analysis. Therefore, the final database includes all road and crash characteristics for the sample of 831.75 miles, which results in a total of 16,635 records, each representing a 0.05-mile sub-segment.

Table 3.3. Information collected for each crash

- Crash type
- Crash location
- Road character of the crash location
- Collision type
- Crash severity
- Traffic control
- Impact location of crash
- Weather condition during crash
- Road surface condition during crash
- Lighting condition during crash
- Vehicle type involvement
- Driver age involvement

Most of the road characteristics (e.g. lane width & type, shoulder width & type, horizontal & vertical curve data, grade) collected from the ODOT online databases were readily used for analysis. Other road characteristics for example, driveway density, side slopes, amount of fixed objects present in the clear zone and guardrail presence were recorded manually while reviewing video log images at 0.05 mile increments. The ratings of side slope and fixed object were subjective, which required assigning values from video log images. The side slope ratings and fixed object ratings were characterized as shown in Table 3.4. These two ratings were assigned for each side of the roadway and then averaged for using in the analysis.

Table 3.4. Characterization of side slope rating and fixed object rating

	Rating	**Characteristics**
Side Slope	1	Flat side slope
	2	Moderate side slope
	3	Steep side slope
Fixed Object	1	Few fixed objects in clear zone
	2	Some fixed objects in clear zone
	3	Many fixed objects in clear zone

CHAPTER FOUR – SAFETY EFFECTS OF ROADWAY GEOMETRY & ROADSIDE FEATURES

This chapter identifies the safety effects of different roadway geometrics and roadside features. In order to identify the safety effects, it seems necessary to understand the overall characteristics of these features and overall crash characteristics, which can be explained by the descriptive statistics of the road sample and crash data. Afterwards, the relationships between individual road characteristics and crashes were established using crash rates, and finally, multivariate regression and correlation analyses were conducted to better understand the relationships.

For this study, crash rate was calculated by normalizing the segment length (0.05 miles) and traffic volume. Crashes per million vehicles miles traveled (Crash/MVMT) was considered as crash rate. The equations for vehicles miles traveled (VMT) and crash rate are:

$$VMT = AADT * Number\ of\ years\ (= 10) * Days\ in\ a\ year (= 365) * Segment\ length\ (= 0.05\ miles) \quad \text{(Equation 4.1)}$$

$$Crash\ Rate = \frac{Number\ of\ Crashes}{\left(\frac{VMT}{1000000}\right)} \quad \text{(Equation 4.2)}$$

Where, AADT = Annual Average Daily Traffic. As 10 years of crash data were used in this study, the AADT is multiplied by 10 (number of years) and 365 (number of days in a year) to represent the total ten years' traffic in the study site; which is again multiplied by segment length (0.05 miles) to get the vehicle miles traveled (VMT). Crash rate is simply calculated by dividing the number of crashes occurred in each segment by the VMT of that segment. VMT was divided by 1,000,000 to get the desired crash/MVMT.

4.1. Characteristics of Roadway Geometry and Roadside Features

All roads of the selected sub-section of 680.85 miles were paved roadways, and more than 99% of roads consisted of asphalt pavement. The lane widths of the sample varied from 9 ft. to more than 12 ft. and the shoulder widths varied from 0 ft. to more than 7 ft. The proportions of lane widths and shoulder widths for the sample are shown in Figure 4.1. The majority of the road sample included 12 ft. or wider lanes (64%), whereas 20% of the sample had no shoulders. From further analysis of shoulder types, 69% of the shoulders were found to be paved, and the rest 11% were found to have gravel shoulders.

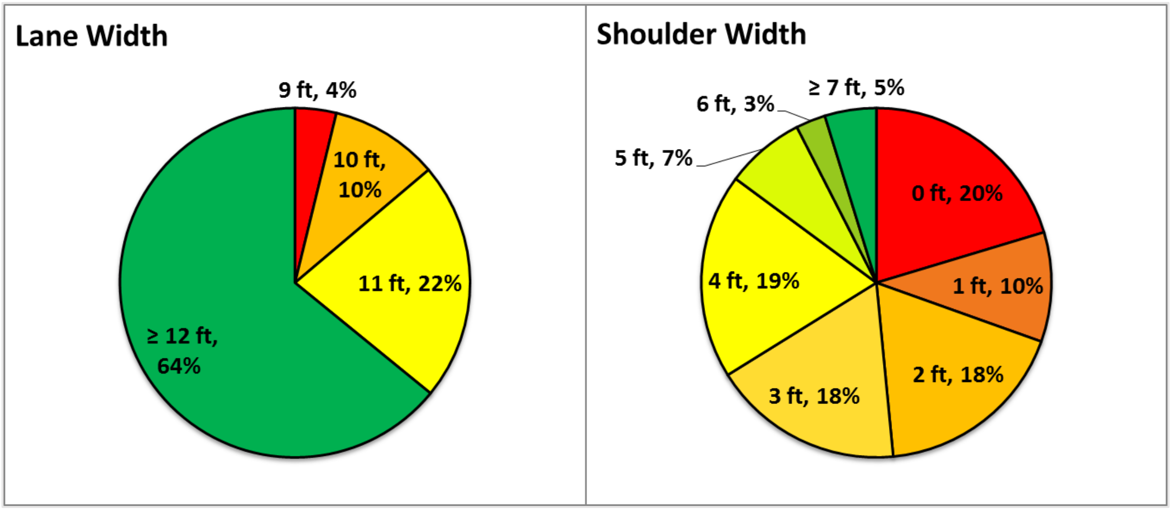

Figure 4.1. Proportion of lane widths & shoulder widths

Horizontal curves were found to present in 142.05 miles of the roadways and vertical curves were present in the 169.25 miles of the roadways. The lengths of horizontal curves and vertical curves varied significantly throughout the sample. Curve lengths of 101 to 200 ft. were found to be more common for both horizontal and vertical curves, as shown in Figure 4.2.

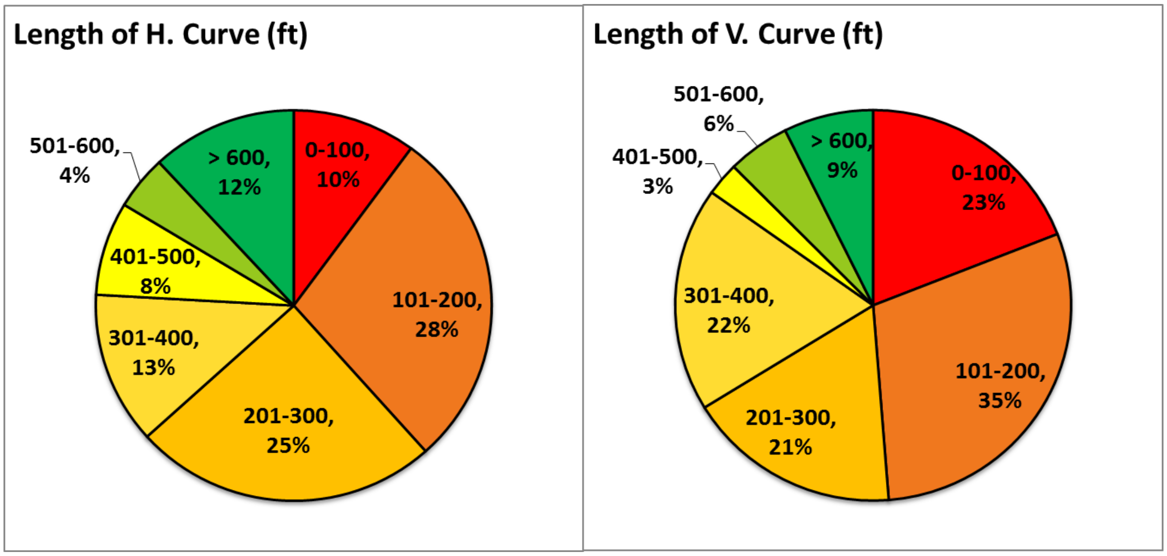

Figure 4.2. Proportion of length of horizontal and vertical curves

The degree of curvature of for horizontal curves throughout the sample varied significantly. Almost half (47%) of the horizontal curves were found to feature a curvature between 0.1 to 9.99 degrees, as shown in Figure 4.3. Curves in the western region were found more numerous and typically much sharper than those in the eastern region, as evidenced by the larger number and greater proportions of Western curves in the higher degree of curvature categories. This might be the result due to the Western region being more mountainous and hilly in its topography.

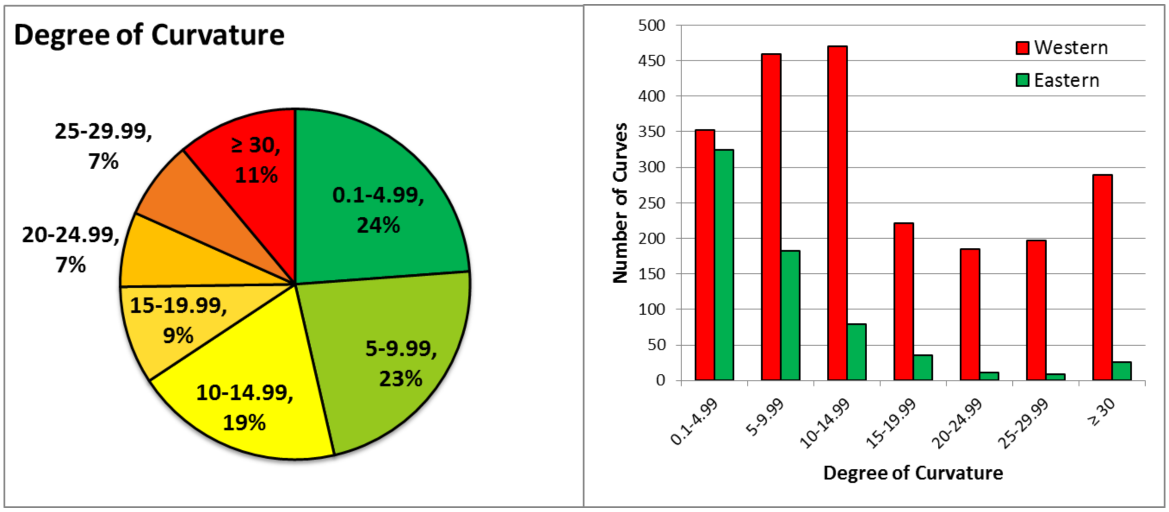

Figure 4.3. Degree of curvature characteristics

The distribution of the grade categories for the roadway sample is shown in Figure 4.4. Most (34%) of the sample had a grade of less than 1 percent. Steeper grades (≥ 5 percent) were present in the 16% of the roadway sample. Similar to the degree of curvature, the geographic differences between the Western region and Eastern region were evident from the grade percent. Western region was found to have more miles of road with grades steeper than 5%, while most of the Eastern segments were on grades less than 1%.

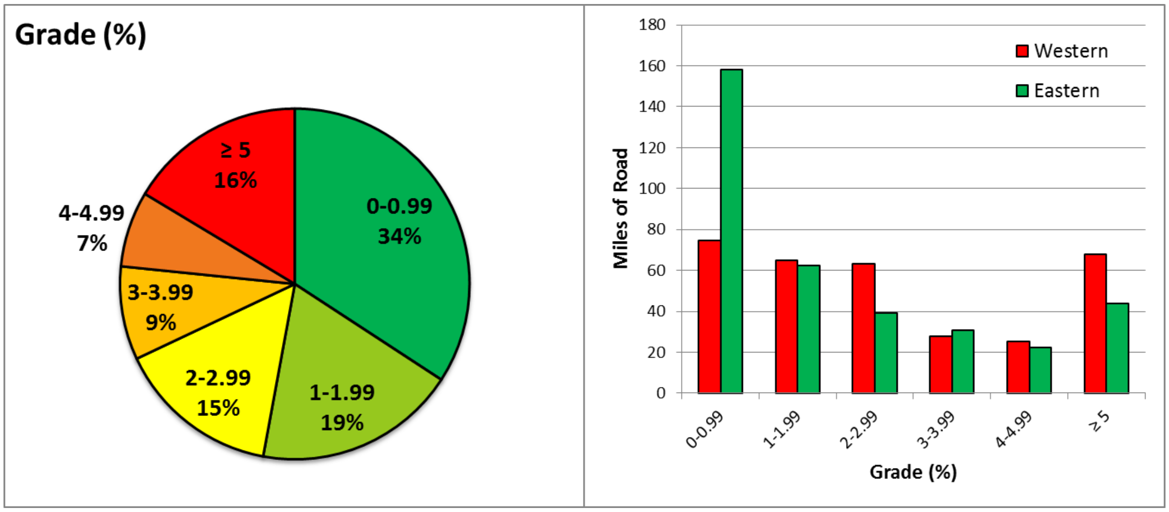

Figure 4.4. Vertical grade characteristics

Proportions of fixed object ratings and side slope ratings are shown in Figure 4.5. The most common fixed objects in the clear zone rating was ‘few’ which comprised 67% of the total sample. The highest amount of fixed objects in the clear zone rating only comprised 2% of the total population. Similarly, very few roadway sections were found to fall into the steepest side slope category, with most represented in the moderate and flat side slope categories.

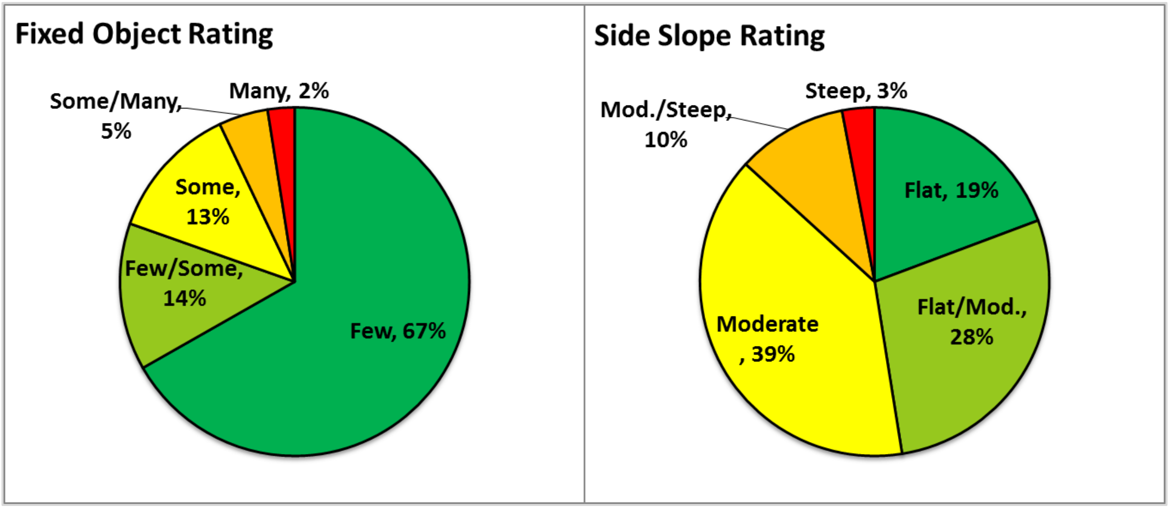

Figure 4.5. Proportion of fixed object ratings and side slope ratings

AADT categories from <200 vpd up to 900-1000 vpd, using increments of 100 vpd are shown in Figure 4.6, along with the driveway density categories. 65% of the roadway sample had daily volume of less than 500 vpd. Driveway densities throughout the sample were almost evenly distributed from 0 to ≥7 driveways per mile, with around 60% of the sample were having 2 driveways per mile or less.

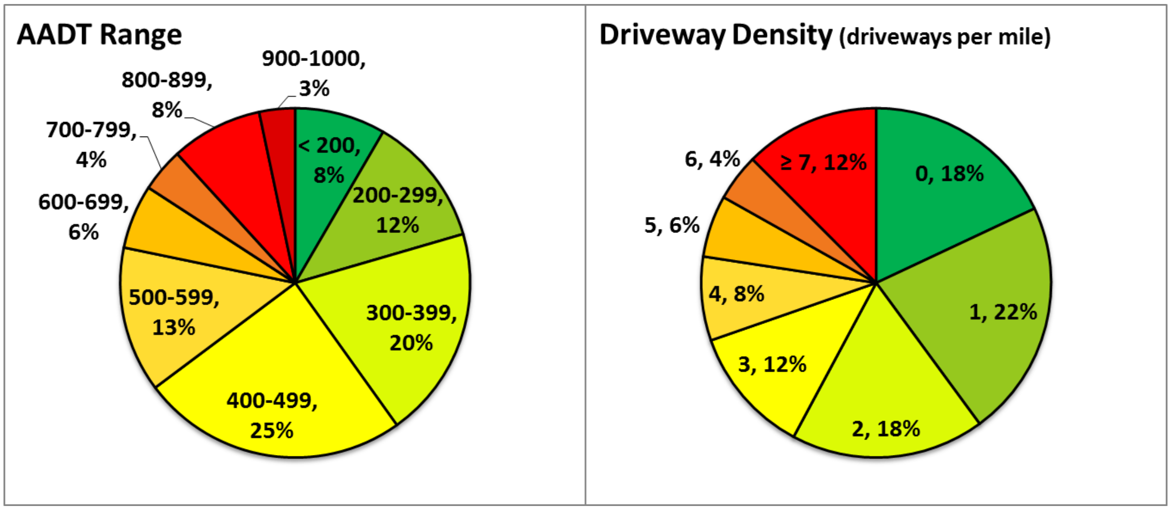

Figure 4.6. Proportion of AADT and driveway density categories

4.2. Crash Characteristics

A total of 1251 reported crashes occurred over the ten-year period on the selected roadway sample. Table 4.1 shows the crash rates per 100 million vehicle miles traveled (VMT) and crash rates per 100 miles, by crash severity (Property Damage Only – PDO, injury and fatal) for the study sample. 45% of all crashes were PDO crashes, 15% were injury C (possible injury), 28% were injury B (non-incapacitating injury), 9% were injury A (incapacitating injury), and 3% were fatal crashes.

Table 4.1. Crash rates by crash type for the study sample

Crash severity	**Total VMT**	**No. of crashes**	**Crash rate (per 100 million VMT)**	**Total length (mile)**	**Crash rate (per 100 mile)**
PDO	1.182 Billion	550	46.51	680.85	80.78
Injury	1.182 Billion	665	56.23	680.85	97.67
Fatal	1.182 Billion	36	3.04	680.85	5.29

Figure 4.7 shows the proportion of different types of crashes and the proportion of vehicle involvement in crashes. Most of the crashes (55%) were found to occur due to vehicles striking a fixed object; and 14% of the total crashes were rollover crashes. Therefore, 69% of the crashes were run-off-the-road crashes. The majority of the crashes (78%) were found to involve passenger cars. Motorcycles and large trucks were involved in 11% and 10% of the crashes, respectively.

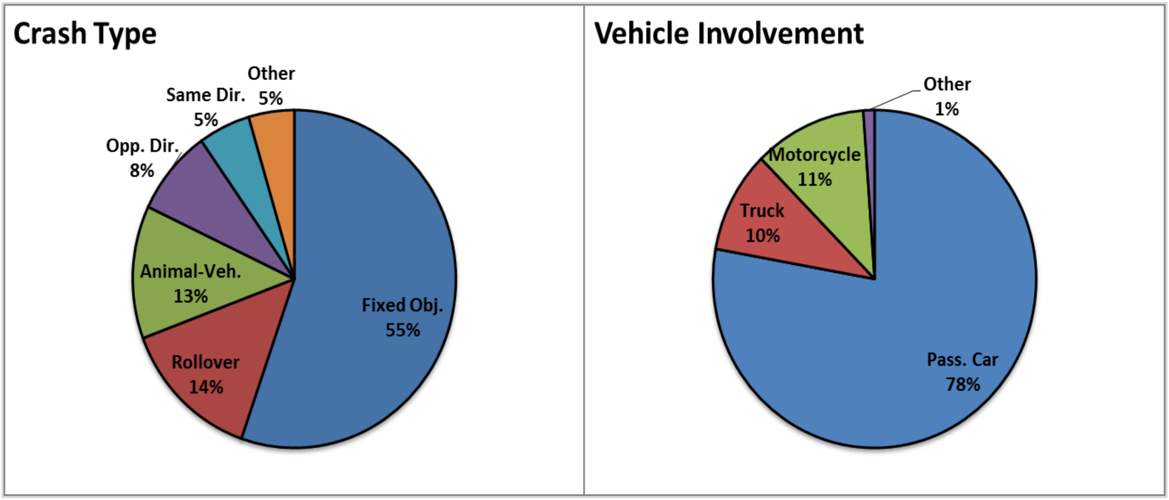

Figure 4.7. Proportion of crash type and vehicle involvement

To analyze the effect of drivers' age on the crash pattern, the age groups of drivers were divided into three categories: young drivers (age < 20 years), middle aged drivers (age between 20 and 64 years) and old drivers (age ≥ 65 years). The young drivers were involved in 13% of the crashes and the old drivers were involved in 15% of the crashes. Middle aged drivers were involved in the remaining 72% of the crashes.

Proportions of the crashes according to the distance from home are illustrated in Figure 4.8. 42% of the crashes involved a driver who was an Oregon resident and within 25 miles of home. Out-of-state drivers were involved in 20% of the crashes. The crash pattern by days of the week, as illustrated in Figure 4.8, shows that crashes were found to occur most often on weekends (Saturdays and Sundays), compared to the weekdays.

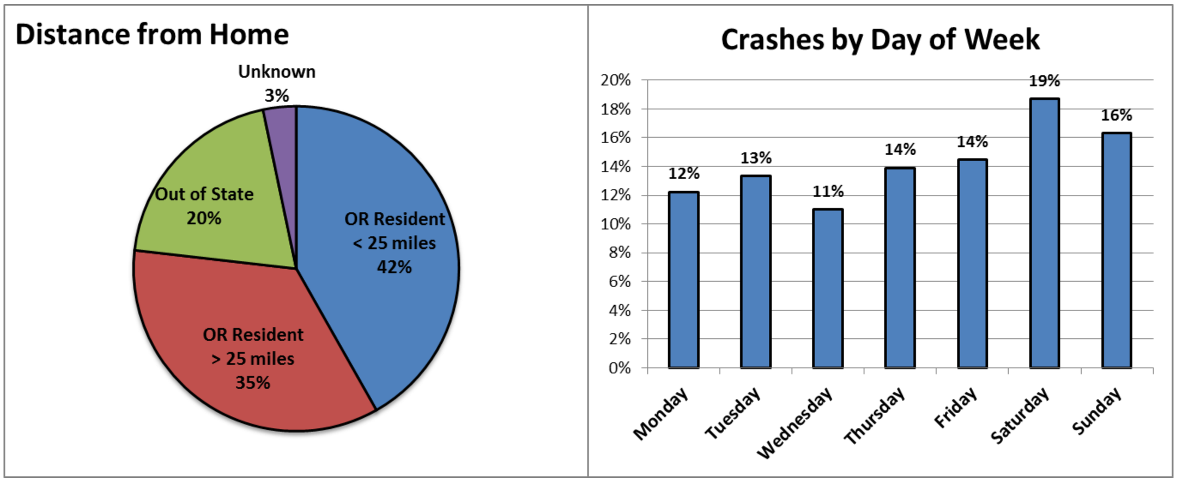

Figure 4.8. Crash pattern by distance from home and days of the week

Western Oregon roads were found to experience higher traffic volumes and a higher crash rate than the Eastern Oregon, which was expected due to the presence of more mountainous terrain in the Western part. Table 4.2 also shows that the crash rates (crashes/mile/year and crashes/MVMT) comparison for Western and Eastern region.

Table 4.2. Comparison of crashes by region

	Western Region	**Eastern Region**	**Total Sample**
Length (miles)	323.7	357.15	680.85
Crashes	844	407	1251
Average AADT (vpd)	580	382	476
Crashes/mile/year	0.26	0.11	0.18
Crashes/MVMT	1.23	0.82	1.059

4.3. Relationship of Crash Occurrence and Roadways Features

Different roadway geometrics and roadside features were examined individually to assess the potential effects of these features on crash occurrence. This section analyzes the relationship of each individual feature to the crash rate.

4.3.1. Lane Width

Figure 4.9 shows the crash rate (crash/MVMT) for each lane width category. Crash rates were observed to increase as the lane width narrowed. The exception was found for lanes with 9 ft. width, but the sample size for 9 ft. lane width was small (<5%), and therefore, the crash rate associated with this category may be less reliable (a shaded bar is used to represent the categories with small sample size). The fact that 9-ft lanes experienced lower crash rates than 10 ft. and 11 ft. lanes may evidence that some unseen factor(s) on 9 ft. lanes (e.g. drivers choosing lower speeds on these narrow lanes) were affecting the crash rates. Lowest crash rate was found to occur on the segments with 12 ft. or wider lanes, and highest crash rate was found to occur on the segments with 10 ft. lanes.

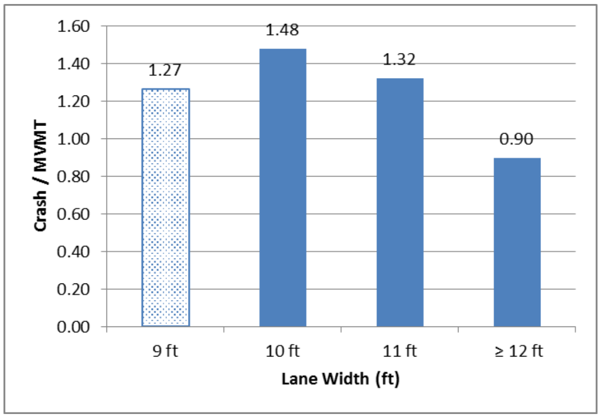

Figure 4.9. Crash rate by lane width

The characteristics of crashes also varied by the lane width category, as shown in Figure 4.10, which shows the proportion of each crash characteristic (severity of crashes, crash location, crash type, and vehicle involvement in crashes) occurring by lane width categories. The crash severity relationships did not exhibit significant differences over the lane width categories. Lane width categories of 10 ft. or greater experienced 64% to 70% off- roadway crashes; while for lanes with a width of 9 ft., this proportion decreased to 50%. Fixed object crashes were the most common type of crashes and lane width category of 10 ft. experienced the highest fixed object crash rate. Opposite direction crashes occurred more often on 9 ft. lanes and decreased with the increasing lane width. This trend may be attributed to the closer proximity that opposing vehicles must travel to one another on segments with a lower design standard. Similar observations were made for the same direction crashes. Vehicle involvement in crashes varied significantly by lane width categories. 46 % of the crashes on 9 ft. wide lanes were found to involve passenger cars, while these involvement rates for other lane width categories were found to be 78% to 80%. Motorcycles involvement rate was found to be much higher for 9 ft. wide lanes.

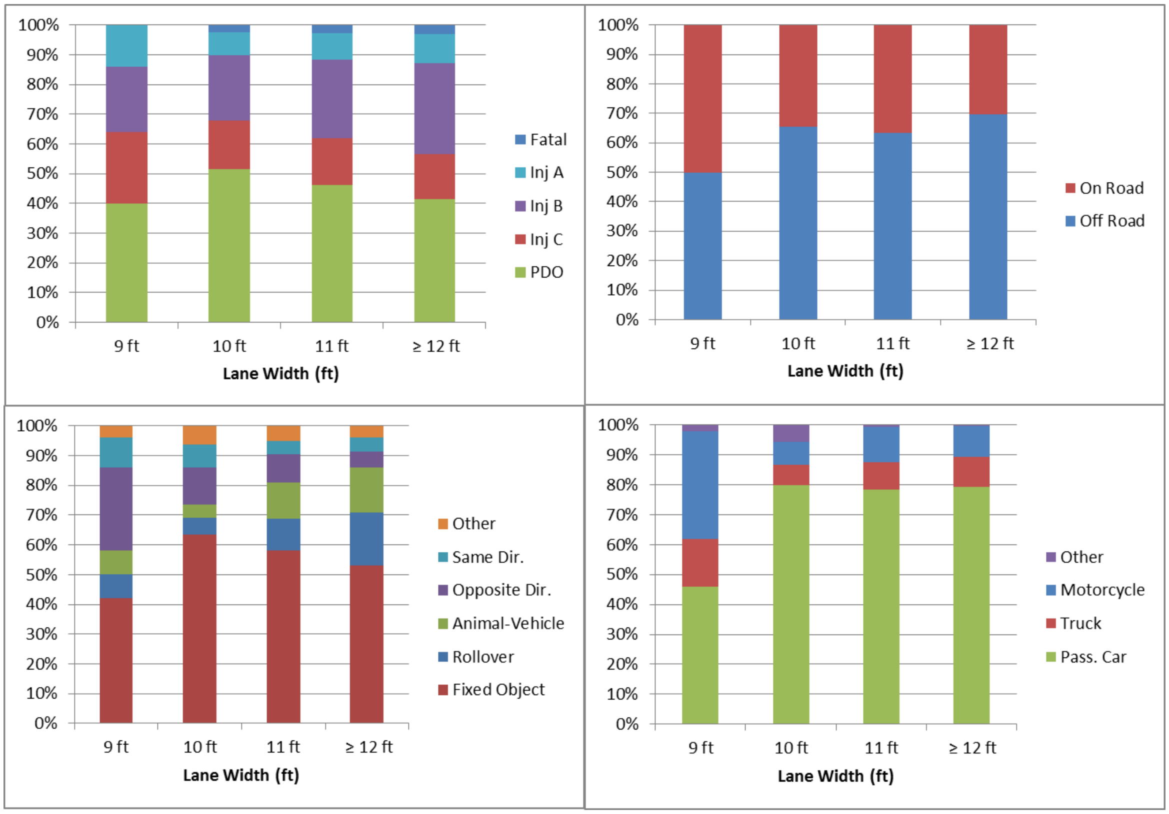

Figure 4.10. Crash characteristics by lane width

4.3.2. Shoulder Width

The left and right shoulders were equal in width for 90% of the sample; for the unequal shoulders, the average shoulder width was used for categorizing. Crash rates were found to vary significantly by shoulder width, as shown in Figure 4.11. No shoulder and narrow shoulders experienced higher crash rates than the shoulders with widths up to 5 ft. Shoulders of 6 feet and wider had higher crash rates compared to 4-ft. and 5-ft. shoulders, which again could be evidenced of unseen factors (e.g. drivers choosing higher speeds on these wide total pavement widths). Moreover, the sample size for 6 ft. and 7 ft. or wide shoulder were very small (≤ 5%), and therefore, the crash rates associated with these categories may be less reliable (represented by shaded bar).

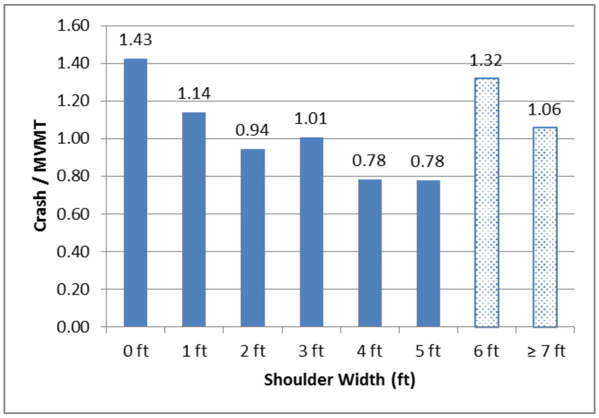

Figure 4.11. Crash Rate by shoulder width

Variation of different crash characteristics by shoulder width categories are shown in Figure 4.12. Crash severity exhibited large differences across the shoulder width categories. Roads with 5 ft. shoulders experienced 31% PDO crashes, while the other shoulder width categories experienced 42% to 55% PDO crashes. Off-road crashes were found to be most common on 6 ft. shoulders and least common on 3 ft. shoulders. The variation of crash types by shoulder width did not follow a predictable pattern. The type of vehicles involved in crashes also varied by shoulder width but in no predictable manner. Truck-involved crashes were found most common on roads with shoulders of 7 or more ft. and least common on roads with 2 ft. shoulders.

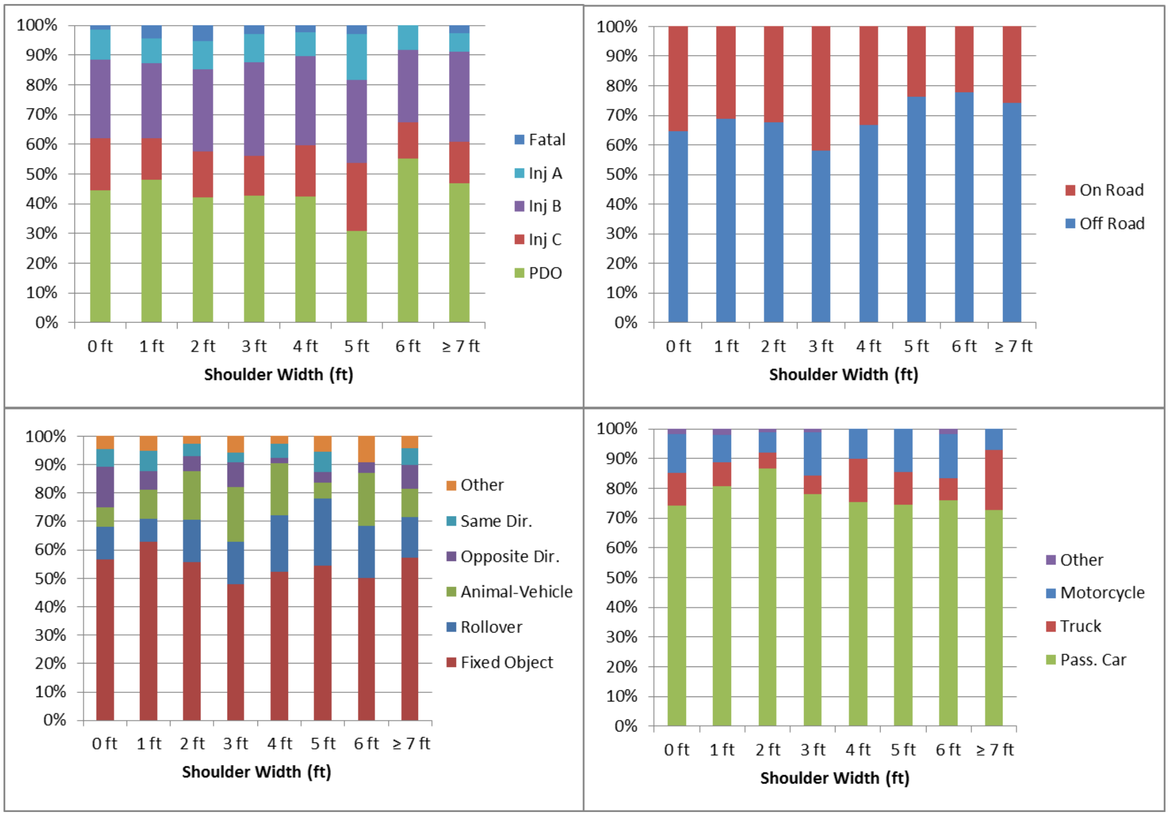

Figure 4.12. Crash characteristics by shoulder width

4.3.3. Grade

The percent grade of the roadway was found to have a significant impact on crash rates. Figure 4.13 illustrates crash rates for different roadway grades. Flatter roadways were associated with lower crash rates and steeper grades were associated with higher crash rates. A significant increase in crash rate was observed for roadways with 4% grade or more. The variation of crash characteristics by different percent grades are shown in Figure 4.14. The crash severity relationships and crash location pattern were observed to vary by percent grade of the roadway but did not follow a predictable pattern. Opposite direction crashes were found to vary in an increasing pattern with the increase of grade. Similarly, the motorcycle and truck involved crashes increased significantly with the increase in grade. This may be partly due to decreased stopping ability on downgrades, as well as large speed differentials between trucks and smaller vehicles on upgrades.

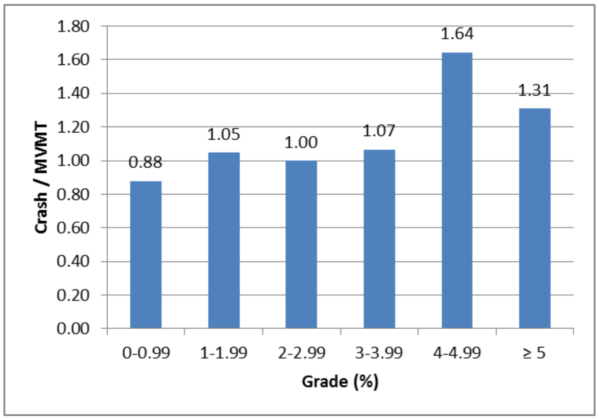

Figure 4.13. Crash rate by percent grade

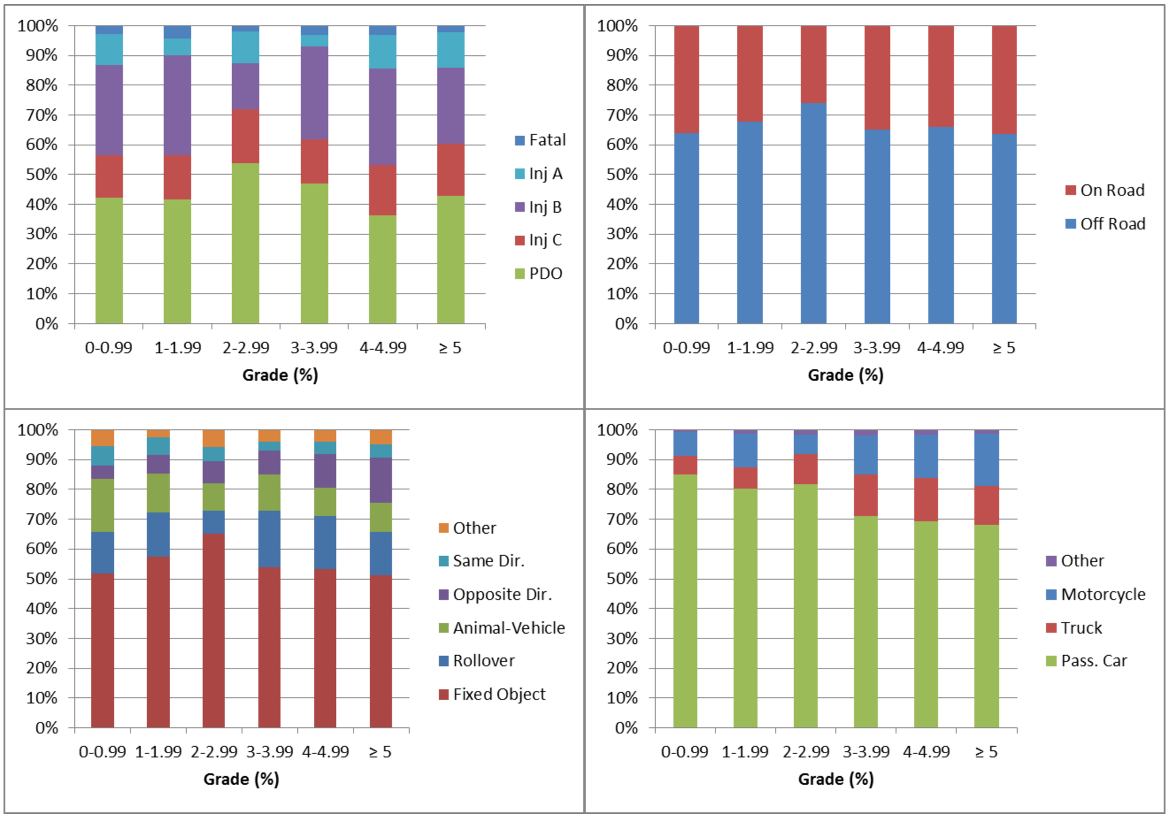

Figure 4.14. Crash characteristics by percent grade

4.3.4. Side Slope

Crash rates varied greatly by slide slope rating as shown in Figure 4.15. The crash rate increased from flatter side slope to steeper side slope, except for the steepest side slope (side slope rating of 3). It should be noted that the crash sample size for steepest side slopes was small; therefore, crash rate associated with that category may be less reliable (marked by a shaded bar). The increasing crash rate pattern could be explained by the principle of recoverable lane departure. If a vehicle leaves the roadway, the driver has a better chance to recover without experiencing a crash if the side slopes near the roadway are flatter.

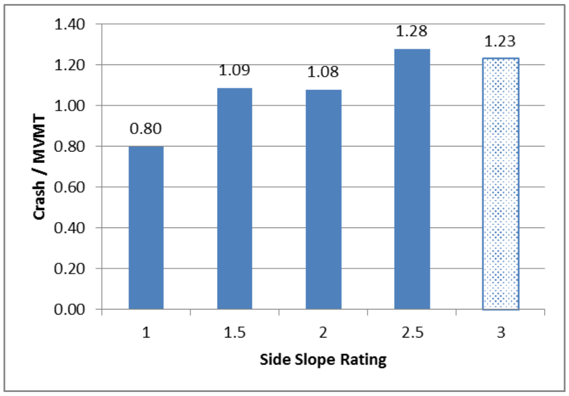

Figure 4.15. Crash rate by side slope rating

Figure 4.16 shows the crash characteristics variation across the side slope rating. The crash severity relationships did not exhibit large differences across side slope rating categories. Off-road crashes were found to be higher on steeper grades and lower on flatter grades; which can be explained by the same principle of recoverable lane departure, as steeper side slopes being less recoverable if a vehicle leaves the roadway.

The crash type and the vehicle involvement varied by side slope rating, but in no predictable pattern.

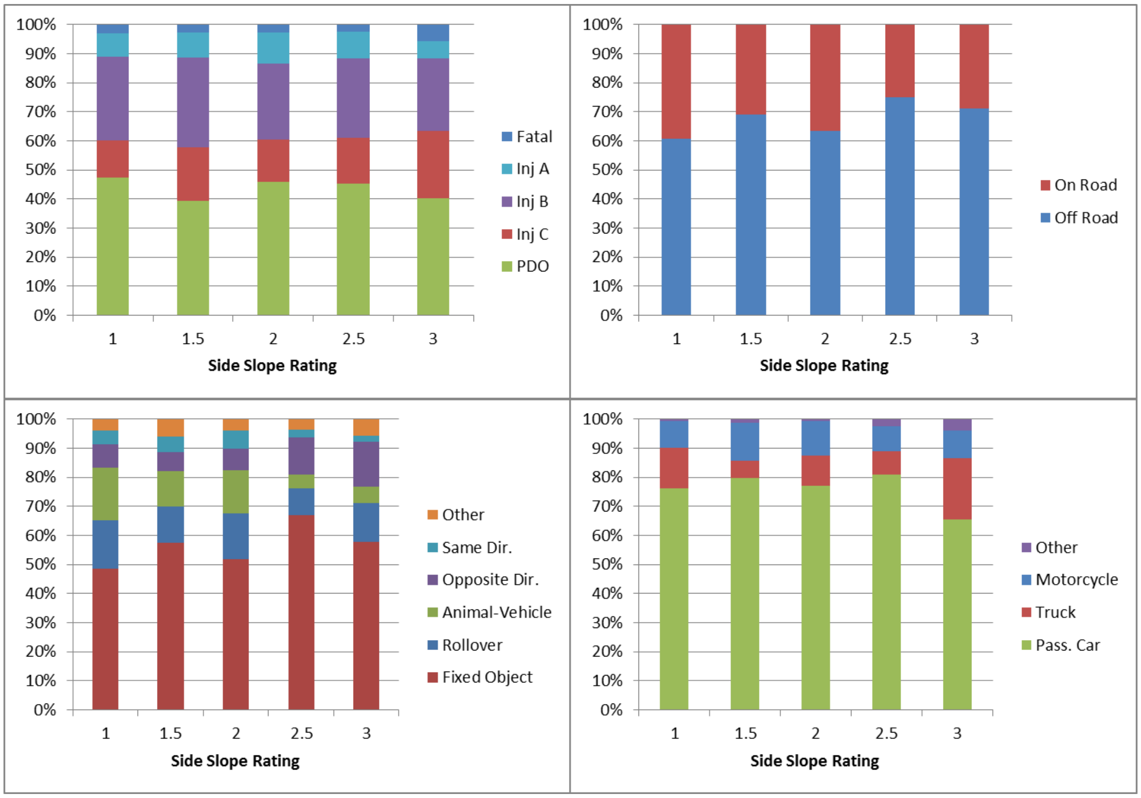

Figure 4.16. Crash characteristics by side slope rating

4.3.5. Roadside Fixed Object

Crash rates were observed to vary differently by roadside fixed object rating, but not in any significant pattern, as illustrated in Figure 4.17. It should be noted that the sample size for side slope rating of 2.5 and 3 were small (represented by shaded bars), and therefore, crash rates associated with these categories may be less reliable. The variation of crash characteristics by different side slope ratings are shown in Figure 4.18. The crash severity relationship and the vehicle involvement proportion did not exhibit a variation across different side slope ratings. Off-road crashes were found to be highest for fixed object ratings of 3 and lowest for fixed object ratings of 2. The proportion of fixed object crashes were found to increase from lowest rating roads to highest rating roads, as expected.

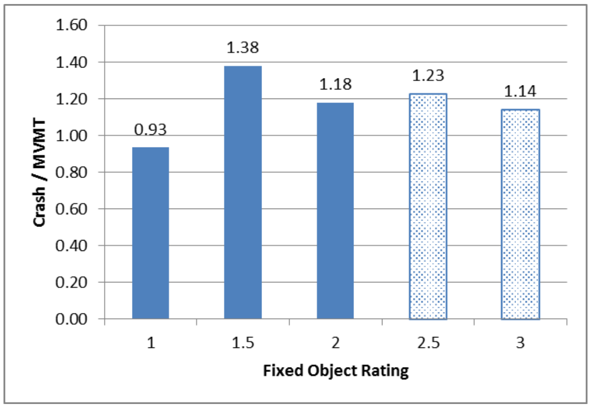

Figure 4.17. Crash rate by fixed object rating

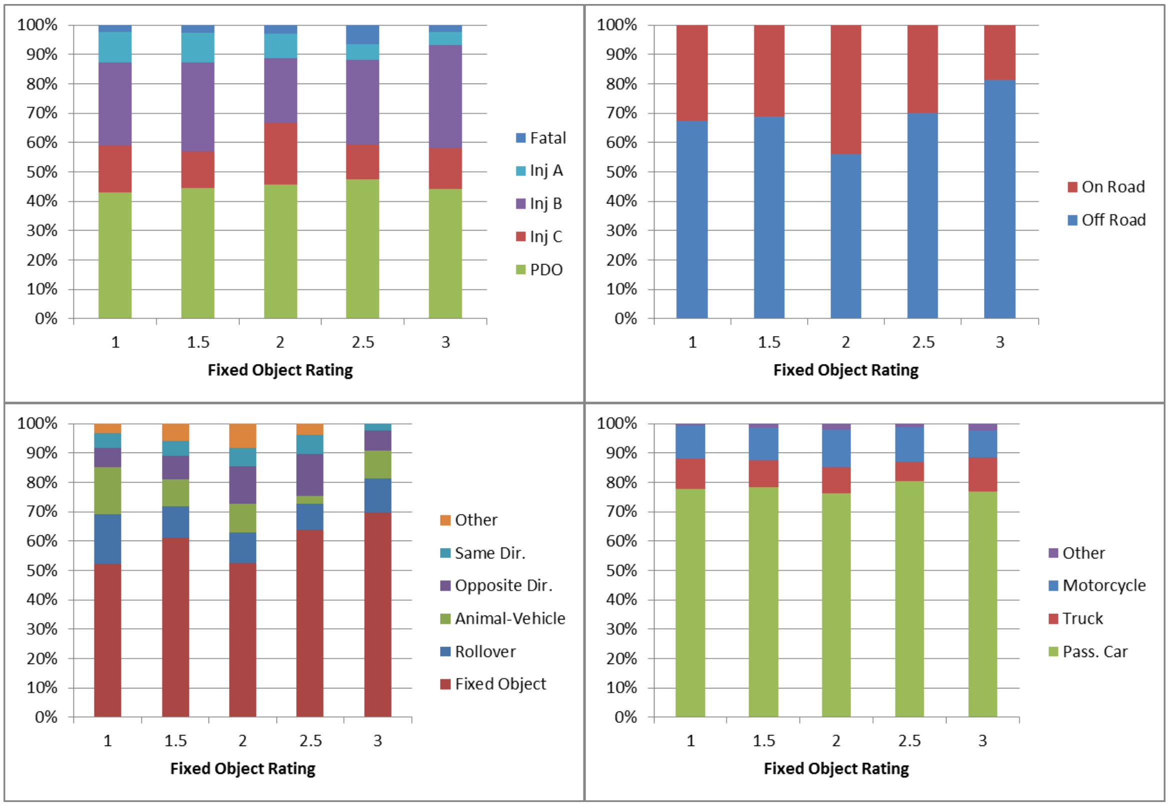

Figure 4.18. Crash characteristics by fixed object rating

4.3.6. Driveway Density

Roads with driveway densities of more than 2 driveways per mile were found to have higher crash rates than roads with lower driveway density. The sample size for driveway density of 6 driveways per mile was very low (represented by a shaded bar), and therefore crash rate for this category might not be reliable.

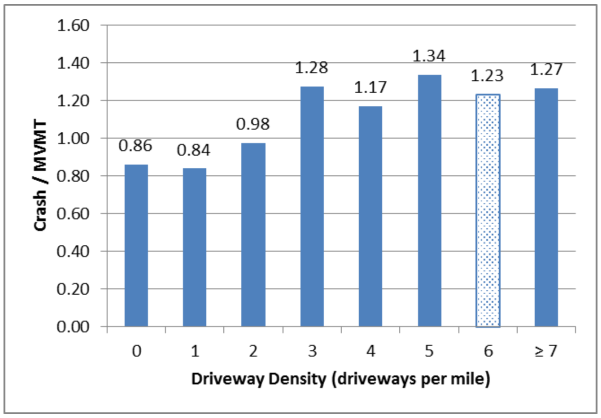

Figure 4.19. Crash rate by driveway density

The variation of crash characteristics across different driveway density categories are shown in Figure 4.20. Crash severity relationships were found to vary significantly by driveway density. The proportion of PDO crashes was found to be lowest (37%) for roads with 4 driveways per mile and highest (50%) for roads with 7 or more driveways per mile. Crash types were observed to vary across the categories but in no apparent pattern. Crash location and vehicle involvement in crashes did not exhibit a significance variation by driveway density.

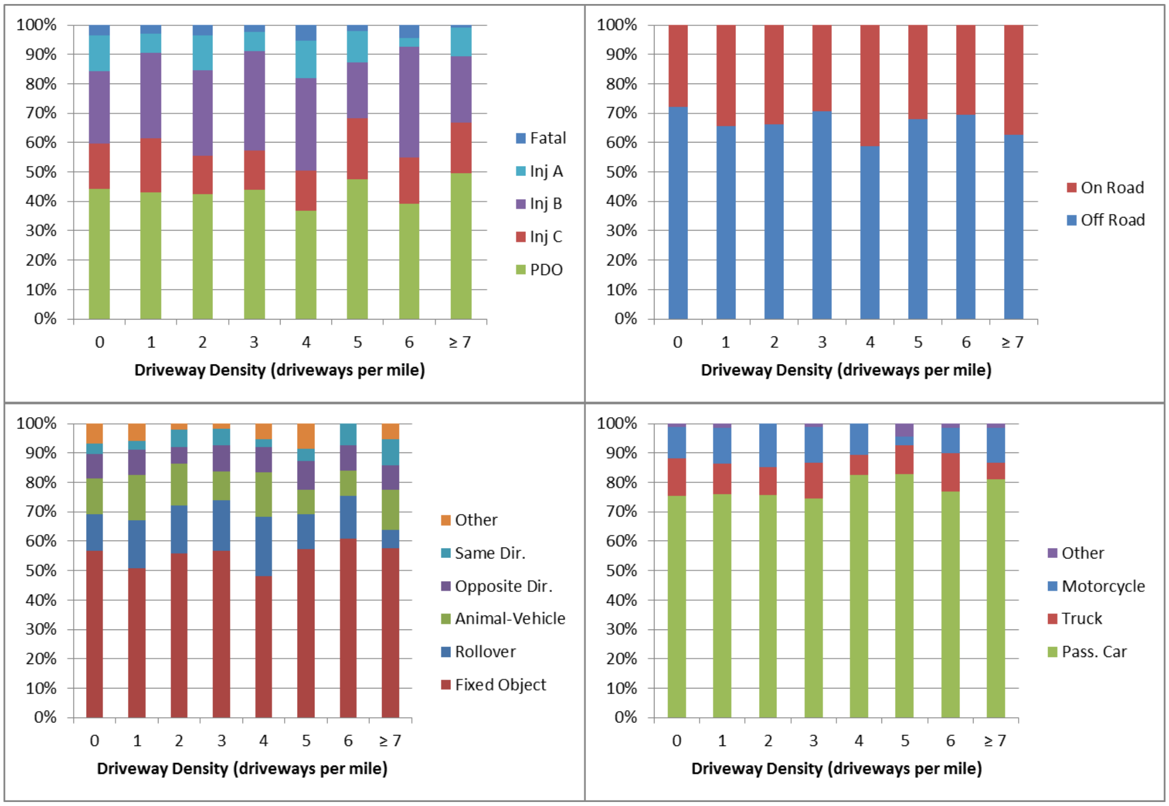

Figure 4.20. Crash characteristics by driveway density

4.3.7. Horizontal Curves

Two important parameters of horizontal curves are degree of curvature and length of curve. The variation of crash rate by these two parameters are shown in Figures 4.21 and 4.22. The degree of curvature of horizontal curves had a massive impact on the crash rate. Crash rates were found to increase with the increase of degree of curvature. Crash rate associated with degree of curvature less than 5 degrees was found to be 0.36 crashes per MVMT. For degree of curvature more than 30 degrees, this rate was found to be 3.81 crashes per MVMT, which is more than 10 times the crash rate associated with curves of less than 5 degrees of curvature. The exact opposite pattern was observed for the variation of crash rate by length of horizontal curves. Crash rates were found to decrease gradually with the increase in length of horizontal curves. Horizontal curves with length of less or equal to 100 feet were associated with a crash rate of 4.87 crash per MVMT, which is more than 20 times the crash rate (0.24 crashes per MVMT) associated with the horizontal curves of length more than 600 feet. This is logical, as longer curves present drivers with a more gradual roadway transition, potentially translating into a decreased risk of performing an errant maneuver, resulting in a crash. As the sample size for horizontal curves 501 to 600 feet was small, crash rate associated with that category may be less reliable.

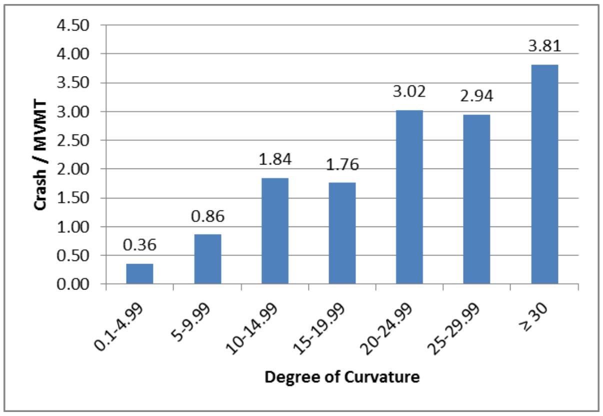

Figure 4.21. Crash rate by degree of curvature

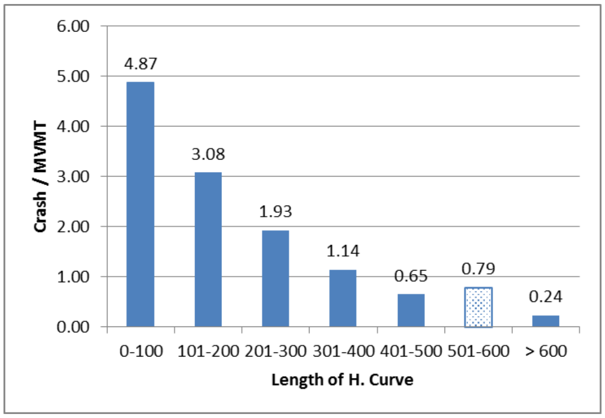

Figure 4.22. Crash rate by length of horizontal curves

The crash characteristics varied with the degree of curvature but not in any evident pattern as shown in Figure 4.23. The same observation was made for the variation of crash characteristics by length of the horizontal curves shown in Figure 4.24.

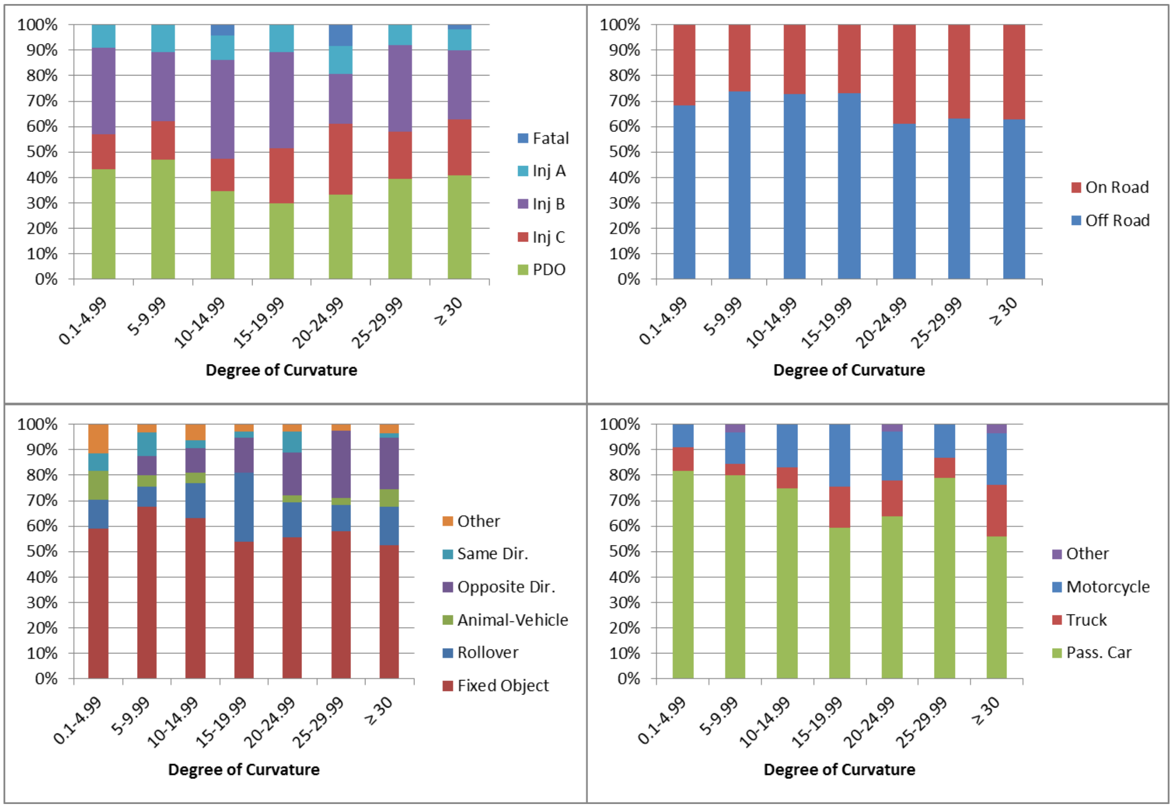

Figure 4.23. Crash characteristics by degree of curvature

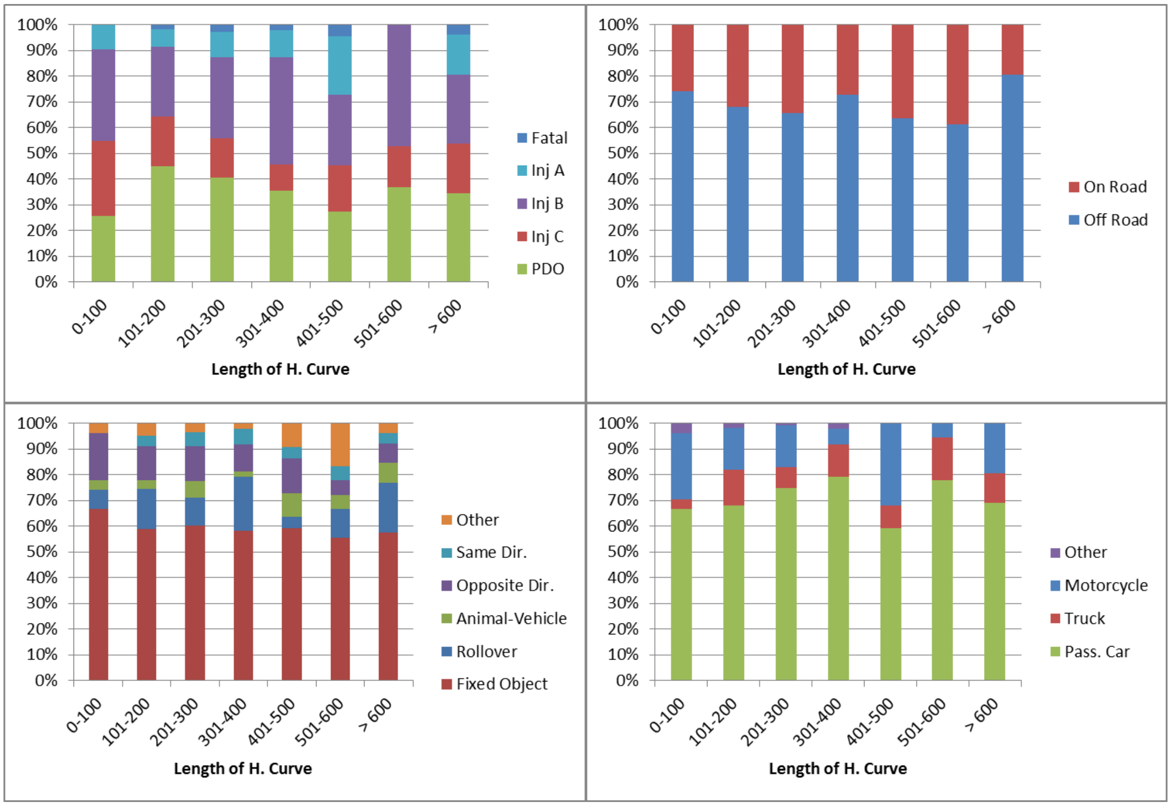

Figure 4.24. Crash characteristics by length of horizontal curves

4.3.8. Vertical Curves

Crash rates exhibited a significant variation by the length of the vertical curves. Similar pattern as length of the horizontal curves was observed for length of vertical curves from Figure 4.25. Vertical curves with length of less or equal to 100 feet were associated with a crash rate of 3.38 crash per MVMT, which is almost 10 times the crash rate (0.34 crashes per MVMT) associated with the vertical curves of length more than 600 feet. It should be noted that the crash sample size for vertical curves of 401 to 500 feet was small, and therefore, crash rate associated with those category may be less reliable. The variation of crash characteristics by length of vertical curves did not show any evident pattern. However, the length of vertical curves between 401 feet and 500 feet showed some significant differences in all characteristics. This length category was associated with 0% fatal crashes, lowest off road crashes, 0% fixed object crashes and 100% passenger car involved crashes. The small sample size of this category might be the reason behind these unusual proportions.

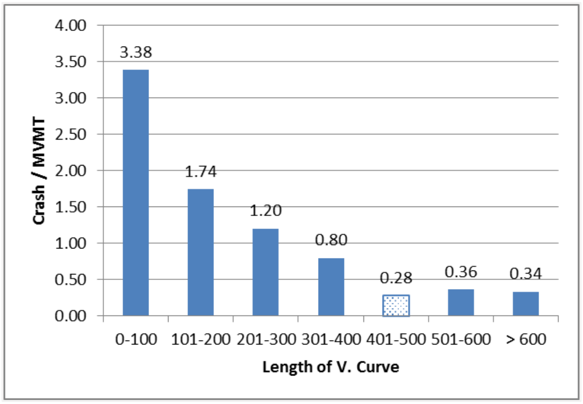

Figure 4.25 Crash rate by length of vertical curves

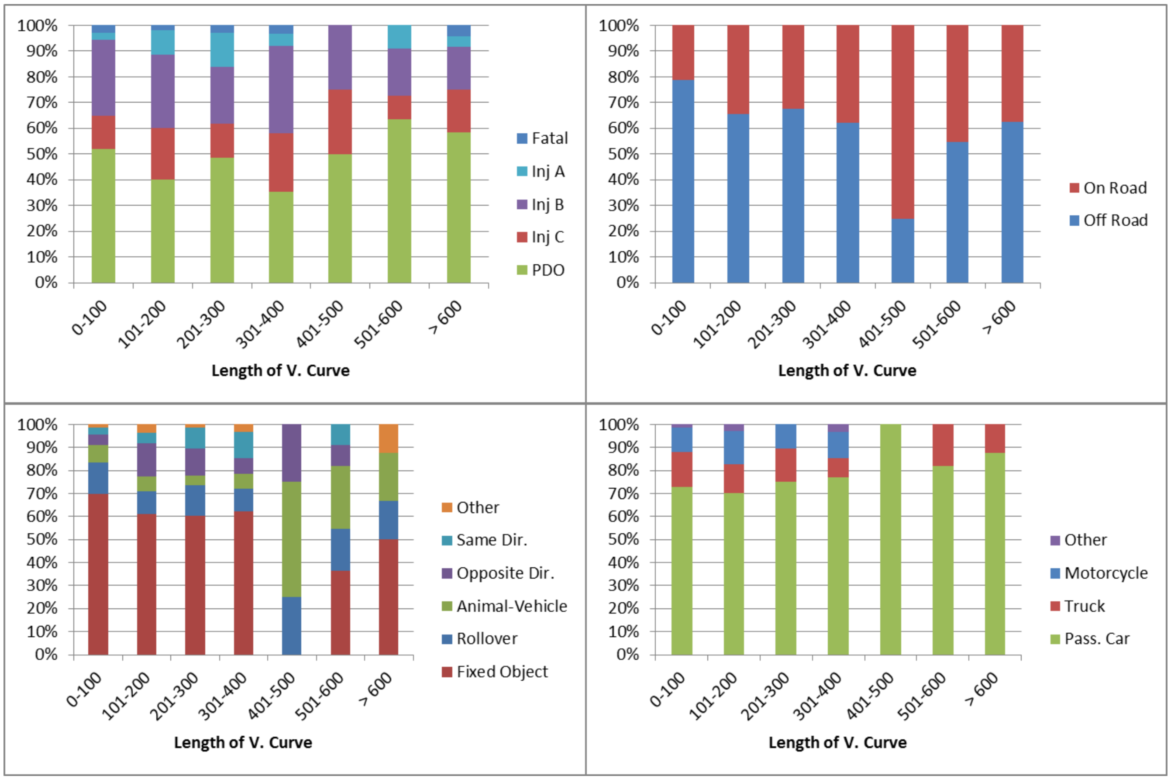

Figure 4.26. Crash characteristics by length of vertical curves

4.4. Regression and Correlation Analyses

In order to understand the relationship between road characteristics and crashes, multivariate regression and correlation analyses were performed. Same 680.85 miles of roadway segments that experienced 1251 crashes during the ten-year study period were used for the regression and correlation analyses. The independent variables considered for the analyses were lane width, shoulder width, grade, degree of curvature, side slope rating, fixed object rating, guardrail presence, vertical curve presence, and driveway density. Two separate dependent variables were considered: crash rate (crashes per MVMT) and crash severity rate. The regression and correlation analyses were performed on three unique samples: a) on the entire 680.85-mile sample (all geometrics), b) on the tangents sample that include only those 0.05 mile sub-segments with no horizontal curve presents, and c) on the curves sample that include only those 0.05 mile sub-segments with horizontal curve presents.

4.4.1. Crash Rate Analyses

As we know crashes are random events and can occur at any location, identifying hazardous locations based on crash history requires a crash frequency that is unlikely to be observed on low volume roads. The regression analyses results shown in Table 4.3 reflected this fact. The R square values for all samples were found to be small, indicating that the linear regression models using the independent variables did not account for any considerable portion of the observed crash rate variability. The low F significance numbers indicated that the regressions were not obtained by chance and were generated using a considerable sample size.

Table 4.3. Summary of crash rate regression results

	All Geometrics	**Tangents**	**Curves**
R square	0.072	0.010	0.012
F (significance)	1.7E-213	1.57E-20	6.38E-05
Statistically significant variables (at 90% conf.)	All of the variables	Lane width, shoulder width, guardrail presence, driveway density	Shoulder width, degree of curvature

All of the nine variables were found to be statistically significant at the 90% confident level using all geometrics sample, while four variables were significant for tangents sample, and two variables were significant for curves sample. Details results of the regression analyses using three samples are provided in Appendix A. The signs (+ or -) of the regression coefficients of most of the variables suggested logical relationships with the dependent variable (i.e. crash rate). Specifically, increase in lane width corresponded to a decrease in crash rate; and increase in side slope rating, fixed object rating, driveway density, degree of curvature, and grade all corresponded to an increase in crash rate. The presence of guardrail and presence of vertical curves corresponded to a reduction in crash rate. An increase in shoulder width corresponded to an increase in crash rate which seems counterintuitive, but somewhat in agreement with the individual crash rate analysis for shoulder widths above 5 ft.

Correlation analysis results for all geometrics sample are shown in Table 4.4, where Cr R is crash rate, LW is lane width, SW is shoulder width, SS is side slope rating, FO is fixed object rating, GR is guardrail presence, G is grade, VC is vertical curve presence, DD is driveway density, and DC is degree of curvature. Correlations of ± 0.10 or greater are in bold text. Crash rates were found to be correlated to some degree with the geometric and roadside features. Increases in lane width and shoulder width were correlated with lower crash rates and increases in side slope rating, fixed object rating, driveway density and degree of curvature were found to be correlated with higher crash rates; as expected. It is also evident that certain independent variable was somewhat correlated with each other. For instance, lane width was positively correlated with shoulder width indicating that roads with wider lanes tend to also have wider shoulders. Complete correlation results for three types of samples are provided in Appendix B.

Table 4.4. Crash rate correlation results (for all geometrics sample)

	Cr R	**LW**	**SW**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**	**DC**
Cr R	1.00									
LW	**-0.19**	1.00								
SW	**-0.10**	**0.44**	1.00							
SS	**0.10**	-0.06	**-0.16**	1.00						
FO	**0.13**	**-0.33**	**-0.30**	**0.32**	1.00					
GR	0.00	**0.10**	0.05	**0.31**	**0.15**	1.00				
G	0.06	-0.05	-0.03	0.06	0.06	0.02	1.00			
VC	0.07	**-0.23**	**-0.20**	-0.02	**0.12**	-0.05	0.04	1.00		
DD	**0.10**	**-0.22**	**-0.26**	-0.05	**0.10**	-0.05	-0.02	**0.13**	1.00	
DC	**0.20**	**-0.32**	**-0.25**	**0.19**	**0.23**	0.04	**0.11**	**0.12**	-0.01	1.00

4.4.2. Crash Severity Rate Analyses

The regression analysis was also performed using crash severity rate as dependent variable. Severity rate was considered in terms of equivalent PDO per MVMT; using equivalent PDO crash cost estimates from the Highway Safety Manual (HSM). In this method the severity weights are given as: PDO = 1, Injury C = 6.19, Injury B = 10.99, Injury A = 30.08 and Fatal = 567.99.

Table 4.5 shows the results obtained from the severity rate regressions, which are similar to the results of crash rate regression. The severity rate R-square values were also found to be small, indicating that the independent variables didn't account for any considerable portion of the observed crash severity rate variability. Again the small F significance number reflected that this regression was not obtained by chance and was generated using a large sample size. Six of the nine variables were found to be statistically significant at the 90% confident level using all geometrics sample, while five variables were found to be significant for tangents sample, and only one variable was found to be significant for curves sample. Detailed results of the regression analyses using three samples are provided in Appendix A.

Table 4.5. Summary of crash severity rate regression results

	All Geometrics	**Tangents**	**Curves**
R square	0.005	0.007	0.003
F (significance)	5.08E-11	4.19E-13	0.625205
Statistically significant variables (at 90% conf.)	Lane width, shoulder width, side slope rating, fixed object rating, guardrail presence, vertical curve presence	Lane width, shoulder width, side slope rating, guardrail presence, driveway density	Degree of curvature

Correlation results for all geometrics sample are shown in Table 4.6, where Sv R is severity rate and the other terms are same as Table 4.4. Correlation of ± 0.10 or greater are in bold text. None of the independent variables showed any good correlation with the crash severity rate. This might be a result of the equivalent PDO severity weights used from the HSM. Multipliers, which were based on comprehensive crash cost estimates, range from approximately 6 (for injury C crashes) up to 568 (for fatal crashes). These large distortions coupled with low traffic volumes, which result in lower crash frequencies, may contribute to the very weak correlations with crash severity rates. Complete correlation results for three types of samples are provided in Appendix B.

Table 4.6. Crash severity rate correlation results (for all geometrics sample)

	Sv R	**LW**	**SW**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**	**DC**
Sv R	1									
LW	-0.01	1.00								
SW	-0.03	**0.44**	1.00							
SS	0.00	-0.06	**-0.16**	1.00						
FO	0.05	**-0.33**	**-0.30**	**0.32**	1.00					
GR	-0.01	**0.10**	0.05	**0.31**	**0.15**	1.00				
G	0.01	-0.05	-0.03	0.06	0.06	0.02	1.00			
VC	-0.01	**-0.23**	**-0.20**	-0.02	**0.12**	-0.05	0.04	1.00		
DD	0.00	**-0.22**	**-0.26**	-0.05	0.10	-0.05	-0.02	**0.13**	1.00	
DC	0.01	**-0.32**	**-0.25**	**0.19**	**0.23**	0.04	**0.11**	**0.12**	-0.01	1.00

CHAPTER FIVE – RISK INDEX DEVELOPMENT

Identification of the high crash locations or hazardous locations has become utmost priority; which is usually done based on the crash history. However, on low-volume roads crash occurrence is less frequent, which makes it difficult to identify the hazardous locations based on crash history. But the low-volume roads may be associated with high risks due to substandard geometry on these roads. Therefore, geometric, traffic and other features may lend themselves toward crashes potentially happening in spot locations. By considering these facts, a risk index has been developed to assess the risk on low-volume roads at the network level using roadway geometry or roadside features, traffic exposure, and crash history. The proposed risk index is proactive in nature as it does not rely heavily on crash occurrence in assessing crash risks. By using this index high risks may be assigned to locations that have not experienced high crash frequencies or rates.

5.1. General Form of the Crash Risk Index

The proposed risk index incorporated three major elements that are believed to reflect the level of risk on roadway. These three elements are geometric and roadside features, crash history, and traffic exposure. Each of these three elements contributed to the overall crash risk index as defined by the crash risk index equation shown in the general form:

$$CRI = W_G\,(x_G) + W_C\,(x_C) + W_T\,(x_T) \qquad \text{(Equation 5.1)}$$

Where,

- ✓ CRI is the crash risk index; a numerical expression of the relative risk,
- ✓ W_G is the geometric and roadside features weight; the contribution of geometric and roadside features to the overall crash risk,
- ✓ W_C is the crash history weight; the contribution of crash history to the overall crash risk,
- ✓ W_T is the traffic exposure weight; the contribution of traffic exposure to the overall crash risk,
- ✓ x_G, x_C, x_T are numerical scores which reflect site characteristics in regards to the three major elements.

The weights used in the crash risk index formula should reflect the agency priorities and preferences. Based on the type and purpose of the project the agency should select the weights. For example, if only limited crash data are used, the weight used in this formulation could be lowered and more weights should be assigned to the other two elements. For the purpose of this study, the weights used for geometric features, crash history, and traffic exposure were selected 45%, 25%, and 30% respectively. Therefore, the crash risk index formula reflecting these weights is:

$$CRI = 0.45(x_G) + 0.25(x_C) + 0.30(x_T) \quad \text{(Equation 5.2)}$$

5.2. Geometric and Roadside Features

The geometric and roadside features that contributed to increase the crash risk were included based on the data analyses from Chapter 4. The geometric and roadside features equation (G) was estimated using the following general formula:

$$G = W_{dc}(y_{dc}) + W_{lvc}(y_{lvc}) + W_{lw}(y_{lw}) + W_{g}(y_{g}) + W_{sw}(y_{sw}) + W_{dd}(y_{dd}) + W_{ss}(y_{ss}) + W_{fo}(y_{fo}) \quad \text{(Equation 5.3)}$$

Where, W terms refer to weights associated with specific geometric and roadside features and y terms are site-specific numerical ratings associated with those features. The subscripts are interpreted as follows: dc for degree of curvature; lvc for length of vertical curve; lw for lane width; g for grade; sw for shoulder width; dd for driveway density; ss for side slope rating, and fo for fixed object rating.

In the geometric and roadside feature equation, length of the horizontal curve was not included. Because length of horizontal curves and degree of curvature are not independent of each other, and therefore, special consideration of their interrelatedness is necessary. The degree of curvature and length of horizontal curve relationship was further analyzed by varying one against the other in order to ensure that horizontal curve effects were not overestimated. Therefore, only degree of curvature was considered in the geometric feature equation and length of horizontal curve was not considered.

5.2.1. Geometric Feature Weights

The weights of each geometric and roadside feature were determined using crash rate descriptive statistics and regression analyses. The weight of each geometric and roadside feature from the crash rate descriptive statistics analysis was set proportional to the deviation or difference in crash rates between the most restrictive value/rating of that geometric (or roadside) feature and the overall crash rate for the study sample. This method ensured that geometric (or roadside) features that exhibited larger influences on observed crash rates were weighted more heavily than those features that showed less influence on crash rates. The geometric feature weight from descriptive statistics was determined using the following formula:

$$Geometric\ Feature\ Weight\ (Wi) = \frac{D_i}{\sum D_i} * (100\%) \qquad \text{(Equation 5.4)}$$

Where, Di is the deviation/difference in crash rates between the most restrictive value/rating of each geometric (or roadside) feature and the overall crash rate for the study sample.

The overall crash rate for the study sample was found to be 1.059 crashes/MVMT from chapter 4. Crash rate associated with the most restrictive rating/category of each geometric (or roadside) feature is shown in Table 5.1. These values were found from the analyses of chapter 4. Table 5.1 also shows the deviation for each feature and the resulting weights.

Table 5.1. Weights from descriptive statistics

Geometric/ Roadside Feature	**Most Restrictive Category/ Rating**	**Crash Rate (Crashes/ MVMT)**	**Deviation from Overall Crash Rate**	**Weight**
Degree of Curvature	≥ 30 degree	3.815	2.756	43%
Length of Vertical Curve	0-100 feet	3.383	2.324	37%
Lane Width	9 feet	1.266	0.207	3%
Vertical Grade	≥ 5 percent	1.308	0.249	4%
Side Slope Rating	3 (Steep)	1.231	0.172	3%
Shoulder Width	0 feet	1.426	0.367	6%
Fixed Object Rating	3 (Many)	1.141	0.082	1%
Driveway Density	≥ 7 driveways/mile	1.266	0.207	3%
		Total	6.364	100%

The weight of each geometric (or roadside) feature also depended on the regression analysis results. Regression analysis based on the crash rates for the total sample showed all of the features were significant at 90% confidence level. Therefore, all geometric and roadside features should have a regression weight associated with them. As a total of eight geometric (or roadside) features were considered for crash risk, the weight associated with each feature was given as 12.5%.

Though the regression results found all features to be significant, the overall regression models did not adequately explain the crash rates observed in the data (i.e. models had very low coefficient of determination). For that reason, the regression results were deemed less reliable overall compared to the crash rate descriptive statistics analysis results. Therefore, in calculating the total geometric feature weight, it was deemed necessary for regression weights to have lower contribution compared to the weights found using descriptive statistics. The total weight was calculated as a weighted average with the descriptive statistics weight being 75% and the regression weight being 25% of the total geometric feature weight. The total resulting geometric feature weights are shown in Table 5.2.

Table 5.2. Overall geometric feature weights

Geometric/ Roadside Feature	**Descriptive Statistics Weight**	**Regression Weight**	**Total Weight**
Degree of Curvature	43%	12.5%	36%
Length of Vertical Curve	37%	12.5%	30%
Lane Width	3%	12.5%	6%
Vertical Grade	4%	12.5%	6%
Shoulder Width	6%	12.5%	7%
Driveway Density	3%	12.5%	6%
Side Slope Rating	3%	12.5%	5%
Fixed Object Rating	1%	12.5%	4%
Total	100%	100%	100%

Using the proposed geometric feature weights, the overall geometric features equation can be written as:

$$G = 0.36(y_{dc}) + 0.30(y_{lvc}) + 0.06(y_{lw}) + 0.06\left(y_{g}\right) + 0.07(y_{sw}) + 0.06(y_{dd}) + 0.03(y_{ss}) + 0.04\left(y_{fo}\right) \quad \text{(Equation 5.5)}$$

5.2.2. Geometric Feature Values

The numerical ratings associated with each geometric feature are the y terms in the x_G equation of the overall crash risk index, which established values for each individual geometric feature based on the observed crash rate analysis from chapter 4. The observed crash rate and geometric feature relationships were plotted and scaled proportionately to ensure a maximum y value of 1.0 for each geometric feature. Trend lines were then fit to the plots to establish the best suited equation for each y term. Linear, parabolic, exponential, logarithmic, and power curve trend lines were fit for all relationships. The best fitting curve line was then chosen based on the R-square value for each trend line as the applicable model and logical minimum and maximum values were defined when necessary. Figure 5.1 shows an example of the chosen trend line with the R-square value and applicable maximum value that defines the geometric feature equation for degree of curvature (y_{dc}). Similar procedures were followed for all of the geometric and roadside features. Trend lines and equations for all of the geometric and roadside features are shown in Appendix C.

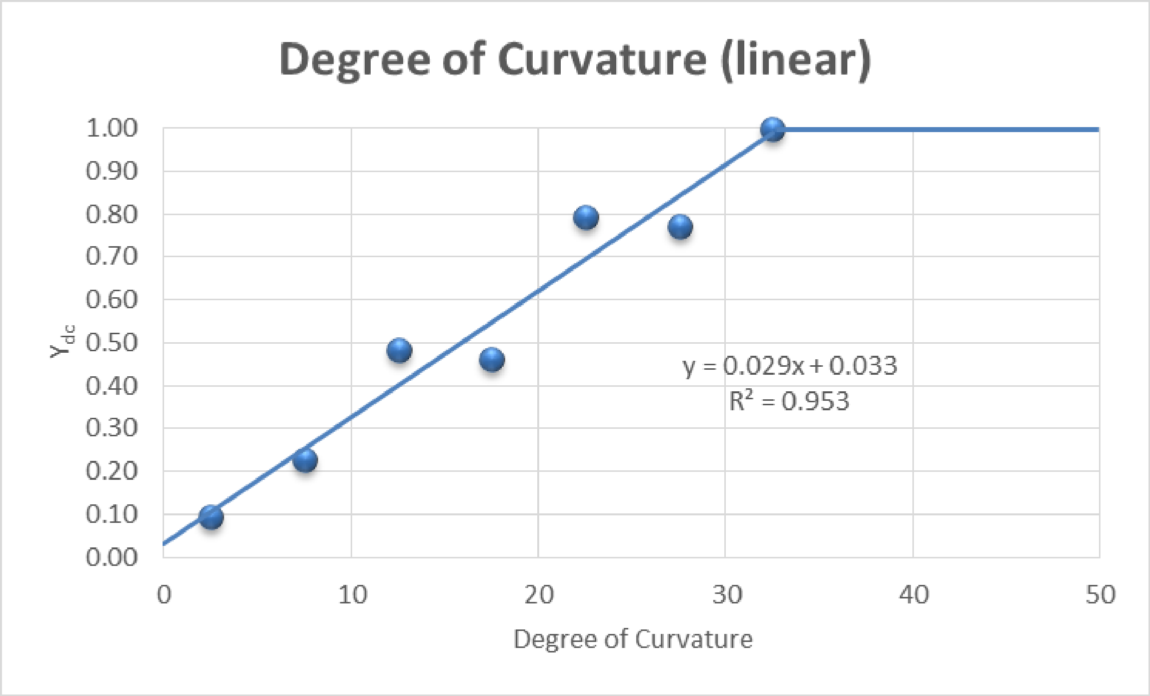

Figure 5.1. Selected equation for degree of curvature

The equations for all geometric and roadside features with the applicable conditions and logical minimum and maximum values are shown in Table 5.3.

Table 5.3. Equations for geometric and roadside features

Geometric and Roadside Features Equation	**Condition**
Degree of Curvature • $y_{dc} = 0.029 * (dc) + 0.033$ • $y_{dc} = 1.00$ • $y_{dc} = 0.00$	 • dc $\leq$ 33 • dc > 33 • no horizontal curve present
Length of Vertical Curve • $y_{lvc} = -0.365 * \ln(lvc) + 2.386$ • $y_{lvc} = 1.00$ • $y_{lvc} = 0.00$ • $y_{lvc} = 0.00$	 • 50 ft. $\leq$ lvc $\leq$ 690 ft. • lvc < 50 ft. • lvc > 690 ft. • no vertical curve present
Lane Width • $y_{lw} = -0.110 * (lw^2) + 2.227 * (lw) - 10.270$ • $y_{lw} = 0.86$ • $y_{lw} = 0.61$	 • 9 ft. $\leq$ lw $\leq$ 12 ft. • lw < 9 ft. • lw > 12 ft.
Grade • $y_g = 0.510e^{0.096*(g)}$ • $y_g = 1.00$	 • g $\leq$ 7% • g > 7%
Shoulder Width • $y_{sw} = 0.025 * (sw^2) - 0.199 * (sw) + 1.000$ • $y_{sw} = 0.83$	 • sw $\leq$ 7 ft. • sw > 7 ft.
Driveway Density • $y_{dd} = -0.010 * (dd^2) + 0.125 * (dd) + 0.611$ • $y_{dd} = 1.00$	 • dd $\leq$ 7 driveways/mile • dd > 7 driveways/mile
Side Slope • $y_{ss} = -0.106 * (ss^2) + 0.593 * (ss) + 0.173$	 • all ss ratings
Fixed Object Rating • $y_{fo} = -0.181 * (fo^2) + 0.763 * (fo) + 0.195$	 • all fo ratings

The x_G term in equation 5.1 and equation 5.2, which defines the geometric feature score in the CRI, was scaled as a result of investigating the range of possible G values for the entire 680.85 mile sample. The average and standard deviation of the G term for the sample were found to be 0.32 and 0.12 respectively. The scale was defined as shown in Figure 5.2, such that one standard deviation below the mean of G value represents $x_G = 0$ and three standard deviations above the mean of the G value represents $x_G = 1$.

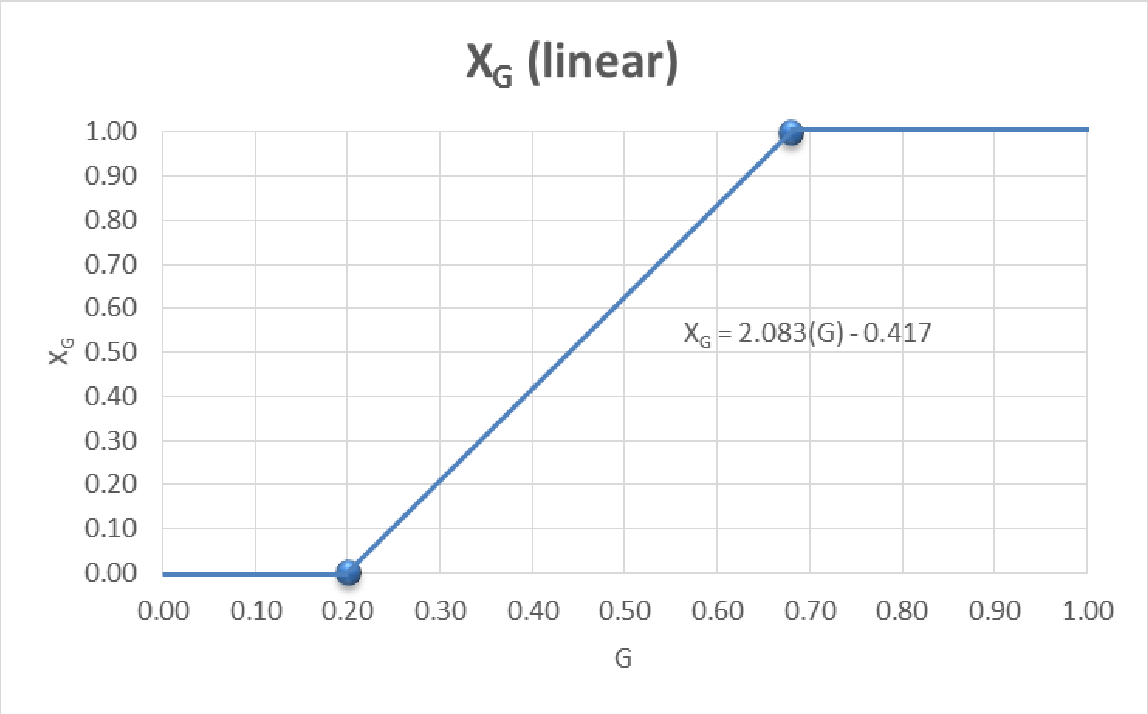

Figure 5.2. Selected equation of geometric feature component (x_G)

The final equation of x_G with the logical minimum and maximum value based on the condition of G is shown in Table 5.4.

Table 5.4. Geometric feature values (x_G)

Equation	**Condition**
• $x_G = 2.083 * (G) - 0.417$	• $0.20 \leq G \leq 0.68$
• $x_G = 0.00$	• $G < 0.20$
• $x_G = 1.00$	• $G > 0.68$

5.3. Crash History

Values for the crash history term (x_C) in the risk index equation (i.e. equation 5.1 and 5.2) were selected based on the average crash rate and critical crash rate for the sample as defined in the Highway Safety Manual (HSM) (*38*). The average crash rate for the sample was found to be 1.059 crashes per million vehicle miles traveled (MVMT). The critical rate is dependent upon the average rate at similar sites, traffic volume, and a statistical level of confidence associated with the Poisson distribution and can be estimated using the following equation:

$$Rc = Ra + k\sqrt{Ra/E} + (1/2E) \qquad \text{(Equation 5.6)}$$

Where,

- ✓ Rc = critical crash rate
- ✓ Ra = average crash rate
- ✓ k = a constant determined by the confidence level
- ✓ E = traffic exposure

The average critical rate for the sample is found to be 2.52 crashes per MVMT for a 90% confidence level. For defining the equation of crash history term (x_C), the minimum crash rate was selected as the half of the average crash rate and the maximum crash rate was selected as the average critical rate for 90% confidence level. Figure 5.3 shows the crash history component value using a linear relationship, and Table 5.5 shows the selected equation for crash history term (x_C) with the logical maximum and minimum value. For the calculation of CRI, rolling 1-mile value of crash history should be used in order to be consistent with the data analysis methods used and to accommodate the reality that crash data reported mile posts may not be accurate to very small resolutions.

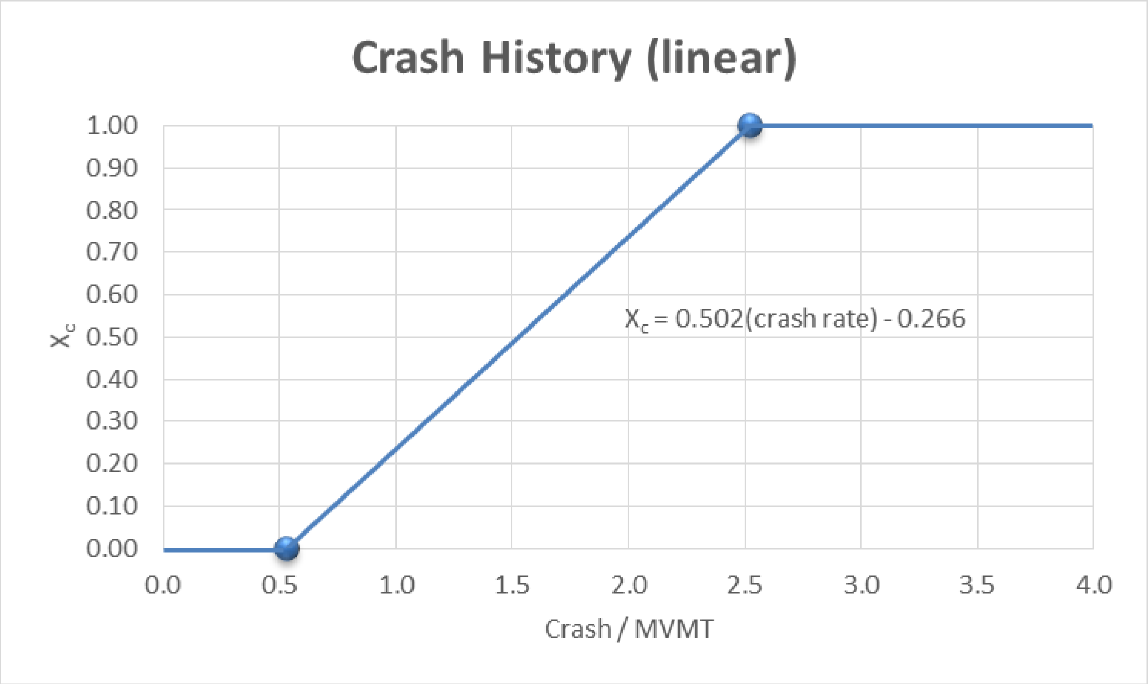

Figure 5.3. Selected equation of crash history component (x_c)

Table 5.5. Crash history values (x_c)

Equation	**Condition**
• $x_c = 0.502 * (crash\ rate) - 0.266$	• $0.53 \leq$ Crash rate ≤ 2.52
• $x_c = 0.00$	• Crash rate < 0.53
• $x_c = 1.00$	• Crash rate > 2.52

5.4. Traffic Exposure

Two aspects of traffic exposure were considered in the proposed crash risk index in estimating the values of exposure term (x_T). These are:

- ✓ Total vehicular traffic volume expressed as annual average daily traffic (AADT)
- ✓ The percentage of heavy vehicles (AASHTO class 4 or larger) in the traffic stream

The fundamental relationship underlying this component of the CRI was that crash risk increases with the increase of total vehicular volume as well as with the increase in the percentage of heavy vehicles. The average percentage of heavy vehicles for the low-volume roads sample used in this study was found to be approximately 29% of the total traffic volume. The standard deviation of the percentage of heavy vehicles for the sample was found to be approximately 10%. The values for the traffic exposure component (x_T) of the risk index were assumed to vary in the range of 0.2-1.0 depending on total traffic volume and the percentage of heavy vehicles. As stated earlier, for the purpose of this study, roads with AADT less than 1,000 vpd were selected. Therefore, maximum traffic exposure (x_T) value of 1 was given for the roads with AADT greater than 900 vpd, regardless of percent of heavy vehicles. The selected thresholds for total traffic were 300, 500, 700 and 900 vpd respectively and the selected thresholds for percentage of heavy vehicles were the average and one standard deviation above the average. The proposed scheme is shown in Table 5.6, which defines the x_T values for different traffic volume and truck percentage compositions.

Table 5.6. Traffic exposure values (x_T)

AADT (vpd)	**Percent of Heavy Vehicles**		
	< 29%	**29% - 39%**	**> 39%**
< 300	0.20	0.30	0.40
300 – 499	0.40	0.50	0.60
500 – 699	0.60	0.70	0.80
700 – 900	0.80	0.90	1.00
> 900	1.00	1.00	1.00

5.5. Case Studies

In order to illustrate the application of proposed risk index, case studies were conducted applying the index on the rural low-volume road corridors. Three sites were selected from different terrain types and climatic regions to cover a wide range of possible risk index and crash history situations: highway 171, highway 036 and highway 380. These study sites were not included in the original sample used for risk index development to eliminate potential bias.

In order to determine the crash risk index values for the three case study locations, data about the geometric and roadside features, traffic volumes and crash history were compiled. The crash risk index was then calculated at 0.05 mile intervals using the method described earlier. The CRI was then averaged using a one-mile sliding segment.

5.5.1. Case Study One – Highway 171

Highway 171 is located in the western region of Oregon, which largely consists of winding roads and significant grades. A Total of 16 miles of this highway, from milepost 33.5 to milepost 49.5 were selected. Figure 5.4 shows the selected site from highway 171.

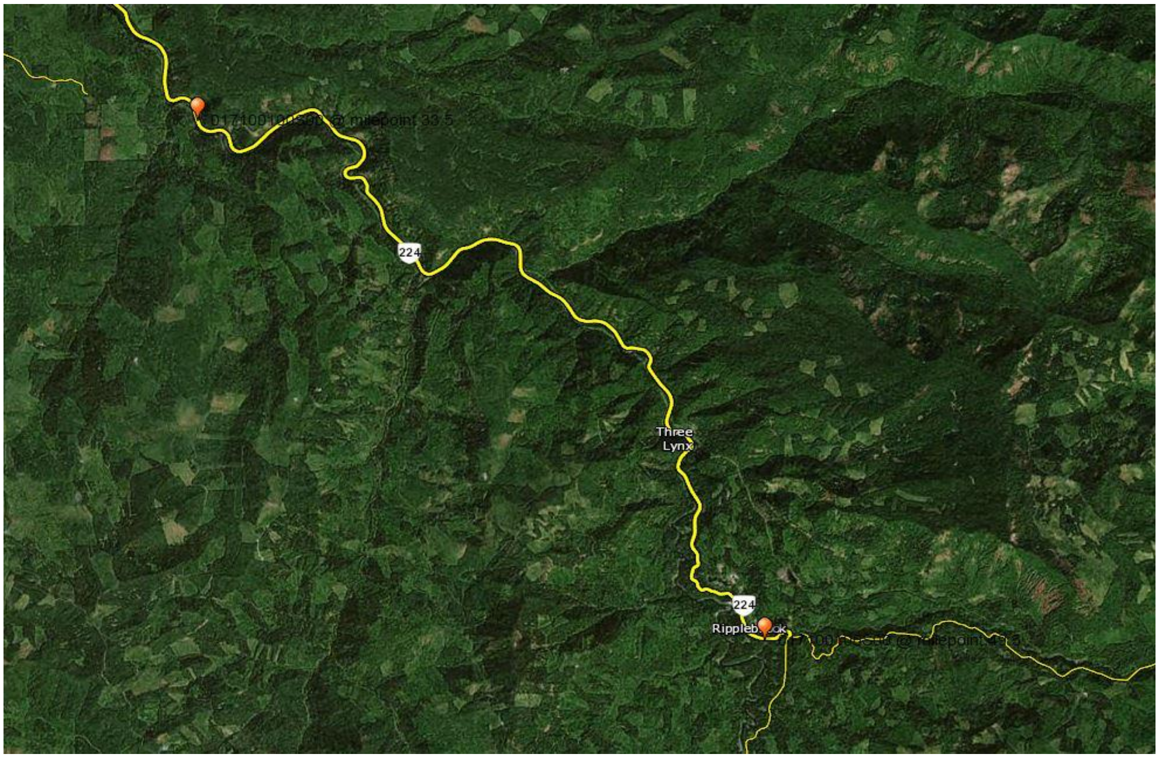

Figure 5.4. Case study site 1 - highway 171 (Source: ODOT TransGIS System)

The one-mile sliding CRI average values along the highway corridor were plotted to observe how the CRI changes along the road. Figure 5.5 shows the one-mile sliding CRI along highway 171 (in black). Besides the one-mile sliding CRI average, the 95% confidence interval was plotted using red dotted lines and the overall CRI average along the corridor was plotted by a red horizontal dashed line. In order to get more insights into the utility of the proposed crash risk index, use of crash history alone was also illustrated by plotting the crash rate along the same corridor (in blue). One-mile sliding segment average crash rate was used in this figure to alleviate the extraordinary fluctuations in crash rates that is expected with the use of 0.05-mile resolution.

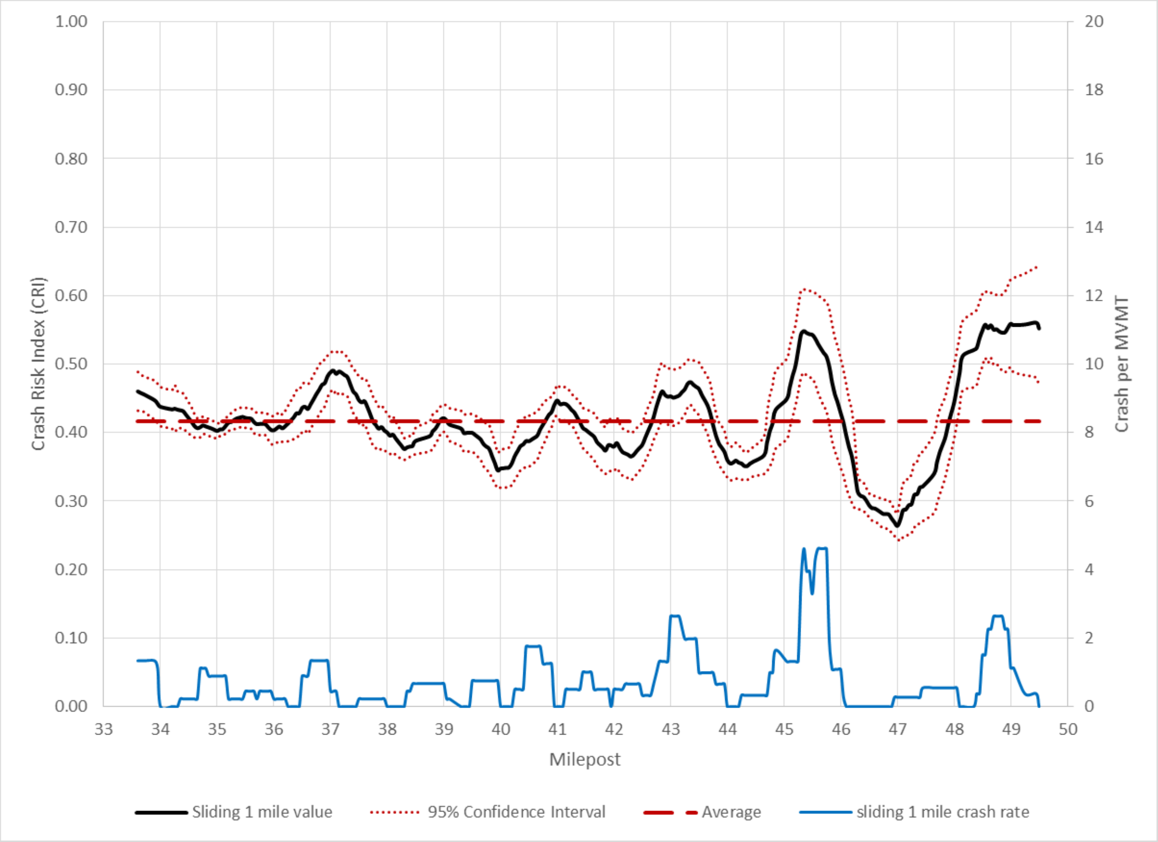

Figure 5.5. Crash risk index (CRI) and crash rate for highway 171 corridor

It is evident that, the roadway segments between mileposts 36.2 & 37.7, 42.7 & 43.7, 44.8 & 45.9 and 48.1 & 49.5 were associated with higher crash risk. These segments had higher crash risks than the corridor average CRI. Therefore, these segments may warrant further investigation to identify risk factors and potential countermeasures. As an agency, certain CRI threshold values would likely be needed to determine if any of the CRI peaks shown for highway 171 warrant safety treatments when considered at the network level. The crash rate in the study corridor fluctuated in a steady pattern with most observations lying between 0-2 crashes per MVMT. In some cases, the peaks of CRI curve and crash rate curve were coincident, which was expected given the fact that crash history is one of the CRI components. Also in some cases, the CRI changed in magnitude differently than the crash history alone. For example, the segment between mileposts 36.2 and 37.7 had lower crash rate than the segment between mileposts 40.4 and 41. However, the latter segment was not identified as a “hot spot” using the CRI method, but the first segment was. This example confirmed the fact that, the use of CRI provides new information about the level of hazard along highway segments compared to using crash history alone.

5.5.2. Case Study Two – Highway 036

Highway 036 is located in the eastern part of Oregon, which consists mostly of straight flat roads with adjacent farm land. A total of 16 miles of this highway, from milepost 11.5 to milepost 27.5 were selected. Figure 5.6 shows the selected site from highway 036.

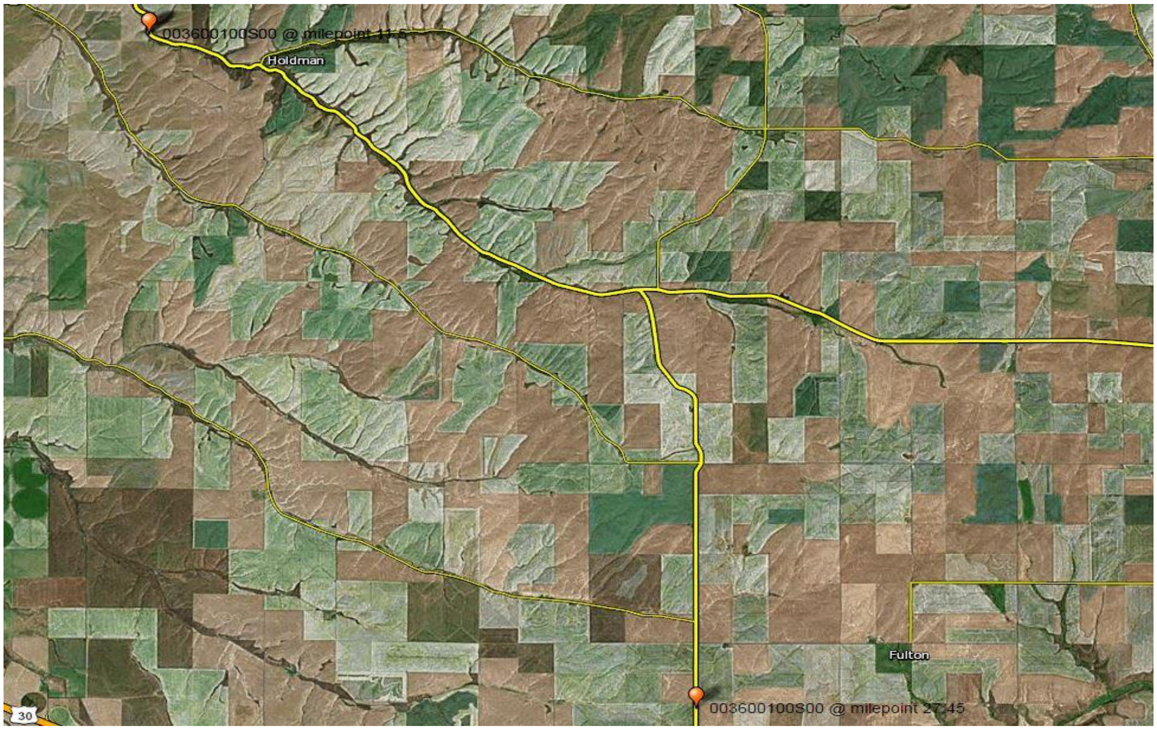

Figure 5.6. Case study site 2 - highway 036 (Source: ODOT TransGIS System)

Figure 5.7 shows the plotting of sliding one-mile crash risk index and crash rate along this highway corridor. Similar observations were found from this corridor as highway 171. Some peaks in the CRI and crash rate curves were coincident with each other; for example, segments between mileposts 12 & 13 and segments between mileposts 21.2 & 22. But the third peak in crash rate curve which occurred at mileposts 15.8 corresponded to a CRI value that is hardly above the average. This suggested that while this location may well belong to the list of sites needing more attention using the crash history alone, it is very unlikely to be identified as such using the CRI value.

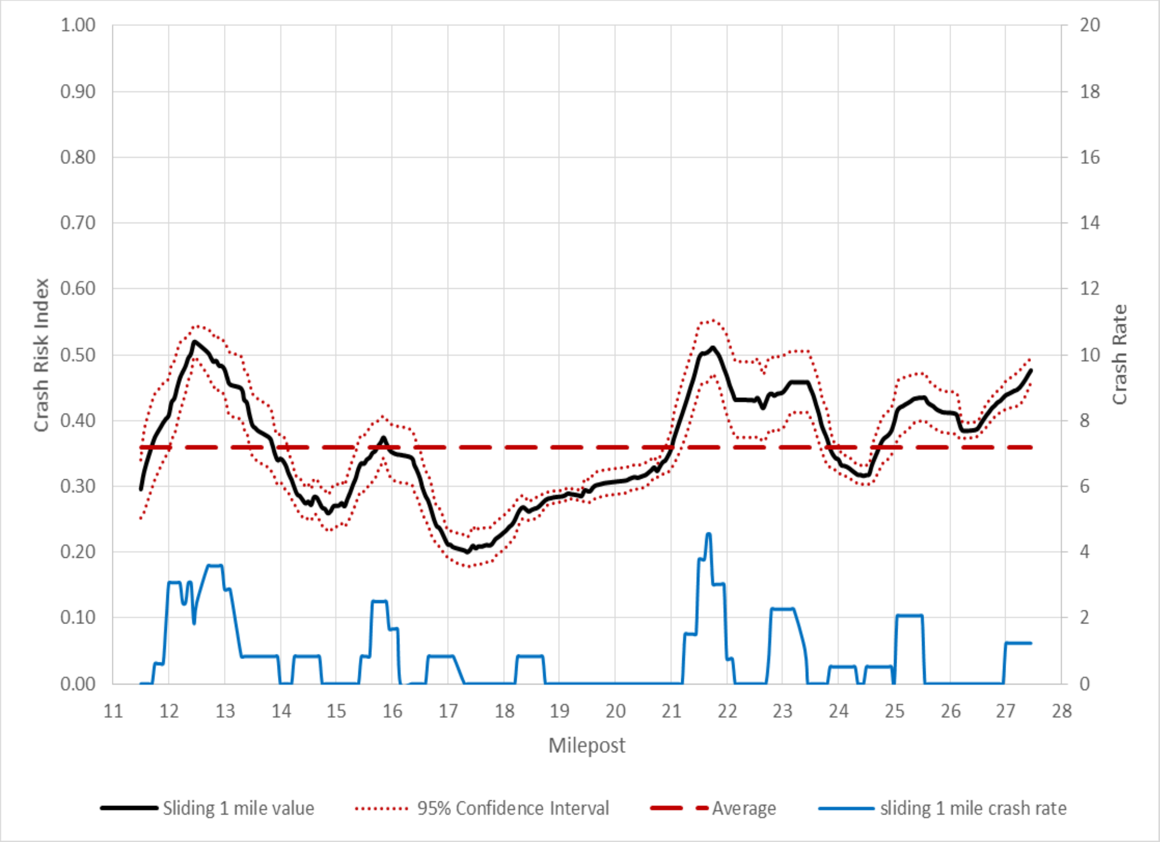

Figure 5.7. Crash risk index (CRI) and crash rate for highway 036 corridor

5.5.3. Case Study Three – Highway 380

Highway 380 is located in the middle part of Oregon, which consists of both winding and flatter roads. A total of 15.6 miles of this highway, from milepost 1.75 to milepost 17.35 were selected. Figure 5.8 shows the selected site from highway 380.

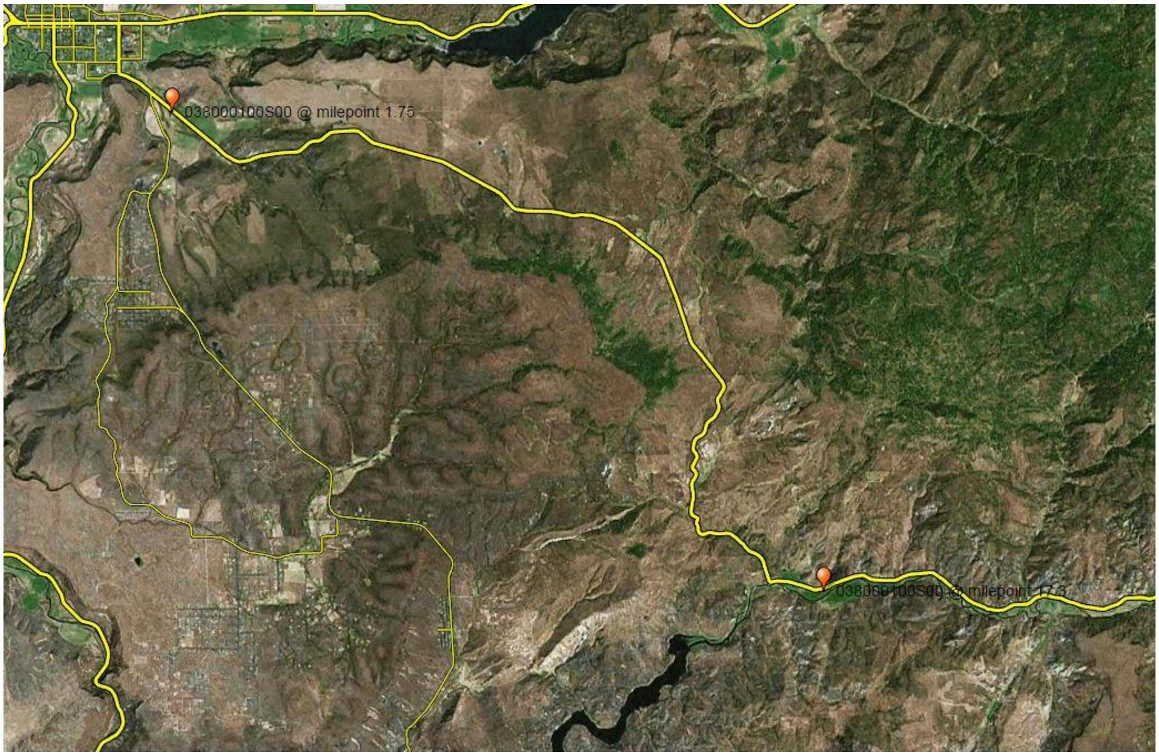

Figure 5.8. Case study site 2 - Highway 380 (Source: ODOT TransGIS System)

Figure 5.9 shows the plotting of sliding one-mile crash risk index and crash rate along this highway corridor. The CRI and crash rate were found to vary significantly along this corridor. Segments between mileposts 5.4 & 6 and segments between mileposts 13 & 13.5 had similar crash rates, but vastly different CRIs (0.30 and 0.50); which is due to differences in geometry and traffic exposure in these two segments. Also, the peak crash rate value between mileposts 7.4 & 8 didn't correspond to a large peak in the CRI value relative to the rest of the study segment.

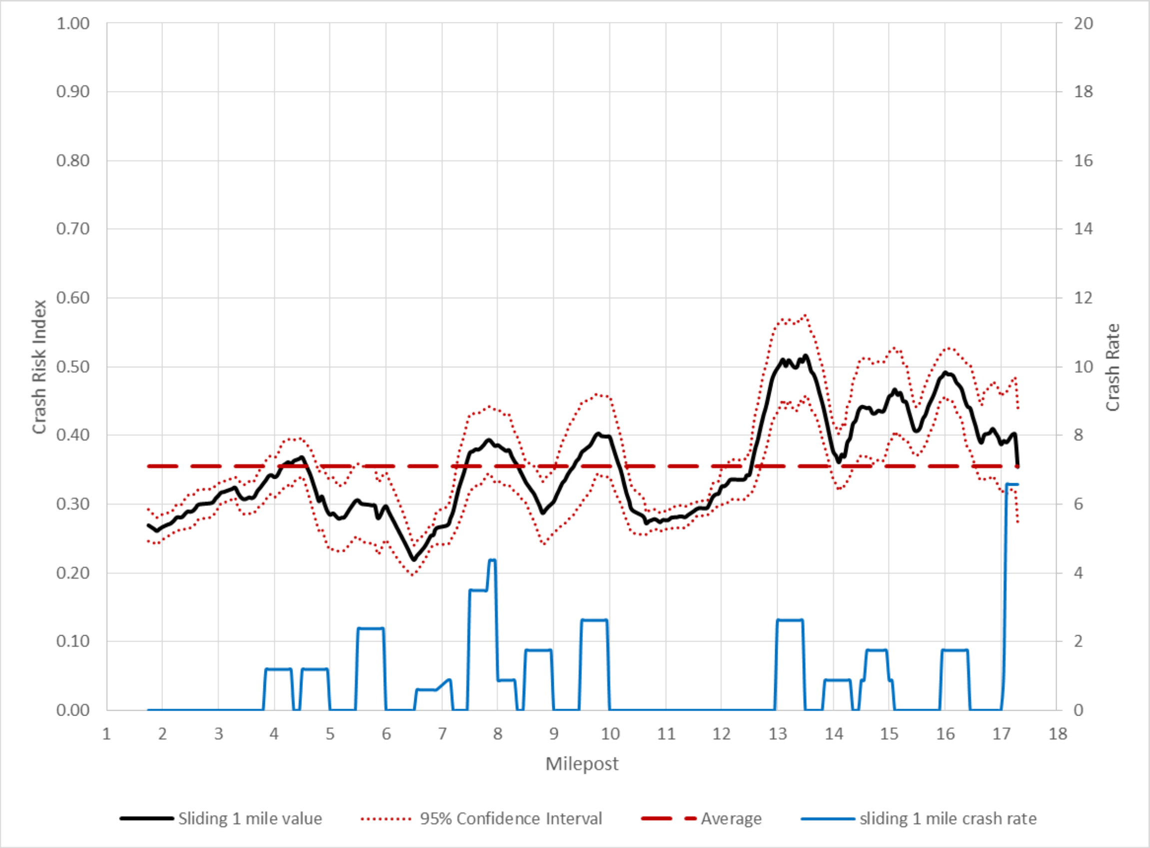

Figure 5.9. Crash risk index (CRI) and crash rate for Highway 380 corridor

These three case studies have shown how the CRI varies along real-world roads and how the CRI would compare to the more traditional analyses using crash history alone. Certain threshold value for CRI by using statistical approaches (e.g. one standard deviation above the mean CRI) needs to be determined by agency in order to identify and rank locations that are likely to have higher crash risks for further investigation and analysis.

CHAPTER SIX – ECONOMIC FEASIBILITY OF SAFETY COUNTERMEASURES

This chapter investigates the economic feasibility of safety countermeasures that could be applied to Oregon’s low-volume roads. The traditional methods for identifying candidate locations for safety improvements has inherent bias in favor of well-travelled roadways that experience higher crash frequencies. However, low-volume roads, that usually don’t experience higher crash frequencies, may be associated with higher level of risks and consequently high potential for crash occurrence. The information published on the economic feasibility of countermeasures is very limited in general, and it is particularly lacking for low-volume roads. Therefore, it seemed necessary to perform the economic feasibility study of safety countermeasures that could potentially be used on low-volume roads. The implication of the economic feasibility principle is the fact that many proven countermeasures on other rural roads may simply prove infeasible on low-volume roads due to low traffic exposure.

The costs of safety countermeasures and crash reduction benefits of these measures were analyzed to identify countermeasures that would produce the highest return on investment. Detailed benefit-cost analyses were performed using the Highway Safety Manual (HSM) (*38*) methods. Cost of the proposed countermeasures and expected crash reductions of the proposed countermeasures were collected from different published reports; and the same ten years of crash data for the selected sample of 680.85 miles were used to perform the benefit-cost analyses.

6.1. Safety Countermeasures on Low-volume Roads

Many low-cost safety countermeasures, as reported in the literature review, were found to result in promising crash reduction benefits. Different highway agencies used these countermeasures to mitigate crash risks and improve the safety on the highway system and published the crash reduction factors (CRFs) and crash modification factors (CMFs) for those countermeasures. Many of these low-cost countermeasures can be directly applied to the low-volume roads using the published CRFs and CMFs. As the benefits required the CRFs or CMFs to perform the economic analyses, only the countermeasures, for which the quantified CRFs or CMFs were available for use, were included in this study. For this study, the proposed countermeasures were separated into four categories based on the types of risks they mitigate:

i. Countermeasures related to highway alignment
ii. Countermeasures related to roadway cross-section
iii. Countermeasures related to roadside features and
iv. Other safety countermeasures.

6.1.1. Countermeasures Related to Highway Alignment

The alignment of the highway can increase the risk of crashes under certain circumstances. Some of the most serious crashes on low-volume roads occur due to the presence of sharp horizontal and vertical curves. Methods to mitigate risky alignments can often be costly (e.g. flattening sharp curves), but some low cost countermeasures have been documented including curve delineations, on-pavement curve warnings and curve warning signs. Installation or improvement of curve delineation can be done using many techniques such as post mounted delineators, reflectors, raised pavement markers, and chevrons. Another technique used to alert drivers of a potentially risky alignment is the use of on-pavement curve warnings, which are usually pavement markings laid directly in the driving lane on approach of the curves. Curve warning signs are also used to mitigate the risky horizontal and vertical alignments. These signs can vary in complexity from static signs with or without speed advisory plaques to dynamic signs equipped with radar detection to warn drivers that may be traveling too fast for the curve. All of these countermeasures do not change the physical alignment of the roadway, but attempt to make the driver aware of the alignment especially at sharp horizontal curves. The low-cost alignment countermeasures that were considered for this study are:

- Horizontal alignment signs
- Horizontal alignment signs with static advisory speeds
- Flashing beacons for curve warning
- Chevrons
- Post mounted delineators for curves
- Raised pavement markers for curves and other features
- Dynamic speed feedback displays on approach to curves
- High friction surface treatments for curves

6.1.2. Countermeasures Related to Roadway Cross-section

Different roadway cross-section elements have an effect on the risk associated with crashes (for example narrow lanes are associated with higher crash rates). Safety treatments that improve the roadway cross-section are costly, but some moderate to lo-cost countermeasures have been documented including lane widening, pavement friction improvements, and shoulder improvements. Lane widening provides the driver with more opportunity to safely correct in the event they are leaving their travel lane. Also drivers can more easily use the wider lane to avoid a possible oncoming or passing vehicle that is encroaching their travel lane. High friction surface treatments can be used to reduce the crashes especially at known problem areas like wet pavements. The excessive friction prevents the vehicle from slipping on wet pavements. Shoulder improvements can be done by many techniques such as shoulder widening, paving shoulders, and stabilizing shoulders. The low-cost alignment countermeasures that were considered for this study are:

- Widen lanes
- Widen paved shoulders
- Widen un-paved shoulders
- Adding paved shoulders
- Stabilizing shoulders
- High friction surface treatments

6.1.3. Countermeasures Related to Roadside Features

Roadside environment can also be improved using some low-cost countermeasures such as clear zone improvements, side slope flattening, and improving pavement edge. These countermeasures can mitigate the crash risk associated with roadside features. Clear zone improvements can be done by several techniques such as removing fixed objects near the roadway, relocating fixed objects near the roadway, installing object markers for the objects near the roadway, and using breakaway structures or posts for hardware. Flattening of side slope can improve the ability of drivers to recover from errant maneuvers. Improvement of pavement edge can be done installing safety edge and preventing pavement edge drops that usually develop from roadside erosion. If these drops become too abrupt or too deep, crashes may result from the drivers' inability to recover errant vehicles. Installation of guardrail can also improve the roadside safety. Guardrail usually reduces the severity of the crashes. Another type of treatment of roadside features is the improvement of roadside hazard rating, which means improvement of different roadside features collectively. The Highway Safety Manual (*38*) rated the roadside from 1 to 7 as shown in Table 6.1.

Table 6.1. Quantitative descriptors of roadside hazard rating (*38*)

Rating	**Clear Zone Width**	**Side-slope**	**Roadside**
1	≥ 30 ft.	Flatter than 1V:4H; recoverable	N/A
2	20 to 25 ft.	About 1V:4H; recoverable	N/A
3	About 10 ft.	About 1V:3H or1V:4H; marginally recoverable	Rough roadside surface
4	5 to 10 ft.	About 1V:3H or1V:4H; marginally forgiving	May have guardrail (offset 5 to 6.5 ft.), exposed trees, poles, and other objects (offset 10 ft.)
5	5 to 10 ft.	About 1V:3H; virtually non-recoverable	May have guardrail (offset 0 to 5 ft.), right obstacles or embankment (offset 6.5 to 10 ft.)
6	≤ 5 ft.	About 1V:2H; non-recoverable	No guardrail; exposed to rigid obstacles (offset 0 to 6.5 ft.)
7	≤ 5 ft.	1V:2H or steeper; non-recoverable	No guardrail; cliff or vertical rocks out

For this study, several treatments related to roadside features were considered:

- Flatten side slopes
- Install safety edge
- Improve roadside hazard rating
- Install object markers for roadside near the roadway
- Relocate objects near the roadway
- Remove objects near the roadway
- Install guardrail

6.1.4. Other Safety Countermeasures

Some other countermeasures that reduce crash risks on low-volume roads did not fit into the previous three categories and therefore, were grouped in a separate “other” category. Examples of these countermeasures include different types of pavement marking, highway signage and use of rumble strips. Pavement marking provide directional guidance, delineation and warnings for drivers, especially at night. Centerline and shoulder rumble strips provide both an audible warning and a physical vibration to alert drivers that they are encroaching into oncoming traffic or leaving the travel lane. Transverse rumble strips are provided to alert drivers when they are expected to slow down such as on curve approaches or on approaches to nearby intersections. Some other low-cost countermeasures to mitigate the animal-vehicle crashes were also considered in this study, as a total of 159 out of 1,251 crashes involved animal. This high proportion of animal-vehicle crashes is expected as some of the highways in study sample run through the some of the national forests of Oregon. The “other” safety countermeasures that were considered for this study are:

- Install shoulder rumble strips
- Install centerline rumble strips
- Install edge-line markings
- Install centerline markings
- Install edge-line and centerline markings
- Widen edge-line markings
- Widen centerline markings
- Install seasonal wildlife warning signs
- Vegetation removal
- Install fence
- Install fence, gap and crosswalk

6.2. Costs of the Countermeasures

It was very challenging to find the comprehensive and up-to-date cost information for all proposed safety countermeasures, as there is hardly any published information on countermeasure costs that could be used in the analysis. Therefore, significant efforts were expended in order to obtain the updated cost information. Accurate cost estimates that cover all situations were also difficult due to potential for large differences in cost between treatment areas that may have varying local factors and individual circumstances. Several state Department of Transportation (DOTs) were contacted for compiling the cost data for all proposed countermeasures. Three agencies, Oregon DOT (*39*), Florida DOT (*40*) and Texas DOT (*41*) provided the cost information on safety countermeasures. Further, the data on life span of different countermeasures were obtained from an FHWA published report (*42*).

Cost data obtained from the three DOTs and other sources were examined carefully to ensure consistency in the reported countermeasures. All cost estimates coming from different sources needed to be converted to the same units of measurements in order to use for analysis. When different cost estimates for same treatment were provided by different agencies, the average cost was used in the analysis. For the analysis, two types of costs were considered. The initial cost that is required for implementation of the safety treatment and the operating or running cost that primarily involves maintenance cost or cost of electric power in a few instances. Some of the treatments involved only initial cost over the lifespan, whereas some other treatments involved both initial and operating costs. All costs were approximate. The costs were adjusted for inflation to represent 2004 dollars using US Bureau of Labor Statistics, Consumer Price Index methods (*43*). The benefit-cost analysis used the net present worth (NPW) method and the cash flow principles where all the costs and benefits during the 10-year period were converted to 2004 values using the discount rate.

Table 6.2 to 6.5 show the treatments' initial costs and any associated maintenance and life cycle replacement type costs. The average cost was used if a range of the cost is provided. From the life cycle and the maintenance cost, the average annual maintenance cost was calculated. From observation of Table 6.2 to Table 6.5, most of the alignment safety countermeasures were found inexpensive; whereas most of the roadway cross-section countermeasures were found costly depending on the distance over which the countermeasures will be applied. Some of the roadside features countermeasures were found inexpensive and some were found expensive depending on the length; whereas most of the countermeasures in the other category were found inexpensive compared to roadway cross-section and roadside features countermeasures.

Table 6.2: Costs of alignment safety countermeasures

Safety Countermeasures	**Initial Cost**	**Maintenance Cost and Life Cycle**	**Annual Maintenance Cost**
Horizontal Alignment Sign (*40, 41*)	$300 to $2,800 per installation	$1,100 / 5 years	$220
Horizontal Alignment Sign with Static Advisory Speed (*40, 41*)	$300 to $2,800 per installation	$1,100 / 5 years	$220
Flashing Beacon for Curve Warning (*44*)	$2,100 per installation	$900 / 2 years	$450
Chevrons (*42, 45*)	$500 to $6,800 per installation	$2,900 / 5 years	$580
Post Mounted Delineators for Curves (*42*)	$4,500 per installation	Life ≥ 10 years	-
Raised Pavement Markers for Curves (*46*)	$600[1] per installation	$600 / 2 years	$300
Dynamic Speed Feedback Display on Approach to Curves (*40, 47*)	$1,900 to $11,500 per installation	$800[2] / 2 years	$400
High Friction Surface Treatment for Curves (*40, 41*)	$10,900[3] to $14,700	Life ≥ 10 years	-

---

[1] Calculated for a 500 foot horizontal curve and 40 foot marker spacing.

[2] No value given, but assumed to be equal to or greater than beacon maintenance.

[3] Calculated for a 500 foot horizontal curve with two 12-foot lanes, 1 inch mill, and 1 inch overlay.

Table 6.3: Costs of roadway cross-section safety countermeasures

Safety Countermeasures	**Initial Cost**	**Maintenance Cost and Life Cycle**	**Annual Maintenance Cost**
Widen 1 ft. Lanes (*41*)	\$60,900 per mile per ft. of width	Life ≥ 10 years	-
Widen 1 ft. Paved Shoulder (*41*)	\$60,900 per mile per ft. of width	Life ≥ 10 years	-
Widen Un-paved Shoulders (*48*)	\$49,600 per mile per ft. of width	Life ≥ 10 years	-
Add Paved Shoulder (*41*)	\$60,900 per mile per ft. of width	Life ≥ 10 years	-
Stabilize Shoulder (*48*)	\$19,900 per mile	Life ≥ 10 years	-
High Friction Surface Treatment (*40, 41*)	\$114,200 to \$157,400[4] per mile	Life ≥ 10 years	-

Table 6.4. Costs of roadside features safety countermeasures

Safety Countermeasures	**Initial Cost**	**Maintenance Cost and Life Cycle**	**Annual Maintenance Cost**
Flatten Side Slopes (*40*)	\$27,900[5] per mile	Life ≥ 10 years	-
Install Safety Edge (*49*)	\$500 to \$2,000 per mile	Life > 10 years	-
Improve Roadside Hazard Rating (*41*)	\$82,100 per mile	Life > 10 years	-
Install Object Markers for Objects Near the Roadway (*40*)	\$4,300 to \$6,800[6] per mile	Life > 10 years	-
Relocate Objects Near the Roadway (*41*)	\$82,100 per mile	Life > 10 years	-
Remove Objects Near the Roadway (*41*)	\$82,100 per mile	Life > 10 years	-
Install Guardrail (*42, 63*)	\$15,800 to \$177,200 per mile	Life > 10 years	-

---

[4] Calculated for 12 foot lanes, 1 inch mill and 1 inch overlay.

[5] Calculated for 3:1 to 6:1 flattening 30 ft width.

[6] Calculated assuming 1 marked object every 100 ft.

Table 6.5. Costs of other safety countermeasures

Safety Countermeasures	**Initial Cost**	**Maintenance Cost and Life Cycle**	**Annual Maintenance Cost**
Install Shoulder Rumble Strips (*45*)	$2,100 per mile	Life > 10 years	-
Install Centerline Rumble Strips (*45*)	$2,100 per mile	Life > 10 years	-
Install Edge-line Markings (*50*)	$1,800 to 4,900 per mile per line	$3,400 / 3 years	$1,140
Install Centerline Markings (*50*)	$1,800 to 4,900 per mile per line	$3,400 / 3 years	$1,140
Install Edge-line and Centerline Markings (*50*)	$3,600 to 4,900 per mile per line	$6,700 / 3 years	$2,240
Widen Edge-line Markings (*40*)	$4,300 per mile per line	$4,300 / 3 years	$1,440
Widen Centerline Markings (*40*)	$4,300 per mile per line	$4,300 / 3 years	$1,440
Install Seasonal Wildlife Warning Sign (*64*)	$1,900 per mile	Life > 10 years	-
Vegetation Removal (*64*)	$1,000 per mile per year	-	$1,000
Install Fence (*64*)	$162,800 per mile	$600/ year	$600
Install Fence, Gap & crosswalk (*64*)	$,86,600 per mile	$600/ year	$600

6.3. Benefits of the Countermeasures

Safety benefits in the form of crash reductions are the only tangible benefits that should be considered in any economic analysis. These benefits can be estimated using crash reduction factors (CRFs) that represent the proportion of total crashes that can be expected to be avoided by using the treatment/countermeasure. Therefore, CRFs were instrumental in assessing the benefits of countermeasures. Other potential benefits associated with a few countermeasures (e.g. wider lanes and shoulders may be associated with higher speeds and lower travel times) were deemed minimal at best.

This study utilized all published information on CRFs including the U.S. Department of Transportation (USDOT) CMFs clearinghouse. One issue that was encountered in assessing countermeasure benefits is that a complete set of CRFs is currently unavailable for all countermeasures and all crash severities. This is well understood, given the fact that this knowledge has been growing and evolving with time, and it will take some time before a comprehensive set of CRFs becomes available. The CRFs included here were meant to be estimates using the best information available. Another issue that was encountered in the process is that the CRFs for a given safety countermeasure may vary in a wide range and inconsistency may exist in the CRFs, especially if those factors are obtained from different sources. Therefore, extreme caution was exercised in applying the CRFs in this study. For a range of CRF values, the average value was used for benefit-cost analysis. Table 6.6 to Table 6.9 show the CRFs for the proposed safety countermeasures.

Table 6.6. CRFs of alignment safety countermeasures

Safety Countermeasures	**CRF**			
	All	**PDO**	**Injury**	**Fatal**
Horizontal Alignment Sign (*51*)	23% to 30%		20%	55%
Horizontal Alignment Sign with Static Advisory Speed[7] (*38, 51*)	20% to 29%		13%	
Flashing Beacon for Curve Warning (*51*)	30%			
Chevrons (*51*)	20% to 50%			
Post Mounted Delineators for Curves (*51*)	20% to 30%			
Raised Pavement Markers for Curves (*35, 51*)	4% to 16%			
Dynamic Speed Feedback Display on Approach to Curves (*52*)	7%			
High Friction Surface Treatment for Curves (*51*)	10% to 24%			

Table 6.7. CRFs of roadway cross-section safety countermeasures

Safety Countermeasures	**CRF**			
	All	**PDO**	**Injury**	**Fatal**
Widen 1 ft. Lanes (*53*)		5%	9%	
Widen 1 ft. Paved Shoulder (*53*)		1%	4%	
Widen Un-paved shoulder – unspecified amount (*51*)	15% to 30%			
Add Paved Shoulder (*51, 54, 55*)	4% to 30%			
Stabilize Shoulder (*51*)	25%			
High Friction Surface Treatment (*51, 53*)	4% to 13%	8%	9%	

---

[7] For B/C ratio calculations for Horizontal Alignment Signs with Advisory Speeds will not have lower CRF than Horizontal Alignment Signs alone despite minor differences.

Table 6.8. CRFs of roadside features countermeasures

Safety Countermeasures	**CRF**			
	All	**PDO**	**Injury**	**Fatal**
Flatten Side Slopes (*35, 51, 56*)	3% to 50%			
Install Safety Edge (*34*)	6%			
Improve Roadside Hazard Rating (*38*)	6% to 33%			
Install Object Markers for Objects Near the Roadway (*51*)	16%	14%	17%	41%
Relocate Objects Near the Roadway (*51*)	25% to 55%		25%	40%
Remove Objects Near the Roadway (*51, 56*)	18% to 61%		30%	50%
Install Guardrail (*65*)		7%	47%	44%

Table 6.9. CRFs of other safety countermeasures

Safety Countermeasures	**CRF**			
	All	**PDO**	**Injury**	**Fatal**
Install Shoulder Rumble Strips (*57*)	33%			
Install Centerline Rumble Strips (*38, 58*)	14%			
Install Edge-line Markings (*51, 59*)	4% to 44%	8%	15%	
Install Centerline Markings (*51*)	30% to 35%			
Install Edge-line and Centerline Markings[8] (*60*)	14%			
Widen Edge-line Markings (*61*)	18% to 30%			
Widen Centerline Markings (*51*)	38%			
Install Seasonal Wildlife Warning Sign (*64*)	26%			
Vegetation Removal (*64*)	38%			
Install Fence (*64*)	86%			
Install Fence, Gap & crosswalk (*64*)	40%			

---

[8] For B/C ratio calculations edge-line + centerline markings will not have lower CRF than edge-line or centerline markings alone despite minor differences.

The crash reduction benefits of the safety countermeasures can be quantified in monetary value using agency defined crash cost equivalencies for different crash severities. Table 6.10 shows the crash costs for different crash types as defined by both Oregon DOT (ODOT) and the American Association of State Highway and Transportation Officials (AASHTO) in the Highway Safety Manual (HSM). Costs were adjusted for inflation to represent 2004 dollars using US Bureau of Labor Statistics, Consumer Price Index and Employment Cost Index methods (*43*) as suggested in the HSM.

Table 6.10. Crash costs by severity

Crash Type	**ODOT Cost[9] (*62*)**	**HSM Cost (*38*)**
PDO	$16,156	$8,016
Injury C	$68,704	$49,726
Injury B		$88,334
Injury A	$1,414,452	$241,852
Fatal		$4,574,553

The Oregon DOT crash costs combine fatal and injury type-A crashes, which is slightly different from the HSM values used that have separate costs for fatal and injury crashes. Similarly, injury B and injury C crashes are combined together for ODOT crash cost estimates and separated for HSM cost estimates. The total crash costs on the road sample were found by applying the cost estimates provided by ODOT and HSM to the observed 10 year crashes on the selected sample. Table 6.11 shows the samples with crash characteristics and total 10-year equivalent crash costs.

---

[9] Costs for Rural, non-Interstate, State Highway

Table 6.11. Estimated crash costs on road sample

Sample	**Quantity**	**10 Year Crash Cost**						**ODOT Cost**	**HSM Cost**
		PDO	**Inj. C**	**Inj. B**	**Inj. A**	**Fatal**	**Total**		
Curves	2841 curves	145	66	120	36	8	375	$77.4M	60.3M
All	680.85 miles	550	199	349	117	36	1251	$262.9 M	238.1M

As the CRFs of countermeasures and crash costs at different severity rates are known, benefits associated with a particular countermeasure can be estimated using the reduction in crash frequency and/or severity expected upon the implementation of the countermeasure. Some safety countermeasures are targeted toward curves while others are applied to all road type segments. For benefit/cost analyses, the crash reduction cost savings for possible alignment safety measures were applied to all horizontal curves in the sample. All other safety countermeasures were targeted toward all road segments and the cost reduction benefits for those were therefore applied to all of the road sample. To determine the potential crash reduction benefits for each treatment, the number of crashes prevented for each crash type per unit (either curve or mile of road) were calculated using the CRFs. Then each treatment's benefit was calculated using the number of crashes prevented and the cost of each type of crash. This resulting 10-year unit benefit was then normalized to 1-year benefit to get the annual benefits or savings in crashes. For calculating the benefit of the countermeasures related to wildlife safety, only the animal-vehicle crashes were considered.

6.4. Economic Feasibility of the Countermeasures

For benefit/cost ration calculation, the net present worth method (NPW) was used in this study. As all of the data for this study collected for the time period of 2004 to 2013, all of the costs were converted to 2004 dollars value. The assumption was that, if the countermeasures were installed in 2004, how much benefit would result over the 10 year period. Therefore, the NPW benefit was calculated using the following equation (*66*).

$$NPW = EUAW\left[\frac{(1+i)^N-1}{i(1+i)^N}\right] \qquad \text{(Equation 6.1)}$$

Where,

EUAW = equivalent uniform annual worth

NPW = net present worth

i = interest rate or discount rate

N = number of years

For this study, the EUAW benefit was estimated as the annual benefits due to crash reductions minus the annual maintenance cost of the countermeasures. The average interest rate or discount rate for the period 2004 to 2013 was used (3.44%). The annual interest rates used in this study are those published by the Internal Revenue Service (*67*). A sample calculation of benefit/cost ratio is shown in Appendix D. Table 6.12 to 6.15 shows the benefit/cost ratio of all of the countermeasures using ODOT and HSM crash cost estimates. Benefit/cost ratios greater than 1.0 are marked (bold underlined values) to show measures that are economically feasible for implementation on low-volume roads.

Table 6.12. Benefit/cost ratios of alignment countermeasures

Safety Countermeasures	**B/C (ODOT values)**	**B/C (HSM values)**
Horizontal Alignment Sign	**2.96**	**1.78**
Horizontal Alignment Sign with Static Advisory Speed	**2.96**	**1.78**
Flashing Beacon for Curve Warning	**1.47**	0.75
Chevrons	0.87	0.39
Post Mounted Delineators for Curves	**1.26**	0.98
Raised Pavement Markers for Curves	**1.11**	0.56
Dynamic Speed Feedback Display on Approach to Curves	0.06	0.01
High Friction Surface Treatment for Curves	0.31	0.24

Table 6.13. Benefit/cost ratios of roadway cross-section countermeasures

Safety Countermeasures	**B/C (ODOT values)**	**B/C (HSM values)**
Widen 1 ft. Lanes	0.08	0.13
Widen 1ft. Paved Shoulder	0.03	0.06
Widen Un-paved shoulder – unspecified amount	**1.46**	**1.32**
Add Paved Shoulder	0.90	0.82
Stabilize Shoulder	**2.02**	**1.83**
High Friction Surface Treatment	0.20	0.19

Table 6.14. Benefit/cost ratios of roadside features countermeasures

Safety Countermeasures	**B/C (ODOT values)**	**B/C (HSM values)**
Flatten Side Slopes	**1.53**	**1.39**
Install Safety Edge	**7.74**	**7.01**
Improve Roadside Hazard Rating	0.77	0.69
Install Object Markers for Objects Near the Roadway	**10.67**	**8.82**
Relocate Objects Near the Roadway	**1.49**	**1.27**
Remove Objects Near the Roadway	**1.84**	**1.56**
Install Guardrail	**1.44**	**1.34**

Table 6.15. Benefit/cost ratios of other safety countermeasures

Safety Countermeasures	**B/C (ODOT values)**	**B/C (HSM values)**
Install Shoulder Rumble Strips	**25.32**	**22.92**
Install Centerline Rumble Strips	**21.49**	**19.46**
Install Edge-line Markings	**9.26**	**7.78**
Install Centerline Markings	**28.45**	**25.49**
Install Edge-line and Centerline Markings	**6.38**	**5.65**
Widen Edge-line Markings	**7.60**	**6.75**
Widen Centerline Markings	**25.70**	**23.00**
Install Seasonal Wildlife Warning Sign	**3.56**	**1.80**
Vegetation Removal	**1.50**	0.00
Install Fence	0.11	0.04
Install Fence, Gap & crosswalk	0.03	0.00

Only a few countermeasures (i.e. horizontal alignment signs, flashing beacons, and post mounted delineators) related to highway alignment were found to have benefit/cost ratios slightly greater than 1. This is despite the fact that the study did not include safety improvements which involve costly changes to alignment (e.g. flattening horizontal and vertical curves). Most of the roadway cross section safety treatments are too costly to result in benefit/cost ratios greater than 1. Only widening unpaved shoulders, adding a paved shoulder, and stabilizing shoulders were found to be cost effective (benefit/cost ratios greater than 1). Unlike the previous two categories, most countermeasures in the third category, i.e. those related to changes in roadside features, were found economically feasible with a couple of measures showing relatively high return on investment (using safety edge and object markers). Most of the countermeasures in the “other” category were found economically feasible with centerline markings and shoulder & centerline rumble strips showing the highest return on investment (benefit/cost ratios greater than 20) followed by installing object markers, installing and widen edge-line marking, installing safety edge (benefit/cost ratios greater than 5). One important consideration during installation of shoulder rumble strip is the consideration of bicyclists. The shoulder rumble strips are believed to compromise the safety of bicyclists due to the difficulties to ride on or over the rumble strips. Specific design standards of the shoulder rumble strips are suggested by researchers when significant amount of bicyclists are present. However, in this study only 1 crash out of 1,251 crashes involved bicycles. Therefore, this safety concern was not considered in the economic feasibility analysis of guardrails. Only two countermeasures related to animal-vehicle crashes were found to be cost effective, namely: seasonal wildlife warning sign and vegetation removal.

While the results for the last two categories are promising, the reader should be cautioned that many of the treatment costs could vary greatly from the costs used in this study due to local factors and circumstances. Overall, the benefit-cost ratios shown in Table 6.12 to Table 6.15 suggest that, the majority of economically feasible countermeasures are low-cost safety improvements which is somewhat expected on low-volume roads due to low traffic exposure.

Figure 6.1 shows the safety countermeasures ranked based on the benefit-cost ratio starting with the most economically feasible measures. This figure clearly shows that the use of centerline markings, rumble strips, object markers, safety edge, and edge-line markings are associated with the highest return on investment (benefit/cost ratios greater than 7). All of the treatments that were found to be most cost-effective are low-cost countermeasures. For example – installation of rumble strips cost only $2100 per mile and no maintenance cost is required. Similarly, installation of object markers, centerline marking and safety edge require a lower initial costs and lower or no maintenance costs. At the other end of the spectrum, higher cost measures (e.g. lane and shoulder widening) were found infeasible for implementation along low-volume roads.

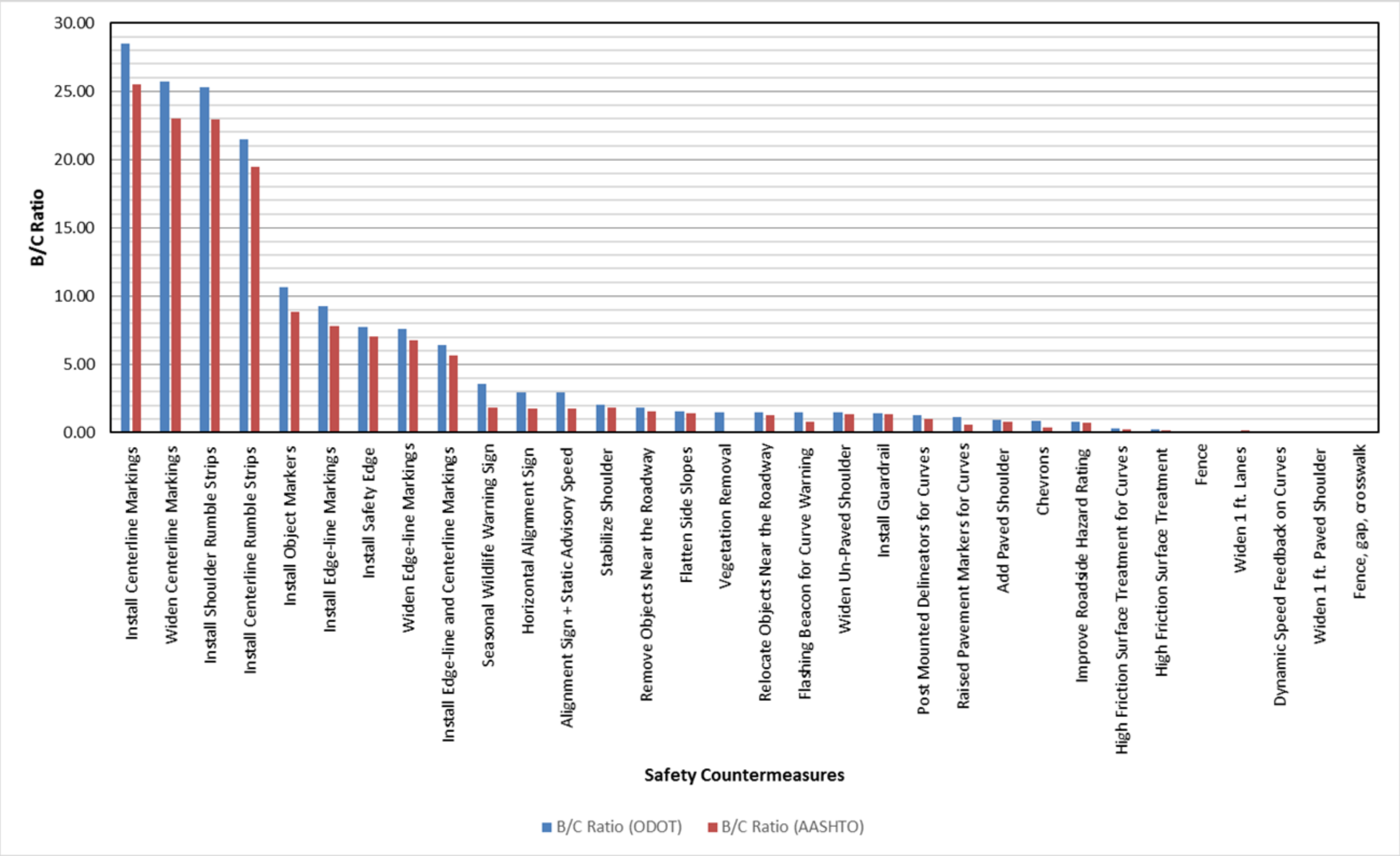

Figure 6.1: Benefit/cost ratios of safety countermeasures ranked in descending order

CHAPTER SEVEN – SUMMARY & CONCLUSIONS

It seemed necessary to investigate the safety aspects of the low-volume rural roads. Due to lower traffic exposure, these roads usually don't experience higher crash frequencies; which makes it difficult to identify the hazardous locations on these roads based on the crash history alone. However, these low-volume roads may be associated with higher level of risks and consequently higher crash rates due to substandard geometry on these roads. Therefore, different tasks were completed in this study in order to identify the factors and features that make the low-volume roads risky and identify the treatments that can be implied to improve the safety of the roads.

First, a literature review was conducted that sought to identify which factors and features have been identified in past work, as presenting a risk to drivers as well as which prospective countermeasures exist to address them. Additionally, this literature review identified and summarized existing approaches to developing risk or safety indices that can be used in identifying where current features pose a potential risk to drivers. After that, the data collection process included gathering of road geometry data, roadside feature data, 10-year crash history, and 10-year traffic data for approximately 830 miles of Oregon's low-volume roads at 0.05-mile resolution, which were then used in the data analysis task.

In the data analysis task, Oregon's low volume roads were sampled and characterized along with crash rate relationships, regressions, and correlations in an effort to understand geometric and other roadway characteristics. This work has been done to determine which roadway characteristics may contribute to crash occurrence and aid in risk identification. The analyses conducted have shown which factors may influence crash risk, and roughly the extent to which the risk may be increased for different situations. Table 7.1 shows a summary of the road characteristics and the resulting crash rate differences between categories of road character. The difference in crash rate expressed in Table 7.1 was due partly to the road characteristics listed, but was also expected to be the result of multiple factors acting in conjunction. For example, degree of curvature and length of horizontal curve are related and thus some of the difference in crash rate between degree of curvature categories may be due to curve length.

Table 7.1. Summary of road characteristics

Road Characteristics	**Category Change**	**Crash Rate Change (Crash/MVMT)**	**Difference (%)**
Length of Horizontal Curve (ft.)	> 600 to ≤ 100	0.24 to 4.87	1929
Degree of Curvature	< 5 to ≥ 30	0.36 to 3.81	958
Length of Vertical Curve (ft.)	> 600 to ≤ 100	0.34 to 3.38	894
Grade (%)	< 1 to 4-5	0.88 to 1.64	86
Shoulder Width (ft.)	4 to 0	0.78 to 1.43	83
Lane Width (ft.)	12 to 10	0.90 to 1.48	64
Side Slope Rating	1 to 2.5	0.80 to 1.28	60
Driveway Density (driveways/mile)	1 to 5	0.84 to 1.34	60
Fixed Object Rating	Variable	Variable	Variable

In the next task, a crash risk index was developed based on the extensive data analysis efforts, which is a function of geometry of the road and roadside features (x_G), crash history (x_C), and traffic exposure (x_T). Furthermore, three case studies were completed to illustrate the use of the crash risk index on real world roads in Oregon. The final equation of the developed risk index with the numerical limits are:

- ➢ $CRI = 0.45(x_G) + 0.25(x_C) + 0.30(x_T)$
    - CRI varies from 0.06 to 1.00.
    - x_G varies from 0.00 to 1.00 based on the G values.
        - o G varies from 0.21 to 1.00 based on the geometric feature weights and values
    - x_C varies from 0.00 to 1.00 based on crash history.
    - x_T varies from 0.20 to 1.00 based on the traffic and truck volumes.

Finally, an economic analysis of potential low-cost safety countermeasures was completed. The economic analysis of the proposed safety measures for the low-volume rural road sample has shown certain treatments to be potentially economically beneficial and feasible for implementation. The results of the economic analysis were highly depended upon the costs of the treatments. While all efforts were made to choose accurate treatment costs, again agency and region specific cost information could improve the localized benefit / cost ratio results that generated these recommended low-volume treatments. The most economically beneficial safety treatments for the low-volume road sample were found to be:

- Install Centerline Markings
- Widen Centerline Markings
- Install Shoulder Rumble Strips
- Install Centerline Rumble Strips
- Install Object Markers for Objects near the Roadway

- Install Edge-line Markings
- Install Safety Edge
- Widen Edge-line Markings
- Install Edge-line and Centerline Markings
- Install Seasonal Wildlife Warning Sign
- Install Horizontal Alignment Sign
- Install Horizontal Alignment Signs with Static Advisory Speed
- Stabilize Shoulder
- Remove Objects near the Roadway
- Flashing Beacons for Curve Warning
- Vegetation Removal
- Flatten Side-slopes
- Relocate Objects near the Roadway
- Widen Un-paved Shoulder
- Install Guardrail
- Raised Pavement Markers for curves
- Post Mounted Delineators for curves

This study was performed based on 831 miles of road data and 10 years of crash data that were collected from Oregon DOT online database. Some error might have occurred from data collection process through the data analysis tasks. Limitations of this study and recommendations to improve this study are:

i. In this study only police reported crashes were used, as usually online database keeps records of these crashes. Many PDO or minor injury crashes go unreported. Therefore, the results found from the study may not be accurate. The accurate results can be obtained, if the data regarding unreported crashes were available for use.

ii. Some human error might occur during the data collection at 0.05-mile resolution, as the roadside hazard rating and side slope rating required assigning values from video log images. This error can be minimized, if the assignment of the roadside hazard and side slope rating was done based on site observation instead of video log images.

iii. For economic feasibility study, costs of the countermeasures from Texas DOT and Florida DOT in addition to Oregon DOT were used. Whereas, crash costs from Oregon DOT and HSM and crash data from Oregon were used for estimation of benefit. The geographical difference of Texas and Florida from Oregon may have an effect on the cost of countermeasures. Therefore, the benefit/cost ratio found from the study may not represent the actual ratio. This limitation can be avoided, if cost information of all of the safety treatments were available from Oregon DOT that represent the cost based on overall condition of Oregon.

Although this study was performed on the low-volume roads of the state of Oregon, other states and agencies with similar road types and traffic conditions may follow the procedure to develop and apply the developed risk index in order to identify the contributing factors of crashes. The results found from this study can be used by other agencies to proactively identify potentially risky road segments that may be unidentified using traditional methods, which often require a localized crash frequency that may be greater than what is realistic given low traffic volumes. The application of the risk index to three sites confirmed the fact that, the use of CRI provides new information about the level of hazard along highway segments compared to using crash history alone. In addition, the cost-effective safety countermeasures identified from this study can be applied by different agencies to similar road types in order to improve the safety of the roads.

REFERENCES CITED

1. Federal Highway Administration. *Manual on Uniform Traffic Control Devices, 2009 ed*. Federal Highway Administration, United States Department of Transportation, Washington D.C.

2. McDonald, Thomas and Robert Sperry. *Evaluation of Mitigation for Safety Concerns on Low-Volume, Unpaved Rural Roads*. Institute for Transportation, Iowa State University, Ames, May 2013.

3. Gross, Frank, Kimberly Eccles and Daniel Nabors. "Low-Volume Roads and Road Safety Audits - Lessons Learned." In *Transportation Research Record: Journal of the Transportation Research Board, No. 2213*, TRB, National Research Council, Washington, D.C., 2011.

4. Federal Highway Administration. *Roadway Widths for Low-Traffic Volume Roads*. Federal Highway Administration, United States Department of Transportation, Washington D.C., July 1994. Accessed at https://www.fhwa.dot.gov/publications/research/safety/humanfac/94023.cfm

5. National Highway Traffic Safety Administration. Fatality Analysis Reporting System (FARS) Data Query Tool, 2013 Data. Gathered June, 2015.

6. U.S. Department of Transportation, Office of Highway Policy Information. Highway Statistics 2013. Accessed at http://www.fhwa.dot.gov/policyinformation/statistics/2013/vm2.cfm

7. Peng, Yichuan, Srinivas Reddy Geedipally and Dominque Lord. "Effect of Roadside Features on Single-Vehicle Roadway Departure Crashes on Rural Two-Lane Roads." In *Transportation Research Record: Journal of the Transportation Research Board, No. 2759*, TRB, National Research Council, Washington, D.C., 2012.

8. Cenek, P., Davies, R., and Henderson, R. *Crash Risk Relationships for Improved Road Safety Management*. Publication 488. New Zealand Transport Agency, 2012.

9. Schrum, Kevin, Karla Lechtenberg, Cody Stolle, Ronald Faller and Dean Sickling. *Cost-Effective Safety Treatments for Low-Volume Roads*. Report No. TRP-03-222-12, Nebraska Department of Roads, Lincoln, August 2012.

10. Souleyrette, Reginald, Mehmet Caputcu, Thomas McDonald, Robert Speery, Zachary Hans and Dan Cook. *Safety Analysis of Low-Volume Rural Roads in Iowa*. Report No. 07-309, Iowa Department of Transportation, Ames, December 2010.

11. Garber, N. and Kassebaum, E. *Evaluation of Crash Rates and Causal Factors for High-Risk Locations on Rural and Urban Two-Lane Highways in Virginia*. Publication FHWA/VTRC 09-R1. Virginia Transportation Research Council, 2008.

12. Gross, F., Jovanis, P., and Eccles, K. "Safety Effectiveness of Lane and Shoulder Width Combinations on Rural, Two-Lane, Undivided Roads." In *Transportation Research Record: Journal of the Transportation Research Board, No. 2103*, Transportation Research Board of the National Academies, Washington, D.C., 2009.

13. Cafiso, Salvatore, Grazia La Cava and Alfonso Montella. "Safety Inspections as Supporting Tool for Safety Management of Low Volume Roads." In *Transportation Research Record: Journal of the Transportation Research Board, No. 2203*, TRB, National Research Council, Washington, D.C., 2011.

14. Prato, Carlo, Thomas Rasmussen and Sigal Kaplan. "Risk Factors Associated with Crash Severity on Low-Volume Rural Roads in Denmark." In *Journal of Transportation Safety & Security*, Vol. 6, No. 1, 2014.

15. McLean, J., Veith, G., and Turner, B. *Road Safety Engineering Risk Assessment Part 1: Relationships between Crash Risk and Standards of Geometric Design Elements*. Publication AP-T146/10. Austroads, 2010.

16. Labi, S. *Effects of Geometric Characteristics of Rural Two-Lane Roads on Safety*. Publication FHWA/IN/JTRP-2005/2. Joint Transportation Research Program, Purdue University, 2006.

17. Findley, Danie, Joseph Hummer, William Rasdorf, Charles Zegeer and Tyler Fowler. "Modeling the Impact of Spatial Relationships on Horizontal Curve Safety." In *Accident Analysis and Prevention*, Vol. 45, No. 1, 2012.

18. Knapp, Keith and Ferrol Robinson. *The Vehicle Speed Impacts of a Dynamic Horizontal Curve Warning Sign on Low-Volume Local Roadways*. Report No. CTS 12-12, Minnesota Department of Transportation, St. Paul, May 2012.

19. Schnieder, William, Peter Savolainen and Karl Zimmerman. "Driver Injury Severity Resulting from Single-Vehicle Crashes along Horizontal Curves on Rural Two-Lane Highways." In *Transportation Research Record: Journal of the Transportation Research Board, No. 2102*, TRB, National Research Council, Washington, D.C., 2009.

20. Matirnez, A., D. Mantaras and P. Luque. "Reducing Posted Speed and Perceptual Countermeasures to Improve Safety in Road Stretches with a High Concentration of Accidents." In *Safety Science*, Vol. 60, 2013.

21. Mahgoub, H., A. A. Selim, and K.C. Pramod. *Quantitative Assessment of Local Rural Road 28 Safety – Case Study*. Proceedings of the 90th Annual Transportation Research Record 29 Meeting, January, 2011. 14 pp.

22. Pardillo-Mayora, Jose, Carlos Dominguez-Lira and Rafel Jurado-Pina. "Empirical Calibration of a Roadside Hazardousness Index for Spanish Two-Lane Rural Roads." In *Accident Analysis and Prevention*, Vol. 42, No. 6, 2010.

23. Waiby, Gina, Fergus Tate and Colin Brodie. *The Development of a Proactive Road Safety Assessment Tool – KiwiRap*. Proceedings of the Australasian Road Safety Research, Policing and Education Conference, Wellington, New Zealand, October, 2012.

24. Nodari, Christine and Luis Lindau. *Proactive Method for Safety Evaluation of Two-Lane Rural Highway Segments*. Proceedings of the 85th Annual Transportation Research Record Meeting, January, 2006.

25. Montella, Alfonso. "Safety Reviews of Existing Roads – Quantitative Safety Assessment Methodology." In *Transportation Research Record: Journal of the Transportation Research Board, No. 1922*, TRB, National Research Council, Washington, D.C., 2005.

26. Montella, Alfonso and Filomena Mauriello. "Procedure for Ranking Unsignalized Rural Intersections for Safety Improvement." In *Transportation Research Record: Journal of the Transportation Research Board, No. 2318*, TRB, National Research Council, Washington, D.C., 2012.

27. Evans, B., J. Jones, and K. Ksaibati. *Implementation of the Wyoming Rural Road Safety Program*. Proceedings of the 91st Annual Transportation Research Record Meeting, January, 2012.

28. deLeur, P., and T. Sayed. "Development of a Road Safety Risk Index." In *Transportation Research Record: Journal of the Transportation Research Board, No. 1784*, TRB, National Research Council, Washington, D.C., 2002.

29. Isebrands, H.N. *Rural Road Safety, Systemic Safety with Low Cost Safety Improvements*. Presentation to the Wisconsin County Highway Association, June 3013.

30. Potts, I., D. Harwood, C. Bokenkroger, and M. Knoshaug. *Benefit/Cost Evaluation of MoDOT's Total Striping and Delineation Program: Phase II*. MRIGlobal. 2011.

31. Mclnerney, R., G. Smith. *Saving Lives through Investment in Safer Roads: The iRAP Partnership*. International Road Assessment Program.

32. Meuleners, L.B., D. Hendrie, and A.H. Lee. “Effectiveness of Sealed Shoulders and Audible Edge Lines in Western Australia.” In *Transportation Research Record: Journal of the Transportation Research Board*, TRB, National Research Council, Washington, D.C., 2011.

33. Srinivasan, R., J. Baek, D. Carter, B. Persaud, C. Lyon, K. Eccles, F. Gross, and N. Lefler. *Safety Evaluation of Improved Curve Delineation*. Report No. FHWA-HRT-09-045. 2009.

34. Federal Highway Administration. *Safety Evaluation of the Safety Edge Treatment: Summary Report*. Report No. FHWA-HRT-11-025. Federal Highway Administration, 2011.

35. Neuman, T., R. Pfefer, K. Slack, K. Hardy, F. Council, H. McGee, L. Prothe, and K. Eccles. *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 6: A Guide for Addressing Run-Off-Road Collisions*. NCHRP Report 500. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C. 2003.

36. Persaud, B., C. Lyon, K. Eccles, and J. Soika. “Safety Evaluation of Centerline plus Shoulder Rumble Strips.” In *Transportation Research Record: Journal of the Transportation Research Board, No. 15-4996*, TRB, National Research Council, Washington, D.C., 2015.

37. Ayala, R.D., and R.E. Turochy. “Preliminary Economic Analysis of Paved Shoulder Installation on High-Priority Segments of Two-Lane Rural Highways in Alabama.” In *Transportation Research Record: Journal of the Transportation Research Board, No. 09-0382*, TRB, National Research Council, Washington, D.C., 2009.

38. American Association of State Highway and Transportation Officials. *Highway Safety Manual*, First Edition. AASHTO, 2010.

39. Oregon Department of Transportation Historical Bid Price Listings by Region, 2014.

40. Phillip "Greg" Davis, State Estimates Engineer, Florida Department of Transportation (FDOT), Correspondence. May, 2015.

41. Darren McDaniel, Safety Engineer, Texas Department of Transportation (TxDOT), Correspondence. May, 2015.

42. Atkinson, J.E., B.E. Chandler, V. Betkey, K. Weiss, K. Dixon, A. Giragosian, K. Donoughe, and C. O’Donnell. *Manual for Selecting Safety Improvements on High Risk Rural Roads*. Federal Highway Administration (FHWA), Washington, D.C., 2014.

43. CPI Inflation Calculator, Bureau of Labor Statistics, United States Department of Labor. Accessed at http://www.bls.gov/data/inflation_calculator.htm

44. Sperry, R., Latterell, J., and McDonald, T. *Best Practices for Low-Cost Safety Improvements on Iowa's Local Roads*. Report CTRE-08-338. 2008.

45. McGee, H., and Hanscom, F. *Low-Cost Treatments for Horizontal Curve Safety*. Report No. FHWA-SA-07-002. 2006.

46. Jiang, Yi. *The Effectiveness and Criteria for Placement of Raised Pavement Markers - Synthesis Study*. Report FHWA/IN/JTRP-2006/6 for the Indiana DOT. 2006.

47. Hallmark, S., Peterson, E., Fitzsimmons, E., Hawkins, N., Resler, J. and Welch, T. *Evaluation of Gateway and Low-Cost Traffic-Calming Treatments for Major Routes in Small Rural Communities*. Center for Transportation Research and Education. 2007.

48. White, D., Mekkawy, M., Jahren, C., Smith, D., and Suleiman, M. *Effective Shoulder Design and Maintenance.* Report IHRB-TR-531 for Iowa Highway Research Board. 2007.

49. Graham, J., Richard, K., O'Laughlin, M., and Harwood, D. *Safety Evaluation of the Safety Edge Treatment*. Summary Report FHWA-HRT-11-025. 2011.

50. Knodler Jr, Michael A., and John Collura. *Massachusetts Traffic Safety Toolbox Final Repor*t. No. SPRII. 03.07. 12. 2008.

51. Gan, A., Shen, P., and Rodriguez, A. *Update of Florida Crash Reduction Factors and Countermeasures to Improve the Development of District Safety Improvement Projects*. Lehman Center for Transportation Research – Florida International University, 2005.

52. Hallmark, S., Hawkins, N., and Smadi, O. *Evaluation of DSFS and Low Cost Treatments to Reduce Speed and Crashes on Rural Curves.* Presentation given at the National Association of County Engineers Conference, April, 2013.

53. Labi, S. "Efficacies of Roadway Safety Improvements Across Functional Subclasses of Rural Two-Lane Highways." In *Journal of Safety Research*, No. 42, 2011. pp. 231-239.

54. Turner, B., K. Imberger, P. Roper, V. Pyta, and J. McLean. *Road safety engineering risk assessment: part 6: crash reduction factors*. No. Publication AP-T151/10. Austroads, 2010.

55. Hallmark, S., Qiu, Y., Pawlovich, M., McDonald, T. “Assessing the Safety Impacts of Paved Shoulders.” In *Journal of Transportation Safety and Security*. Vol. 5, 2013. pp. 131-147.

56. Federal Highway Administration. “Technology Partnerships Program to Evaluate LED Raised Pavement Markers.” *Highways for Life Program: Innovator*. FHWA-HIF-12-017, Vol. 5, Issue 28. Jan/Feb, 2012.

57. Abdel-Rahim, A. and Khan, M. *Potential Crash Reduction Benefits of Safety Improvement Projects – Part A: Shoulder Rumble Strips*. National Institute for Advanced Transportation Technology, Report No. FHWA-ID-12-191A. 2012.

58. Persaud, B., Retting, R., and Lyon, C. *Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads*. Insurance Institute for Highway Safety, Arlington, VA, 2003.

59. Sun, X. and Das, S. *Safety Improvements from Edge Lines on Rural Two-Lane Highways*. Report No. FHWA/LA.11/487, University of Louisiana at Lafayette. 2012.
60. Al-Masaeid, H. and Sinha, K. “Analysis of Accident Reduction Potentials of Pavement Markings.” In *Journal of Transportation Engineering.* Vol. 120, No. 5. 1994. pp. 723-736.

61. Park, E., Carlson, P., Porter, R., and Andersen C. “Safety Effects of Wider Edge Lines on Rural, Two-Lane Highways.” In *Accident Analysis and Prevention*, Vol. 48, 2012. pp. 317-325.

62. Oregon Department of Transportation Highway Safety Projects Benefit/Cost Analysis Worksheet.

63. *Guardrail Replacement and Repair*. St. Mary's County, Maryland. Accessed at http://www.stmarysmd.com/dpw/Guardrails.asp

64. Huijser, Marcel P., John W. Duffield, Anthony P. Clevenger, Robert J. Ament, and Pat T. McGowen. "Cost–benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: a decision support tool." In *Ecology and Society* 14, no. 2 (2009): 15.

65. Crash Modification Factors Clearinghouse, U.S. Department of Transportation, Federal Highway Administration. Accessed at http://www.cmfclearinghouse.org/

66. Garber, Nicholas, and Lester Hoel. *Traffic and highway engineering*. Cengage Learning, 2014.

67. Historical IRS Discount Rates. Accessed at
http://www.pgcalc.com/support/historical-irs-discount-rates.htm

APPENDICES

APPENDIX A

REGRESSION RESULTS

Table A.1. Crash rate regression results (for all geometrics sample)

Regression Statistics	
Multiple R	0.26852348
R Square	0.07210486
Adjusted R Square	0.07149113
Standard Error	1.11593387
Observations	13617

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	9	1316.755	146.3061	117.4858	1.7137E-213
Residual	13607	16944.91	1.245308		
Total	13616	18261.67			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.31652133	0.165294	14.01457	2.58E-44	1.992522736	2.64051992
LW	-0.162601	0.013589	-11.966	7.83E-33	-0.189236541	-0.1359654
SW	0.00943646	0.002504	3.768361	0.000165	0.004528024	0.01434491
SS	0.15649602	0.021227	7.37236	1.77E-13	0.114887386	0.19810466
FO	0.09061717	0.02124	4.266355	2E-05	0.048983931	0.1322504
GR	-0.05717	0.031535	-1.81289	0.069871	-0.11898366	0.00464358
G	0.00548857	0.001459	3.762336	0.000169	0.002629079	0.00834805
VC	0.04205558	0.022997	1.82875	0.067459	-0.003021531	0.08713268
DD	0.02918136	0.002919	9.99764	1.88E-23	0.023460057	0.03490266
DC	0.01984137	0.001241	15.98873	5.06E-57	0.017408917	0.02227382

Table A.2. Crash rate regression results (for tangents sample)

Regression Statistics						
Multiple R	0.101656					
R Square	0.010334					
Adjusted R Square	0.009599					
Standard Error	12.20648					
Observations	10776					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	8	16751.51	2093.939	14.05345	1.56653E-20	
Residual	10767	1604264	148.9983			
Total	10775	1621016				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	10.63793	2.262929	4.700955	2.62E-06	6.202168238	15.073683
LW	-0.80918	0.184909	-4.37608	1.22E-05	-1.17163215	-0.446721
SW	0.143595	0.029802	4.818313	1.47E-06	0.08517752	0.20201176
SS	-0.25035	0.263834	-0.9489	0.34269	-0.7675165	0.26680992
FO	-0.21394	0.280257	-0.76336	0.445267	-0.76329187	0.33541954
GR	1.297533	0.397654	3.262967	0.001106	0.51805726	2.0770088
G	-0.00427	0.029169	-0.14637	0.883632	-0.06144623	0.0529073
VC	-0.02869	0.293956	-0.0976	0.922251	-0.60489742	0.54751682
DD	0.292674	0.03644	8.03171	1.06E-15	0.221245464	0.3641031

Table A.3. Crash rate regression results (for curves sample)

Regression Statistics	
Multiple R	0.113428
R Square	0.012866
Adjusted R Square	0.009378
Standard Error	12.82416
Observations	2841

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	6066.123	606.6123	3.688528	6.38024E-05
Residual	2830	465419.5	164.4592		
Total	2840	471485.6			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.614161	3.220077	0.50128	0.616213	-4.69977404	7.9280961
LW	0.079726	0.273856	0.291124	0.770978	-0.45725175	0.6167042
SW	0.137601	0.075092	1.832429	0.066993	-0.00963984	0.2848411
SS	0.06156	0.524314	0.11741	0.906543	-0.96651661	1.0896361
FO	-0.18397	0.446552	-0.41199	0.68038	-1.05957289	0.6916263
GR	-0.2736	0.733026	-0.37324	0.708996	-1.71091574	1.163723
G	-0.00561	0.020067	-0.27944	0.779926	-0.04495446	0.0337395
VC	-0.09705	0.519112	-0.18695	0.851715	-1.11492228	0.9208288
DD	-0.04438	0.072221	-0.61447	0.538951	-0.18598813	0.0972327
DC	0.062628	0.020137	3.110129	0.001889	0.023143596	0.1021116

Table A.4. Crash severity rate regression results (for all geometrics sample)

Regression Statistics	
Multiple R	0.070244194
R Square	0.004934247
Adjusted R Square	0.004276086
Standard Error	77.11050751
Observations	13617

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	9	401197.8	44577.54	7.497025	5.08497E-11
Residual	13607	80907635	5946.03		
Total	13616	81308833			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-4.807462546	11.42172	-0.42091	0.673831	-27.1956137	17.5806886
LW	2.223543552	0.938967	2.368074	0.017895	0.383038247	4.06404886
SW	-0.560255546	0.173034	-3.23783	0.001207	-0.89942651	-0.2210846
SS	-2.712760562	1.466803	-1.84944	0.064416	-5.58789802	0.1623769
FO	9.466755165	1.46767	6.450191	1.15E-10	6.589918059	12.3435923
GR	-5.136121781	2.179077	-2.35702	0.018436	-9.40741387	-0.8648297
G	0.103138101	0.100804	1.023158	0.306251	-0.09445107	0.30072727
VC	-3.402554499	1.589075	-2.14122	0.032274	-6.51736138	-0.2877476
DD	-0.2630397	0.201689	-1.30418	0.192194	-0.65837884	0.13229944
DC	0.028301881	0.08575	0.330052	0.741366	-0.13977948	0.19638324

Table A.5. Crash severity rate regression results (for tangents sample)

Regression Statistics	
Multiple R	0.08349954
R Square	0.00697217
Adjusted R Square	0.00623434
Standard Error	347.82303
Observations	10776

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	9145725	1143216	9.449558	4.19104E-13
Residual	10767	1.3E+09	120980.9		
Total	10775	1.31E+09			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	216.528055	64.48202	3.35796	0.000788	90.131418	342.924693
LW	-14.46274	5.268969	-2.74489	0.006063	-24.7908898	-4.1345896
SW	2.60635392	0.849202	3.069181	0.002152	0.941761711	4.27094613
SS	-13.452597	7.517933	-1.7894	0.073578	-28.1891308	1.28393775
FO	-2.6635873	7.985911	-0.33354	0.738736	-18.3174447	12.99027
GR	42.8536793	11.33114	3.78194	0.000156	20.64256459	65.0647941
G	0.0336219	0.831171	0.040451	0.967734	-1.59562649	1.66287028
VC	-2.1516643	8.376246	-0.25688	0.797279	-18.5706512	14.2673225
DD	6.89649734	1.038351	6.641777	3.25E-11	4.861137466	8.93185721

Table A.6. Crash severity rate regression results (for curves sample)

Regression Statistics	
Multiple R	0.05321626
R Square	0.00283197
Adjusted R Square	-0.00069159
Standard Error	348.2912571
Observations	2841

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	974971.5	97497.15	0.803724	0.625204805
Residual	2830	3.43E+08	121306.8		
Total	2840	3.44E+08			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	9.452114093	87.45402	0.108081	0.913939	-162.027946	180.932174
LW	-0.5580469	7.437656	-0.07503	0.940196	-15.1418229	14.0257291
SW	2.401489291	2.039421	1.177535	0.239081	-1.59741195	6.40039053
SS	-0.5910925	14.23984	-0.04151	0.966892	-28.5126008	27.3304158
FO	9.048713203	12.12789	0.746108	0.455664	-14.7316824	32.8291089
GR	-0.12229962	19.90824	-0.00614	0.995099	-39.1584334	38.9138341
G	-0.1297188	0.544993	-0.23802	0.811883	-1.19834233	0.93890472
VC	-0.49769205	14.09855	-0.0353	0.971842	-28.1421578	27.1467737
DD	0.882510444	1.961439	0.44993	0.652795	-2.96348444	4.72850533
DC	1.075297314	0.546891	1.9662	0.049373	0.002951573	2.14764305

APPENDIX B

CORRELATION RESULTS

Table A.7. Crash rate correlation results (for all geometrics sample)

	Cr R	**LW**	**SW**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**	**DC**
Cr R	1.00									
LW	-0.19	1.00								
SW	-0.10	0.44	1.00							
SS	0.10	-0.06	-0.16	1.00						
FO	0.13	-0.33	-0.30	0.32	1.00					
GR	0.00	0.10	0.05	0.31	0.15	1.00				
G	0.06	-0.05	-0.03	0.06	0.06	0.02	1.00			
VC	0.07	-0.23	-0.20	-0.02	0.12	-0.05	0.04	1.00		
DD	0.10	-0.22	-0.26	-0.05	0.10	-0.05	-0.02	0.13	1.00	
DC	0.20	-0.32	-0.25	0.19	0.23	0.04	0.11	0.12	-0.01	1.00

Table A.8. Crash rate correlation results (for tangents sample)

	Cr R	**LW**	**SW**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**
Cr R	1.00								
LW	-0.05	1.00							
SW	0.02	0.39	1.00						
SS	-0.01	0.00	-0.11	1.00					
FO	0.01	-0.31	-0.26	0.27	1.00				
GR	0.02	0.09	0.05	0.31	0.16	1.00			
G	0.00	-0.05	0.00	0.06	0.05	0.04	1.00		
VC	0.01	-0.21	-0.16	-0.04	0.09	-0.05	0.06	1.00	
DD	0.08	-0.28	-0.27	-0.03	0.12	-0.05	-0.02	0.12	1.00

Table A.9. Crash rate correlation results (for curves sample)

	Cr R	**LW**	**SW**	**DC**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**
Cr R	1.00									
LW	-0.01	1.00								
SW	0.01	0.46	1.00							
DC	0.08	-0.27	-0.25	1.00						
SS	0.02	-0.01	-0.11	0.16	1.00					
FO	0.00	-0.20	-0.23	0.14	0.34	1.00				
GR	0.01	0.17	0.11	0.05	0.30	0.12	1.00			
G	0.00	0.00	-0.03	0.08	0.03	0.03	0.01	1.00		
VC	0.00	-0.16	-0.24	0.06	-0.04	0.07	-0.08	0.01	1.00	
DD	-0.03	-0.03	-0.17	-0.17	-0.16	0.00	-0.09	-0.06	0.13	1.00

Table A.10. Crash severity rate correlation results (for all geometrics sample)

	Sv R	**LW**	**SW**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**	**DC**
Sv R	1.00									
LW	-0.01	1.00								
SW	-0.03	0.44	1.00							
SS	0.00	-0.06	-0.16	1.00						
FO	0.05	-0.33	-0.30	0.32	1.00					
GR	-0.01	0.10	0.05	0.31	0.15	1.00				
G	0.01	-0.05	-0.03	0.06	0.06	0.02	1.00			
VC	-0.01	-0.23	-0.20	-0.02	0.12	-0.05	0.04	1.00		
DD	0.00	-0.22	-0.26	-0.05	0.10	-0.05	-0.02	0.13	1.00	
DC	0.01	-0.32	-0.25	0.19	0.23	0.04	0.11	0.12	-0.01	1.00

Table A.11. Crash severity rate correlation results (for tangents sample)

	Sv R	**LW**	**SW**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**
Sv R	1.00								
LW	-0.03	1.00							
SW	0.01	0.39	1.00						
SS	-0.01	0.00	-0.11	1.00					
FO	0.01	-0.31	-0.26	0.27	1.00				
GR	0.03	0.09	0.05	0.31	0.16	1.00			
G	0.00	-0.05	0.00	0.06	0.05	0.04	1.00		
VC	0.01	-0.21	-0.16	-0.04	0.09	-0.05	0.06	1.00	
DD	0.07	-0.28	-0.27	-0.03	0.12	-0.05	-0.02	0.12	1.00

Table A.12. Crash severity rate correlation results (for curves sample)

	Sv R	**LW**	**SW**	**DC**	**SS**	**FO**	**GR**	**G**	**VC**	**DD**
Sv R	1.00									
LW	-0.01	1.00								
SW	0.01	0.46	1.00							
DC	0.04	-0.27	-0.25	1.00						
SS	0.01	-0.01	-0.11	0.16	1.00					
FO	0.02	-0.20	-0.23	0.14	0.34	1.00				
GR	0.01	0.17	0.11	0.05	0.30	0.12	1.00			
G	0.00	0.00	-0.03	0.08	0.03	0.03	0.01	1.00		
VC	0.00	-0.16	-0.24	0.06	-0.04	0.07	-0.08	0.01	1.00	
DD	0.00	-0.03	-0.17	-0.17	-0.16	0.00	-0.09	-0.06	0.13	1.00

APPENDIX C

GEOMETRIC FEATURES' EQUATION

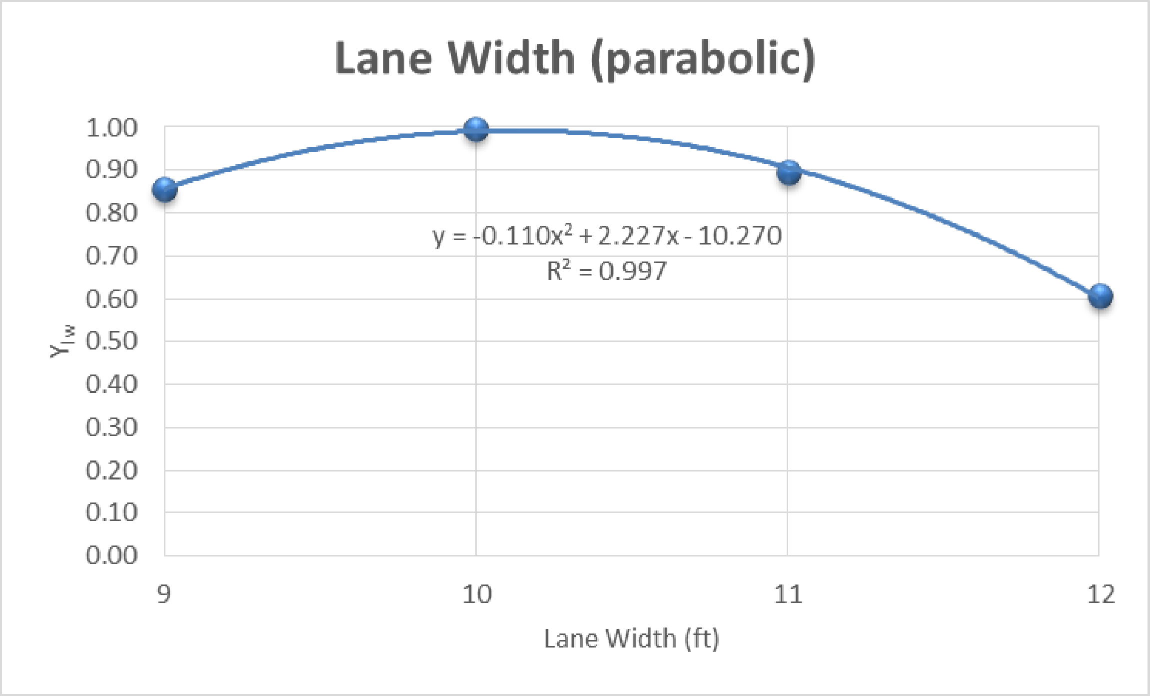

Figure A.1. Selection of equation for lane width

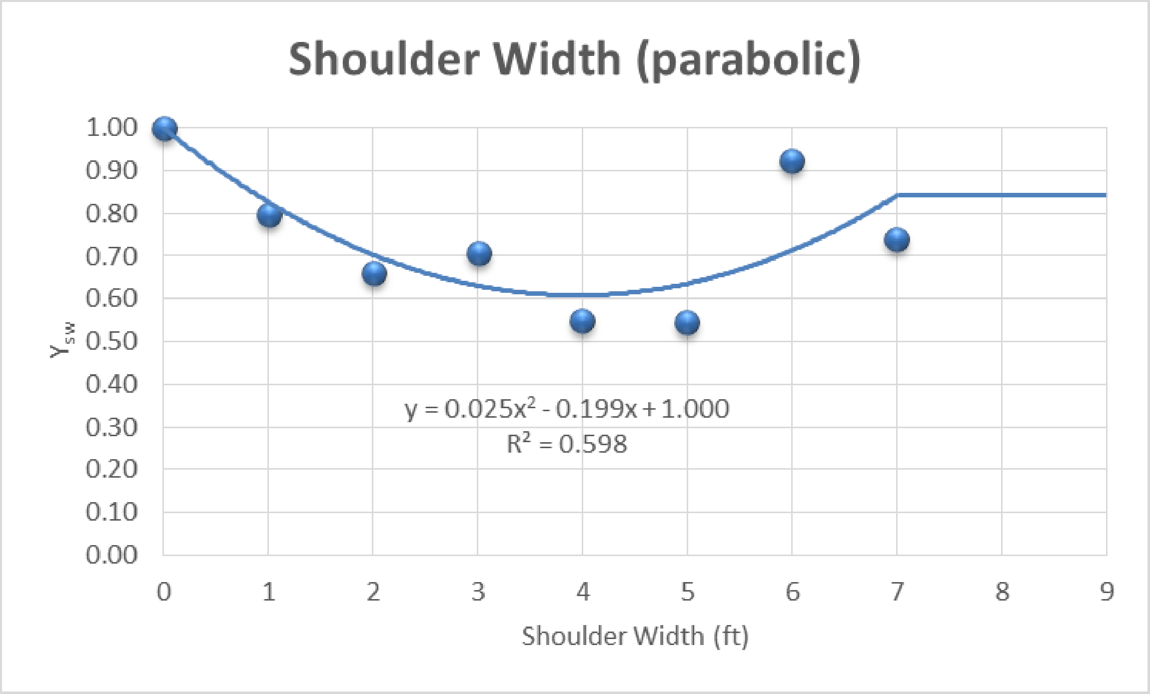

Figure A.2. Selection of equation for shoulder width

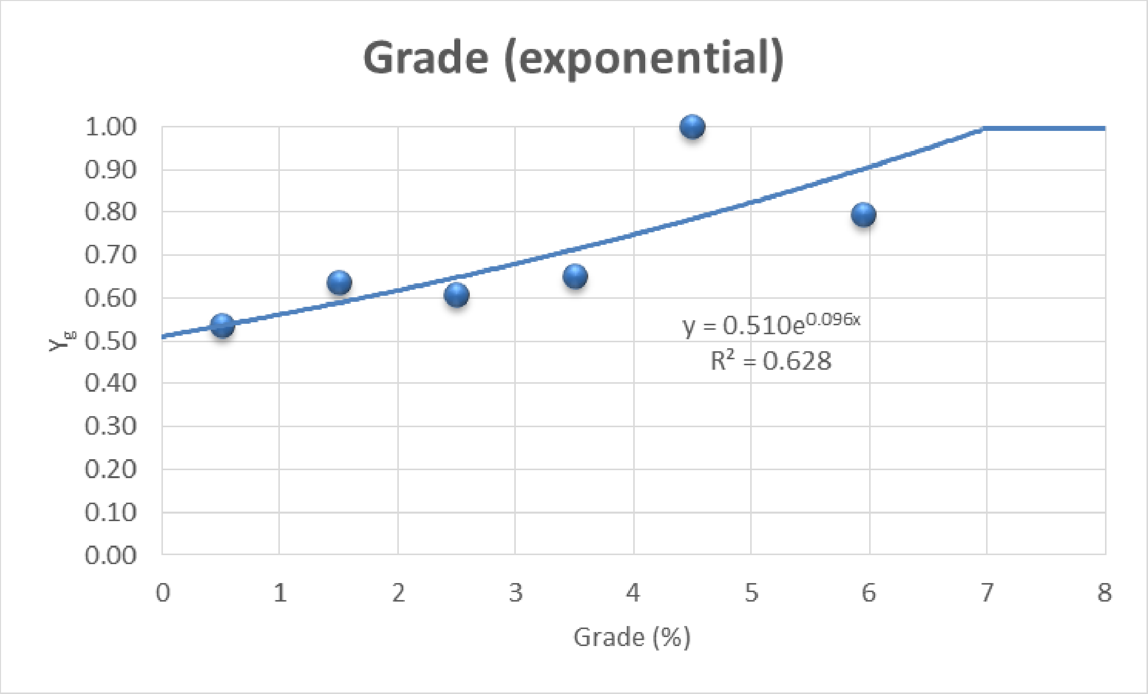

Figure A.3. Selection of equation for grade

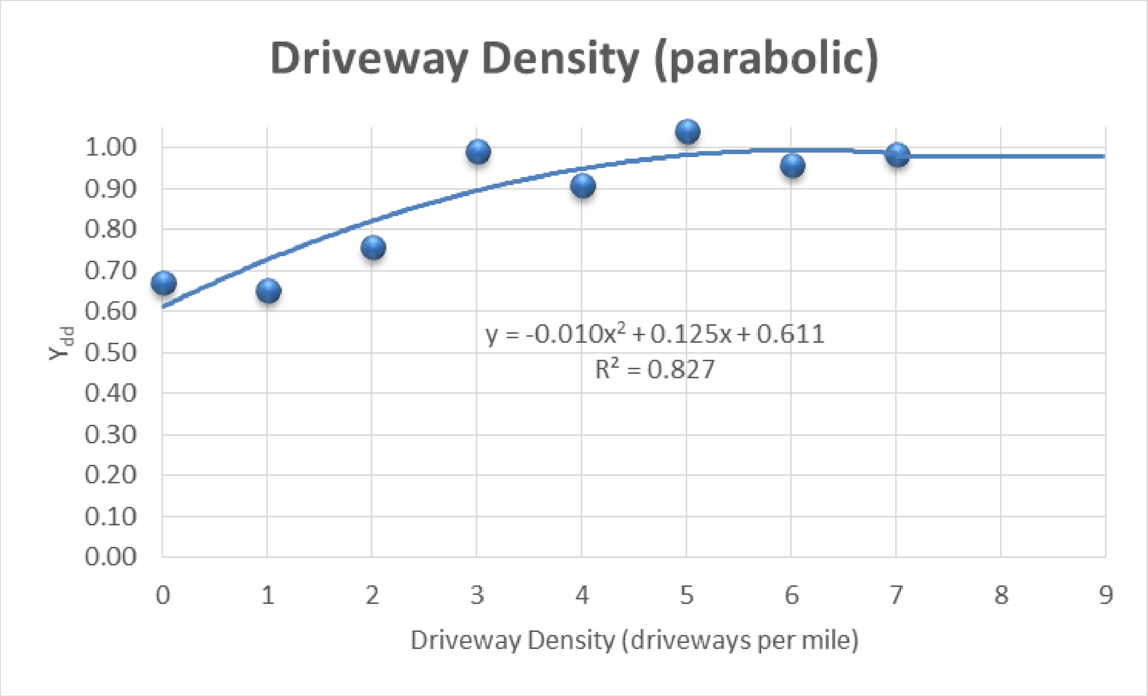

Figure A.4. Selection of equation for driveway density

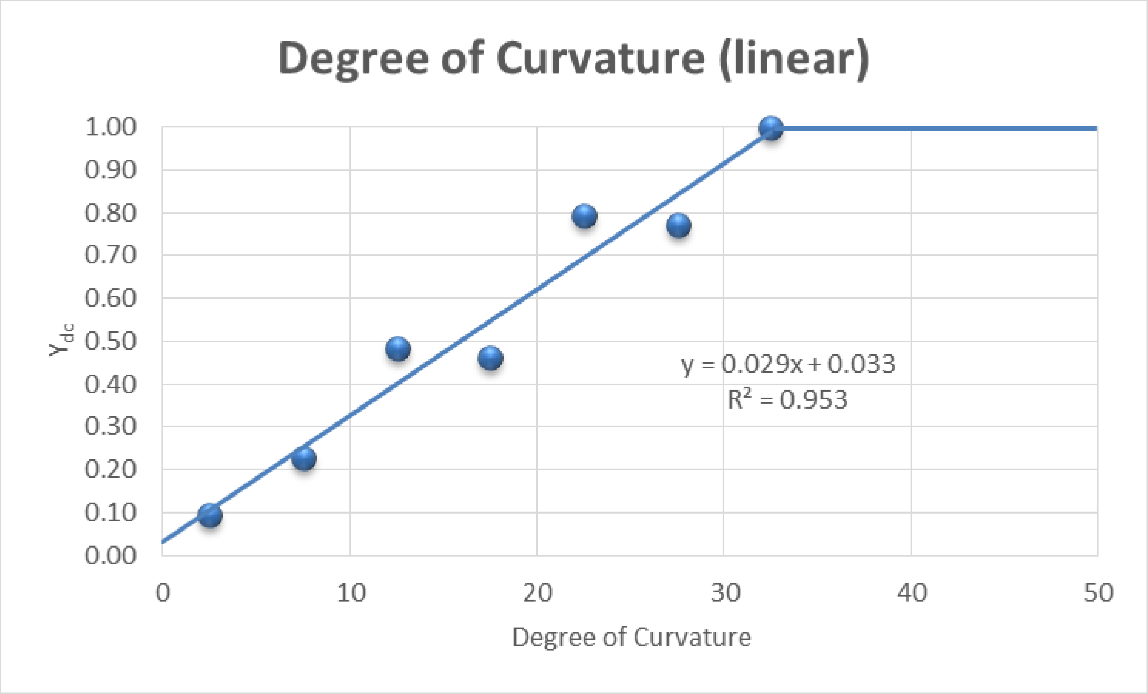

Figure A.5. Selection of equation for degree of curvature

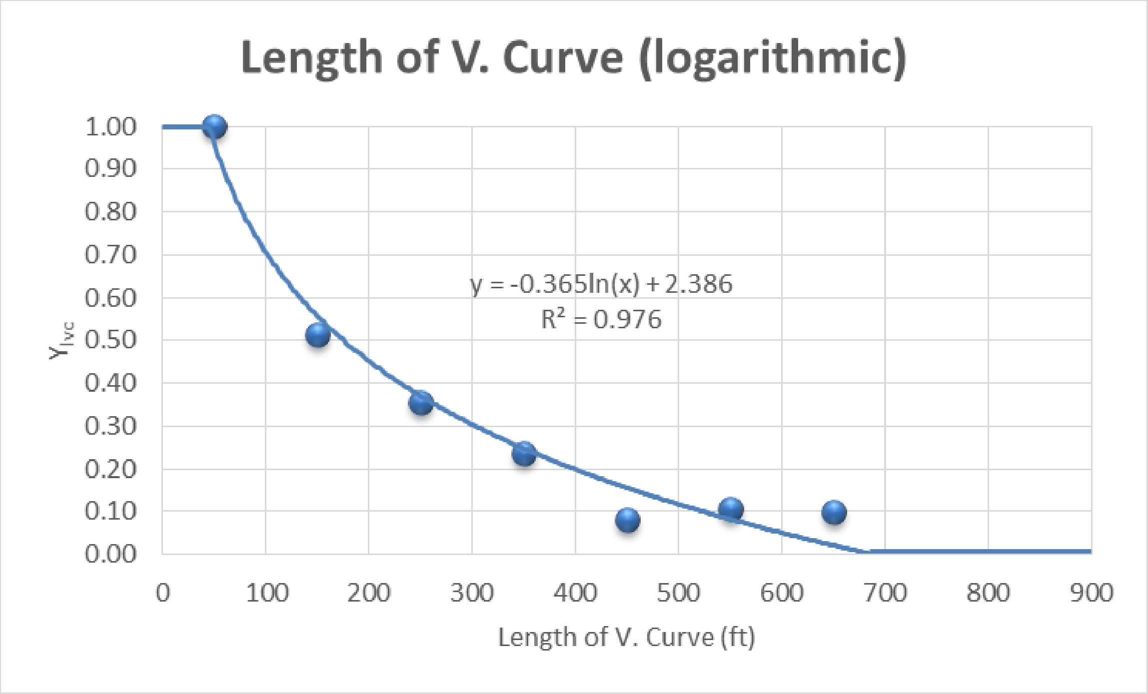

Figure A.6. Selection of equation for length of vertical curve

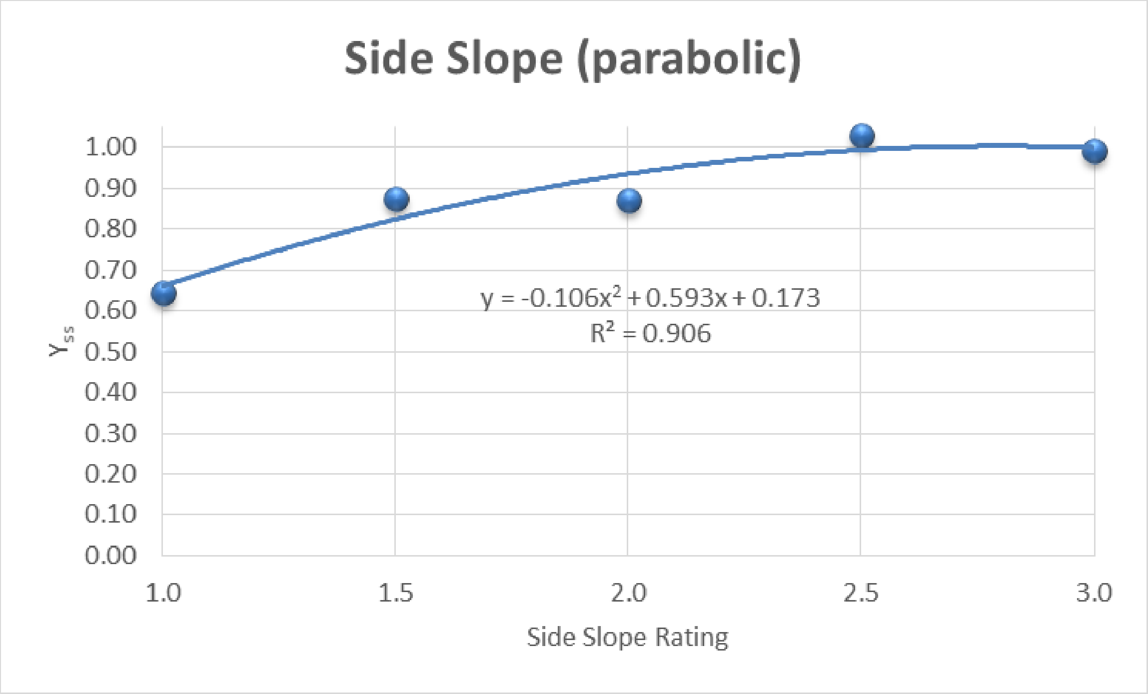

Figure A.7. Selection of equation for side slope rating

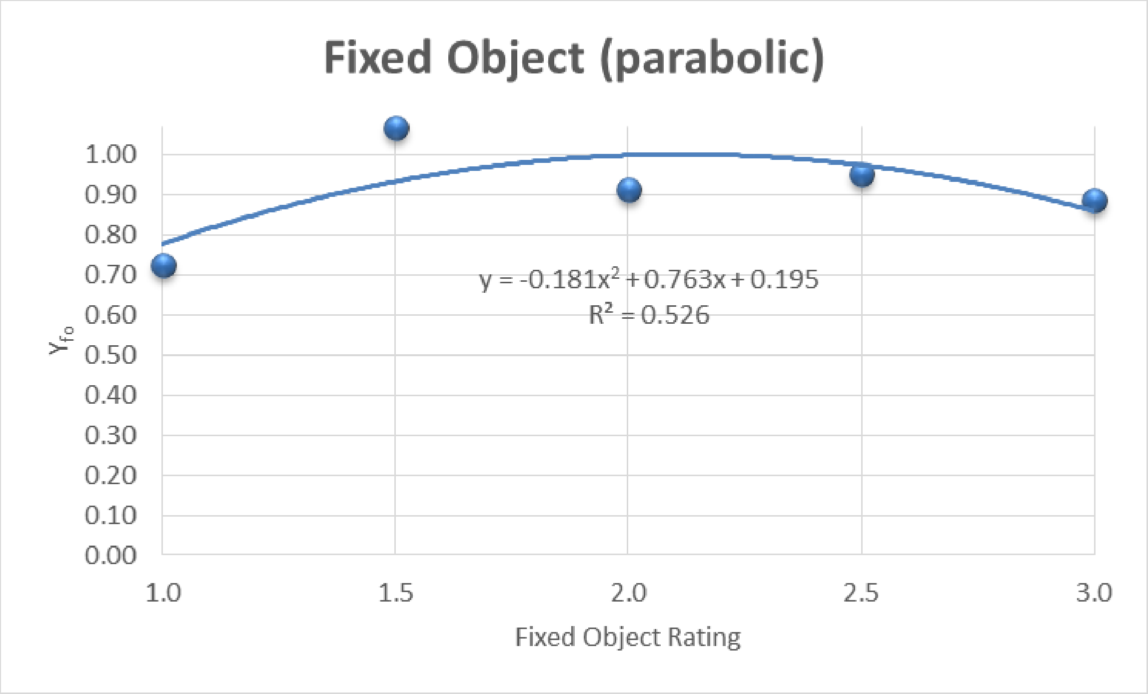

Figure A.8. Selection of equation for fixed object rating

APPENDIX D

BENEFIT/COST RATIO CALACULATION

For Horizontal Alignment Signs on Sample:

- 2,841 horizontal curves
- 375 total crashes in 10 years on curves (145 PDO; 186 injury B & C; 44 fatal & injury A)
- ODOT crash costs: \$16,156 PDO; \$68,704 injury B \$ C; \$1,414,452 fatal & injury A
- Horizontal alignment sign CRFs: 26.5% PDO[10]; 20% injury; 55% fatal
- Initial cost required for installing horizontal alignment sign = \$300 to \$2,800
- Annual Maintenance cost for the alignment sign = \$220

Number of Crashes Prevented per Curve by Type for Horizontal Alignment Sign:

$$PDO_{PRV} = \frac{No.PDO * CRF_{PDO}}{Total\ Curves} = \frac{145 * 26.5\%}{2841} = \mathbf{0.01353}$$

$$InjCB_{PRV} = \frac{No.InjCB * CRF_{InjCB}}{Total\ Curves} = \frac{186 * 20\%}{2841} = \mathbf{0.01309}$$

$$Fat\&A_{PRV} = \frac{No.Fat\&A * CRF_{Fat\&A}}{Total\ Curves} = \frac{44 * 55\%}{2841} = \mathbf{0.00852}$$

---

[10] Use average of the range of CRFs for all crashes since no PDO specific value available.

Benefit per Curve per year for Horizontal Alignment Sign:

$$Annual\ benefit\ (or\ savings) in\ crashes$$

$$= \frac{(PDO_{PRV} * Cost_{PDO}) + \left(InjCB_{PRV} * Cost_{InjCB}\right) + (Fat\&A_{PRV} * Cost_{Fat\&A})}{10\ years}$$

$$= \frac{(0.0135 * \$16{,}156) + (0.0131 * \$68{,}704) * (0.0085 * \$1{,}414{,}452)}{10} = \$1{,}320$$

NPW of the benefit

$$NPW = EUAW \left[\frac{(1+i)^N - 1}{i(1+i)^N}\right]$$

$$= (Annual\ benefit\ in\ crashes - Annual\ maintenance\ cost) \left[\frac{(1+i)^N - 1}{i(1+i)^N}\right]$$

$$= (\$1{,}320 - \$220) \left[\frac{(1+0.0344)^{10} - 1}{0.0344(1+0.0344)^{10}}\right] = \mathbf{\$9{,}176}$$

Cost per Curve for Horizontal Alignment Sign:

$$Average\ Cost\ of\ Sign = \frac{(300+2{,}800)}{2} = 1{,}550$$

$$Cost\ per\ Curve = (Average\ Cost\ of\ Sign * Signs\ per\ Curve) = \$1550 * 2$$

$$= \$\mathbf{3,100}$$

B/C Ratio:

$$\frac{B}{C} = \frac{Benefit\ per\ curve}{Cost\ per\ curve} = \frac{\$9{,}176}{\$3{,}100} = \mathbf{2.96}$$