FINAL REPORT

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State of Wyoming

DEVELOPING A NEW BARRIER CONDITION INDEX (BCI) TO OPTIMIZE BARRIER IMPROVEMENTS IN WYOMING

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16. Abstract:

Traffic barriers are installed on roadsides and medians to shield motorists from hazardous objects and other vehicles. Due to the important role played by traffic barriers in promoting safety, it is important to continuously assess their condition and performance. This study prioritized and ranked traffic barriers on Wyoming's highways for safety improvement by enhancing the height of barriers below recommended thresholds. This was achieved by conducting a benefit-cost analysis to estimate the reduction in crashes that would be gained by adjusting barrier heights. The analysis indicated that substantial benefits would be accrued if barrier heights are optimized. Traffic barriers on Wyoming's highways were then ranked based on the estimated benefits. As part of the study, a safety evaluation was carried out to identify the geometric factors of traffic barriers that impact crash severity. Finally, a condition assessment procedure referred to as the Barrier Condition Index (BCI) was used to demonstrate a new approach in the condition assessment, rating, and prioritization of traffic barriers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ACRONYMS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AADTT	Average Annual Daily Truck Traffic
BCA	Barrier Condition Assessment
BCI	Barrier Condition Index
CARE	Critical Analysis Reporting Environment
EPDO	Equivalent Property Damage Only
FHWA	Federal Highway Administration
LON	Length of Need
LQM	Linear Quantile Model
MASH	Manual for Assessing Safety Hardware
MGS	Midwest Guardrail System
NB	Negative Binomial
NHTSA	National Highway Traffic Safety Administration
NCHRP	National Cooperative Highway Research Program
RDG	Roadside Design Guide
RSAP	Roadside Safety Analysis Program
RP	Random Parameters
ROTR	Run-off-the-Road
ROW	Right of Way
SPF	Safety Performance Function
WYDOT	Wyoming Department of Transportation
WRIR	Wind River Indian Reservation

CHAPTER 1: INTRODUCTION

Highway crashes exact a severe toll on lives and property in the United States. In 2017, over 37,000 people were killed in road crashes with about 2.7 million injuries recorded. (NHTSA, 2019). Over the last decade, the number of people killed in police-reported crashes has remained above 30,000 annually. The estimated cost of motor vehicle crashes in the United States in 2010 (the most recent year for which cost data is available) was an estimated $242 billion. (NHTSA, 2019).

Fatalities, due to crashes with roadside hazards, are a challenge in the United States. Crashes with roadside hazards occur for various reasons. These may be because of drivers who have lost control of their vehicles, fallen asleep, become intoxicated, or due to poor visibility. Unimpeded, the penalty for such crashes is death or serious injuries. According to the statistics, about 20 percent of motor vehicle fatalities result from a vehicle leaving the roadway and hitting fixed objects alongside the road. (Insurance Institute for Highway Safety, 2019). About half of the deaths in fixed object crashes occurred at night and alcohol was cited as a frequent contributing factor. In 2017, a total of 7,833 people died in fixed-object crashes representing a three percent decrease in comparison to recorded fixed-object fatalities, in 2016, and 26 percent lower than in 1979. (Insurance Institute for Highway Safety, 2019).

Crashes may also result when a vehicle crosses a median, enters opposing lanes, and collides with oncoming traffic. These types of crashes are referred to as cross-median crashes and are some of the most dangerous types of highway crashes. Vehicles that cross medians may cause other vehicles in the opposing lanes to collide with each other or with roadside objects. Closing speeds may easily exceed 100 miles per hour in cross-median crashes and resulting crashes are usually violent and result in multiple injuries and fatalities. (Eric T. Donnell & Mason, J, 2006; Gabler, Gabauer, & Bowen, 2005).

Traffic barriers are installed as protective devices on highways to prevent crashes resulting from collisions with roadside objects and median incursions. Traffic barriers are not meant to prevent crashes, but they change the characteristics of the crashes leading to a reduction in crash severity. Traffic barriers are broadly classified as roadside (guardrails) and median barriers according to the Roadside Design Guide (RDG). (AASHTO, 2011b). Roadside barriers are described in the RDG as longitudinal barriers installed on the sides of roads to shield motorists from natural or man-made obstacles located on either side of the roadway. Roadside barriers also offer protection to bystanders, pedestrians, and cyclists from vehicular traffic under special circumstances. Median barriers, on the other hand, are installed to prevent cross-median crashes on divided highways. They are designed to redirect vehicles that strike on either side of the barrier. Median barriers may also be used to separate through traffic from local traffic, or to separate high occupancy vehicle (HOV) lanes from general-purpose lanes.(AASHTO, 2011b).

A well-designed barrier system promotes safety by decreasing crash severity and providing opportunities for run-off-the-road (ROTR) drivers to control their vehicles. Conversely, poorly designed barrier systems aggravate road safety by becoming hazardous fixed objects. According to statistics provided by the National Highway Traffic Safety Administration (NHTSA), traffic

barriers had a direct influence on about 1,000 fatalities and 28,000 injuries in 2010. (NHTSA, 2012). Inappropriate traffic barrier configurations such as blunt-end (spoon) terminals, turned-down (slope-end) terminals, and concrete posts may worsen safety.

Construction and installation of barrier systems also play a key role in safety. Prevalent barrier systems on United States' highways were designed and installed over thirty years ago when the traffic volumes, speed limits, vehicle types, and traffic regulations were different from what they are currently. Current vehicles are heavier than before with pickup trucks and sport utility vehicles (SUVs) more widespread. However, most of the existing barrier systems were not designed with current vehicle configurations in mind. The geometric characteristics of old barrier systems pose considerable risks to vehicles due to their non-crashworthy status. For instance, low barrier heights increase the propensity of vehicle rollover and override, while tall barriers promote vehicle underride.(Julin, Asadollahi, Stolle, Reid, & Faller, 2017). Wiebelhaus et al., 2013 indicated that low heights of 24 and 26 inches increase the risk of vehicle override in W-beam guardrails.. This override can be dangerous for vehicles with a high center of gravity in low-height barriers. However, the 27, 29, and 30 inches height have been found to redirect vehicles.

Also, speed limits have seen significant changes from 1974 when the first national speed limit was set in the United States. The maximum speed limit on United States highways was 65 miles per hour (mph) until 1995, when it was increased. Current speed limits on some United States' highways are as high as 85 mph. Higher posted speed limits result in high severity impacts with barrier systems leading to a higher risk of fatalities and injuries.

The discussion above highlights the need for highway agencies to assess and improve their barrier systems due to the current traffic demands on United States highways. This study aims to evaluate the condition of barrier systems, in Wyoming, and provide recommendations to enhance safety. Shifts in crash severity proportions due to barrier height enhancement were estimated for the barrier types on Wyoming's interstate and state highway system. Optimization was then conducted to rank traffic barriers on the interstate and state highway system systems for prioritization of improvement activities. The optimization considered geometric, economic, and future crashes as important factors.

Study Objectives

This study was undertaken to evaluate the impact of traffic barrier geometric factors on crash severity. Also, the study aimed to propose a methodology to provide an index that represents the overall condition of barriers and also rank barriers based on benefits to be derived by enhancing barrier heights. The main objectives of this study are:

- Evaluate the impact of traffic geometric factors on crash severity.
- Estimate the shift in crash proportions due to adjusting barrier heights to recommended height ranges.
- Estimate the benefits of optimizing barrier heights and rank barriers based on the benefits.
- Propose a barrier condition index that provides a uniform procedure in assessing the conditions of barriers.

Report Organization

This report is organized into six chapters. The first chapter discusses the use of traffic barriers, barrier types, and outlines the study objectives. The second chapter is a review of the literature on topics relating to barrier selection considerations, and the use of the different barrier types. Chapter three discusses the methodology adopted for this study. The discussion includes the formulation of the random parameters ordered logit, negative binomial (NB) model, hurdle models, and quantile models. Chapter four describes the data collection process and the data types collected. A summary of the barrier data is also provided in this chapter. The fifth chapter provides the results of the analysis conducted. The effect of geometric factors of median and side traffic barriers on crash severity is presented in this chapter. Also, an analysis was carried out to estimate the shift in crash severity proportions due to enhancing barrier heights. The last analysis presented in chapter five relates to assessing barrier conditions at three locations using a proposed BCI. The final chapter summarizes the findings of the study and presents recommendations.

CHAPTER 2: LITERATURE REVIEW

This chapter presents topics important to traffic barrier evaluation and prioritization. Also, barrier types, their characteristics and warrants are discussed. Previous studies with regards to the evaluation of barriers are also reviewed in this section. The chapter concludes by discussing the BCI procedure.

Traffic Barrier Selection Considerations

Traffic barriers are an option for a forgiving roadside. In a forgiving roadside, hazards are eliminated, relocated, or shielded.(AASHTO, 1987). Shielding on highways is typically done by installing roadside barriers for hazards, such as steep side slopes that are difficult to treat any other way. The installation of traffic barriers is based on several considerations, including geometric features of the section, traffic volume, potential hazards, and clear zones, among other factors. In addition to determining if a traffic barrier is warranted, highway agencies also have to decide which barrier system is appropriate for specific site conditions.(Russo & Savolainen, 2018). Traffic barriers are developed, tested, and installed to contain or redirect passenger vehicles and pickup trucks. Barrier alternatives include W- or thrie-beam barriers, concrete barriers, and low- or high-tension cable barriers. The associated costs and benefits of each barrier type play a critical role in selection for a specific road segment. According to the RDG, costs associated with barriers, such as installation costs, maintenance, and crash costs, are compared to similar costs without barriers.(AASHTO, 2011b). The procedure is used to compare three options: (1) remove or reduce the area of concern so that it no longer requires shielding, (2) install an appropriate barrier, or (3) leave the area of concern unshielded.(AASHTO, 2011b). Other factors considered in determining guardrail barrier needs include presence and characteristics of embankments, roadside obstacles (culverts, trees, ditches, retaining walls, utility poles, etc.) pedestrians, bystanders, bicyclists, and motorcycles.

The policy guideline recommends that median barriers are installed when the median width is equal to or less than 30 feet, and the average annual daily traffic (AADT) volume exceeds 20,000 vehicles per day. The policy guideline recommends that median barriers are installed when the median width is equal to or less than 50 feet, and the average annual daily traffic (AADT) volume exceeds 20,000 vehicles per day.

Performance assessments are also required for traffic barriers before they can be placed in service. Full-scale impact testing is the most common method of evaluating guardrails, median barriers, and other roadside safety hardware. The Manual for Assessing Safety Hardware (MASH), developed by AASHTO, replaced the National Cooperative Highway Research Program (NCHRP) Report 350, Roadside Design Guide.(AASHTO, 2011b). MASH presents uniform guidelines for crash testing and recommends evaluation criteria to assess the results. MASH retained the testing guidelines contained in NCHRP Report 350 but added changes in requirements for testing including changes to the test vehicles. According to the RDG, a traffic barrier is accepted as crashworthy if it has met all the evaluation criteria listed in MASH or NCHRP Report 350 for each of the required crash tests or if the barrier has been found acceptable after an in-service performance evaluation. The evaluation of a device, as specified in

NCHRP Report 350, is based on three factors. These are structural adequacy, post-impact vehicle trajectory, and occupant risk. (Ross, Sicking, Zimmer, & Michie, 1993). Structural adequacy is described as the ability of the device to perform its intended task. For traffic barriers, the vehicle has to be contained and redirected. Impacts should not result in vehicle underride, override, or penetration. Post-impact vehicle trajectory ensures that deflection will not cause subsequent harm, such as a vehicle being redirected into the opposing traffic. The occupant risk criterion requires that detached elements do not penetrate the occupant compartment, or that occupant intrusion is not severe enough to cause severe injury, and that the vehicle does not rollover but remains upright during and after impact. (Gabler et al., 2005).

Barrier Types

Typically, traffic barriers are composed of a rail used to redirect a vehicle, and posts that hold up the rail and dissipate energy by being displaced, deformed, or fractured. Traffic barriers may be categorized as flexible, semi-rigid, or rigid based on their deflection characteristics from an impact. (AASHTO, 2011b). Flexible barriers allow a lot of deflection to contain vehicles that have crashed. Friction from the crash slows the vehicle and helps bring it to a stop. Flexible barriers are usually made of wire rope supported between posts and require frequent repair following impacts. An example of a flexible barrier is the cable barrier. Semi-rigid barriers allow some deflection but not as much as flexible barriers. Semi-rigid barriers provide restraint and redirection of errant vehicles through a combination of bending and tensioning. An example of a semi-rigid barrier is the beam guardrail. Rigid barriers are usually made from concrete and permit little or no lateral displacement. They do not absorb any crash energy and are usually installed on high-volume road worksites to protect road users. Rigid barriers provide the highest level of safety for heavy vehicles and require very little to no maintenance even after vehicle impacts.

Traffic barriers may also be classified as weak-post and strong-post systems. The post in a weak-post barrier holds the rail at a height that ensures that the rail contacts a vehicle in the most appropriate location. The rails absorb most of the crash impact and dissipate the resulting energy while the posts contribute relatively little to the energy dissipation. (Ray & McGinnis, 1997). The rail elements in weak-post barriers are usually cables, W-beams, or box beams. Conversely, the post in a strong-post barrier dissipates a significant amount of energy. Commonly, large steel or wood posts are used with blockouts to prevent wheel snagging. W-beam or thrie-beam rails are typically used with strong posts.

Four main barrier types are described in the RDG with several variations. These are the cable, W-beam, box beam, and concrete barriers. These barriers are described below.

Cable Barriers

Cable barriers are designed to be flexible and deflect vehicles more in comparison to other barrier types. They are composed of steel cables mounted on posts. Cable barriers redirect impacting vehicles by tightly fastened cables pulling away from connectors. To develop tension to restrain impacting vehicles, each end of the cable run is anchored. Primary advantages attributed to cable barriers include low initial cost, effective vehicle sizes and installation

conditions, and low impact forces on vehicle occupants. Disadvantages include the need for repair following an impact, not being suitable on curves with short radii, and the sensitivity of cable barriers to correct height installation and maintenance. (AASHTO, 2011b). Cable barriers are installed with either high-tension or low-tension on roadsides or along medians. The NCHRP Report 350 recommends that the lower cables of the low-tension barrier be installed at 533 mm (21 inches) and the top cable at 762 mm (30 inches) above the ground. These heights have also been successfully tested to the standards in the NCHRP Report 350.

W-Beam Barriers

The W-beam barrier consists of corrugated steel sheeting mounted to either a weak post or blocked-out on a heavy post. The weak post produces large deflections and has a W-beam rail that relies very much on guardrail tension to redirect impacting vehicles. The W-beam weak post barrier is recommended for a mounting height of 558 mm (22 inches). This barrier height was found to be vulnerable to vehicle vaulting or underride caused by incorrect mounting height. A modification was therefore made by raising the mounting height to 820 mm (32.3 inches).

To reduce the incidence of vehicle vaulting and snagging, the strong-post W-beam was developed. It is made up of wood posts and wooden blockouts or steel posts. According to the RDG, these blockouts are incorporated into the barrier design to minimize vehicle snagging and vaulting by maintaining the rail height during the initial stages of post-deflection. (AASHTO, 2011b). However, the strong-post W-beam barrier may produce severe lateral deceleration of impacting vehicles that may lead to injuries.

A variation of the W-beam is the thrie-beam traffic barrier. The thrie-beam barrier has a corrugated steel rail mounted on posts and is similar to the W-beam rail. However, it has three corrugations on the rail instead of two. Three types of thrie-beam barriers have been tested under NCHRP Report 350. These are the blocked-out thrie-beam, modified thrie-beam, and the proprietary strong-post thrie-beam system.

The original recommended height to the top of the rail for the strong post W-beam was 686 mm (27 inches). Based on impact tests, it was recommended that strong post W-beam barriers should be installed at 706 mm (27.75 inches) on new highway construction projects. (AASHTO, 2011b). The RDG notes that many W-beam barriers have been installed at 686 mm (27 inches) based on the previous recommendations. Such barriers should be retained and upgraded during reconstruction or new construction projections as they have been found to have an acceptable level of performance. W-beam barriers are installed either as median barriers or roadside barriers. However, the weak-post W-beam is not recommended as a median barrier where terrain irregularities exist because it is deemed to be sensitive to height variations.

Box Beam Barriers

The box beam barrier is made of a railing that is a rectangular steel tube mounted on posts. Redirection of vehicles is through beam action. For the weak-post box beam barrier, posts located near the point of impact are designed to break away, distributing the impact force to adjacent posts in the process. The recommended mounting height from the ground to the top of the rail is 686 mm (27 inches). The advantages of the box beam barrier include the requirement

for less space for deflection, and it being less of a visual obstruction compared to a W-beam. However, it is more expensive than a cable or weak-post W-beam barrier and is more difficult to repair. Box beam barriers may be installed on the roadside or as median barriers.

Concrete Barriers

Concrete barriers are rigid systems that have varying shapes and heights commonly installed at 810 mm (32 inches) and 1070 mm (42 inches). Concrete barriers are available as cast-in-place or as precast construction. Common shapes of the concrete barriers are the New Jersey shape, F-shape, and constant slope shape. The New Jersey barrier has a sloped front face and a vertical back face. The 810 mm (32 inches) New Jersey barrier is the most widely used concrete barrier in the United States. (Ross et al., 1993). Due to the high compressive strength of the concrete, barrier penetration is not an issue, and so the function of the barrier is to redirect the vehicle ensuring that the smallest amount of vehicle damage occurs. (Gabler et al., 2005). New Jersey barriers and concrete barriers, in general, require very little maintenance and are designed for minimal to no deflection during vehicle impacts. Thus, they are ideal for locations with narrow medians. The New Jersey barrier is also used on roadsides.

Along with the New Jersey barrier, the F-shape barrier meets the test requirements of NCHRP Report 350. Tests have suggested that the F-shape offers a slight performance advantage over the New Jersey barrier. The F-shape barrier was designed to minimize vehicle damage as a result of low-angle impacts and to reduce crash impact forces on occupants in comparison to a vertical wall.(AASHTO, 2011b).

The constant slope barrier represents the latest improvement of the concrete barrier.(AASHTO, 2011b). The barrier consists of a single sloping face of either 9.1 or 10.8 degrees. This barrier is also installed at a height of 810 mm (32 inches) and 1070 mm (42 inches). The constant slope barrier has been tested with pickup trucks and single-unit trucks with the performance found to be satisfactory.

Safety Performance Analysis of Traffic Barriers

Safety performance analysis of traffic barriers has been undertaken in the literature using different approaches in addition to the full-size crash testing procedures described in NCHRP Report 350 and MASH. The following section discusses two other major approaches in safety performance evaluation of traffic barriers, crash simulation, and the analysis of historical crash data.

Crash Simulation Analysis of Traffic Barrier Performance

Simulation analysis of traffic barriers has been an approach adopted by some researchers in assessing traffic barriers. Albuquerque et al., 2015 used crash data analyses and simulation utilizing the recently updated Roadside Safety Analysis Program (RSAPv3) to evaluate guardrail lengths-of-need (LON) associated with the lowest crash costs (injuries and property damage) and maximum cost-effectiveness for freeways. The study found that there was both a safety and an economic benefit to reducing the installed LON and utilizing different runout lengths for left and right-side departures for divided roadways. It was concluded that a 36-inch height should be

considered as the maximum height that does not constitute a threat to vehicles in terms of underride crashes.

Many simulation studies have relied on a finite element approach using the LS-DYNA software program. (Gabler, Gabauer, & Hampton, 2010; Hampton & Gabler, 2012; Julin et al., 2017; Pajouh, Julin, Stolle, Reid, & Faller, 2018; Tan, Tan, & Wong, 2008; Teng, Liang, Hsu, Shih, & Tran, 2016). The LS-DYNA is a general-purpose finite element program that can simulate real-world problems. (Livermore Software Technology, 2011). It is a common simulation program in many fields of engineering including automobile, aerospace, construction, and military. LS-DYNA is suitable for situations of changing boundary conditions, large deformations (such as crumpling of sheet metal parts), and for nonlinear materials that do not exhibit ideal elastic characteristics. (Livermore Software Technology, 2011). LS-DYNA has a material library that allows for the crash simulation of metals, plastics, glass, fabrics, concrete, and soils among other materials.

Using LS-DYNA, Hampton and Gabler, 2012, conducted a study to assess the removal of one, two, or three posts from strong-posts W-beam barrier systems with varying impact points using simulation and two crash tests. The results indicated that the removal of a single post compromised vehicle safety due to the risk of snagging and rollover.

To test the effect of rail height effects on the safety performance of the Midwest Guardrail System (MGS), simulation models were employed along with crash testing to assess the standard MGS. (Pajouh et al., 2018). Crash testing was conducted by impacting the MGS at different rail heights with passenger cars and assessing if the test results matched the MASH evaluation criteria. The tests were used to calibrate LS-DYNA computer simulation models. The results indicated that a mounting height of 36 inches is the maximum height that would safely contain and redirect a small passenger car. The simulations indicated that heights in excess of 37 inches would likely result in a small car underride. A previous study on the MGS, by Julin et al. 2017, using full-scale crash tests on an 1100C passenger car, came to the same conclusions on the maximum mounting height of the MGS to prevent underride and vehicle snagging. (Julin et al., 2017).

Historical Crash Analysis of Traffic Barriers

The use of historical crash data is another method used in evaluating the safety performance of traffic barriers. This method usually involves estimating frequency or probability models to predict changes in crash frequency/severity attributable to the presence of traffic barriers. Based on historical crash data, other studies utilized a before-after approach in specific locations after installing new traffic barrier systems.

Crash frequency analysis is carried out by aggregating different types of crashes and analyzing them jointly. For crash frequency analysis, the negative binomial (NB) regression model is considered the most adequate. (Tarko, Villwock, & Blond, 2008). The NB regression model has been used by several researchers to investigate the impact of traffic barrier types or the specific features of the barriers on crash frequency. (Chimba, Emaasit, Allen, Hurst, Nelson, et al., 2014; E.T. Donnell & Mason, 2006; Russo & Savolainen, 2018; Tarko et al., 2008). This model has

been found to be superior to the linear regression model that assumes the response variable to be continuous; a situation not observed with crash data. The Poisson regression model has been considered previously for crash data but this approach results in biased estimates if the mean is not equal to the variance. (Washington, Karlaftis, Matthew, & Mannering, 2011). The interpretation of the effect of variables on crash frequency is based on the magnitude and signs of the coefficients.

The expected severity of crashes with respect to traffic barriers has been estimated by several types of models. These models are usually discrete choice outcome models including logit models, probit models, nested logit models, and ordered and unordered models.

Binary probit or logit models are used when the response outcome is binary (eg. injury or non-injury). Tarko et al., 2008 estimated crash severity models for single-vehicle (SV), multiple-vehicle same direction (SD) crashes associated with median barrier crashes on divided highways. The study developed binary logit models to estimate the probability of a severe crash (fatal and injury). A depressed median, at least 50 feet wide, without a longitudinal barrier, was used as the baseline of the study. The results indicated that for the SV model, the presence of high- or low-tension cable barrier in medians at least 30 feet wide resulted in a lower probability of severe crashes in comparison to the baseline barrier. For the SD model, a low-tension cable or concrete barrier installed in medians of 30-50 feet wide increased the probability of severe injury crashes.

The multinomial logit (MNL) has been used to estimate the probability of crashes involving traffic barriers by some researchers. (Eric T Donnell & Mason, 2004; M Rezapour, Molan, & Ksaibati, 2019; Russo & Savolainen, 2018). MNL models consider three or more outcomes and do not explicitly account for the ordering that may be present in the outcomes. Also, the traditional MNL model does not impose parameter restrictions that the ordered probability models do. (Savolainen, Mannering, Lord, & Quddus, 2011).

Ordered logit and probit models account for the ordering inherent in injury data. Previous studies have estimated the ordered logit model to evaluate crash severity. (Khattak, Pawlovich, Souleyrette, & Hallmark, 2002; O'Donnell, C.J., Connor, 1996; Mahdi Rezapour, Moomen, & Ksaibati, 2019; Wang & Abdel-Aty, 2008). Russo and Savolainen, 2018, estimated an ordered logit model to analyze median crash severity. The analysis indicated that concrete barrier sections and thrie-beam guardrail sections increased the probability of severe injury crashes. On the other hand, increasing lane width, pickup trucks, and increasing the number of lanes decreases the probability of severe injury crashes.

Other studies have evaluated the safety performance of traffic barriers by conducting before-after studies. In before-after studies, crashes before the installation of traffic barriers are compared to the crashes after the barrier installation. Changes in the proportion of crashes are then attributed to the installation of the traffic barriers. Crash modification factors (CMFs), which estimate the expected number of crashes after implementing a safety feature, may be estimated from a before-after study. CMFs may also be estimated from the parameter estimates of coefficients from a cross-sectional study.

Chapter Summary

A literature review was undertaken in this chapter to understand the need for traffic barriers and typical barrier types installed on highways in the United States, barrier selection considerations, and measures of evaluating barrier performance. Barrier types were classified as median or roadside, flexible, semi-rigid, and rigid barriers. Predominantly identified barriers from the RDG include cable barriers, W-beam barriers, box beam barriers, and concrete barriers. Typical dimensions and height thresholds of these barrier types were also reviewed.

From the literature, it was found that the installation of traffic barriers depends on several considerations. The keys among these considerations are the geometric section of the segment, traffic volume, clear zone, and cost.

Barriers are tested and evaluated before installation. Performance assessment of barriers includes crash tests, simulation tests, and the use of historical crash data. Crash testing is currently done according to MASH and the NCHRP Report 350 specifications. According to the literature, crash simulation of new traffic barrier types is done predominantly using finite element analysis on the LS-DYNA software. The LS-DYNA is a general-purpose program that is capable of simulating real-world problems. Traffic barrier performance assessment using historical crash data involves statistical approaches. Crash severity/frequency models are usually estimated so that changes in crash severity or frequency may be attributed to the presence of the traffic barrier. Common approaches include before-after methods, count models (NB, Poisson, zero-inflated models, etc.) and discrete choice models (binary logit/probit, nested logit, ordered probit/logit, etc.).

Based on the literature review, the most appropriate methods of analysis were selected for this research and are described in the following chapters.

CHAPTER 3: METHODOLOGY

This chapter discusses the methodology adopted for this study. The procedures and analysis undertaken to achieve the goals of the study are discussed. The processes to develop a rating system for barriers are first discussed. Next, the formulation of the random parameters ordered logit model to evaluate factors impacting crash severity is presented. The formulation of the NB, quantile, and hurdle models for the analysis in the study are discussed. The flowchart of the study is presented in Figure 1.

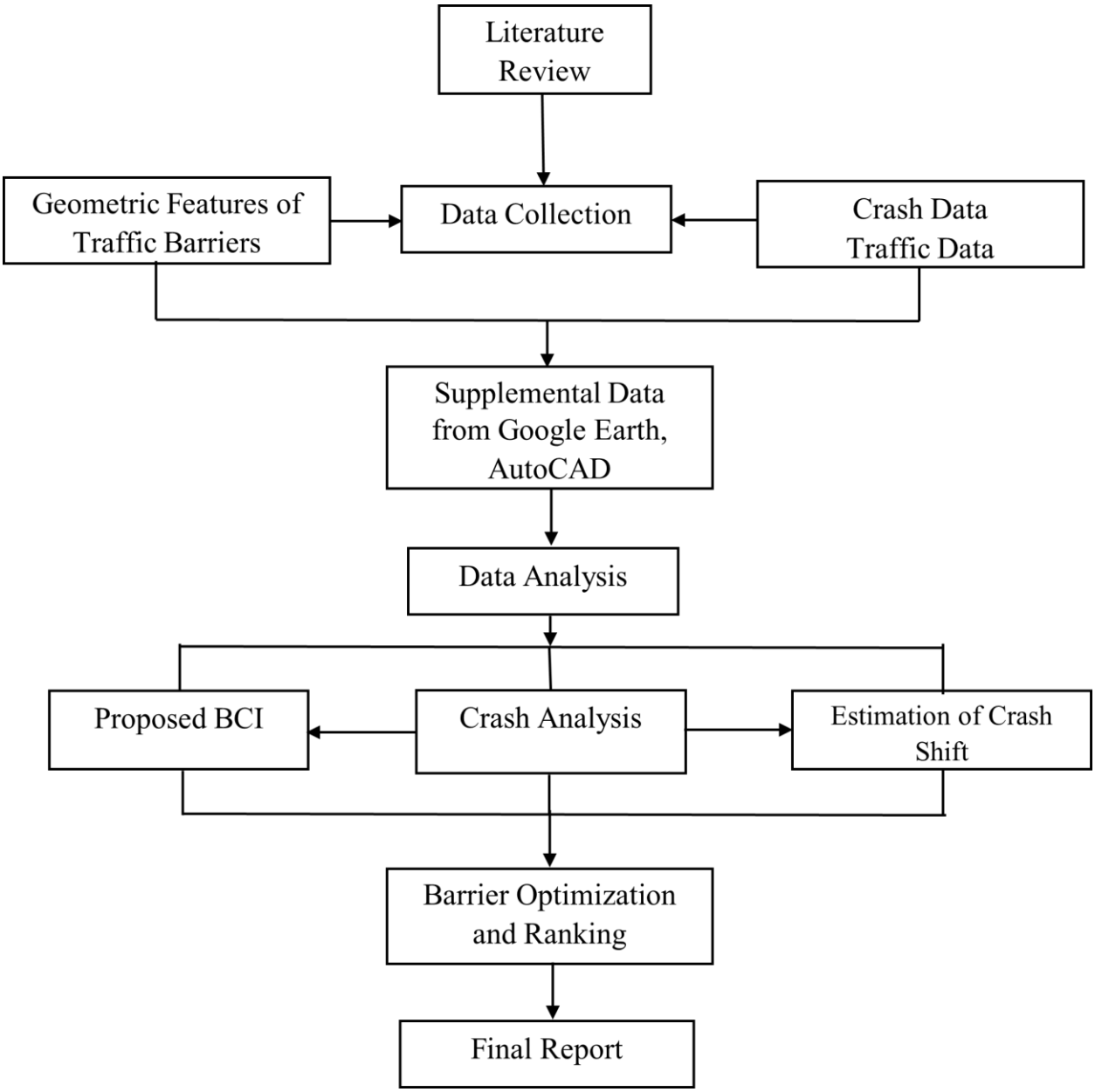


Figure 1. Chart. Methodology of Study

The first step in the study was a literature review. The literature review was conducted to identify barrier types, barrier performance, and crash analysis conducted in previous studies. Methodologies adopted to achieve the objectives of the study were also identified during the literature review. The next step in the study was data collection. Geometric, traffic, crash, and location data were collected for all traffic barriers. Crash data from the Critical Analysis Reporting Environment (CARE) package was combined with the geometric and traffic data to form a comprehensive database. Data analysis was then conducted on the database.

Barrier Condition Index (BCI)

To build a rating system for barriers, a crash analysis was employed to develop the main structure of the system. The crash analysis was used to investigate the effect of different barrier geometric variables (height, offset, length, etc.) on safety. Crash severity and frequency models were utilized to achieve this purpose. Afterward, the barrier segments were rated on a scale from 1 to 4 to provide a measure of barrier performance and condition. This rating system is named Barrier Condition Index (BCI) and is a main part of the study. The purpose of the BCI is to provide a uniform system to assess barriers in Wyoming. A score of 4 represents an ideal barrier condition with no error in terms of design, dimensions, and barrier end-treatments used. A rating of 1 shows a propensity for high severity crashes indicating that the barrier is obsolete and is no longer able to function safely. The ratings of 2 and 3 belong to the medium and low severity conditions respectively. The criteria used for the BCI rating were inspired based on the tests carried out in the NCHRP Report 656, Criteria for Restoration of Longitudinal Barriers, which provided test results of different barrier types identified in the RDG. (Gabler et al., 2010).

Random Parameters Ordered Logit Model

The standard ordered response logit model **(**Figure 2) is derived by defining an unobservable variable *z*, which is used as a basis for modeling the ordinal ranking of data. (Washington et al., 2011). The discrete injury severity categories are assumed to be associated with this latent variable. This latent variable is mostly specified as a linear function for each observation as seen in Figure 2. (Washington et al., 2011).

$$z = \beta X_i + \varepsilon_i$$

Figure 2. Equation. The Standard Ordered Response Logit Model

Where, X_i is a vector of variables determining the discrete ordering for each crash observation, β is a vector of estimable parameters, and ε_i is a random error term. Using the above equation, observed injuries *(y)* which are ordinal, for each observation can be expressed as seen in Figure 3:

$$y = 1 \;\; if \; z \leq \mu_0$$
$$y = 2 \;\; if \; \mu_0 \leq z \leq \mu_1$$
$$y = 3 \;\; if \; \mu_1 \leq z \leq \mu_2$$

Figure 3. Equation. The Ordinal Observed Injuries (Y) For Each Observation.

Where, μ are estimable threshold parameters that define *y*, and correspond to integer ordering. To estimate the parameter μ, with the model parameters β, an assumption is made on the

distribution of the random error term, ε. If the distribution of the error term is assumed to be logistically distributed across observations, an ordered logit model results. On the other hand, a normal distribution assumption of the error term will result in the ordered probit model. The lower threshold μ_0, is usually set to negative infinity and results in the outcome probabilities is seen in Figure 4:

$$P(y = i) = \nabla(\mu_i - \beta X) - \nabla(\mu_{i-1} - \beta X)$$

Figure 4. Equation. Ordinal logit model

Where μ_i and μ_{i-1} represent the upper and lower thresholds for injury severity i. (Washington et al., 2011).

To obtain unbiased results in the analysis, it is important to account for unobserved heterogeneity across observations relating to roadway, driver, and vehicle. Such heterogeneity could include unobserved factors, such as driver socioeconomic status, risk perception, level of enforcement, reaction to external stimuli. (Gkritza and Mannering 2008; Mannering et al. 2016). It is therefore necessary to apply a methodological approach that allows for parameter estimates of variables to vary across observations of the crash data.

To consider random parameters in the ordered logit model, the simulated maximum likelihood estimation is incorporated into the modeling process. Estimation efficiency is improved by using 200 Halton draws during the estimation of the model. (Greene, 2007).

After the model is estimated, the signs of the parameter estimates are important for interpreting the model results. A positive sign indicates an increase in the probability of the most severe outcome (fatal/incapacitating injury) and a decrease in the probability of the least severe outcome (property damage only). The interpretation is reversed for a negative parameter estimate.

Estimation of the Shift in Crash Proportions

The next step in the study was estimating the shift in crash proportions due to a change in barrier heights. Shifts in crash proportions were considered due to the changes in crash severity resulting from changing barrier heights. The methodology adopted for this section required the use of a Safety Performance Function (SPF) estimated from an NB regression model. The NB structure is preferred for crash frequency prediction models to the Poisson framework, which restricts the mean to be equal to the variance. Crash data are usually over dispersed meaning the mean of the crash frequency is larger than the variance. The use of Poisson models for over dispersed data leads to inconsistent and biased estimates. (Washington et al., 2011). In the Poisson model, the probability $P(y_i)$ of observing y_i crashes on a given roadway segment, i, is defined as seen in Figure 5:

$$P(y_i) = \frac{\exp(-u_i) {u_i}^{y_i}}{y_i!}$$

Figure 5. Equation. The Poisson Model

Where, y_i is the number of crashes and u_i is the mean number of crashes. Since the Poisson model requires the mean to be equal to the variance, the NB model is implemented to account for data over dispersion by introducing the over dispersion parameter, k. The variance of the crash frequencies then defined by the following equation (Figure 6) under the NB framework:

$$var[y_i] = u_i(1 + ku_i)$$

Figure 6. Equation. The variance of the crash frequencies

From Figure 7, as k → 0 the NB model reduces to the Poisson model. The mean function of the NB model is defined in Figure 7.

$$u_i = N_{SPFi} = \exp(\beta X_i + \epsilon_i)$$

Figure 7. Equation. The Definition of the Mean Function

Where, N_{SPFi} is the estimated number of crashes from an SPF; X_i is a vector representing independent variables, and β is a vector of estimable parameters. The probability of observing y_i crashes is set out in (Figure 8), assuming the crash frequencies follow a NB distribution.

$$\Pr(X = k) = \frac{\Gamma(r+k)}{k!\,\Gamma(r)} \left(\frac{r}{r+m}\right)^r \left(\frac{m}{r+m}\right)^k \quad \text{for } k = 0, 1, 2, \ldots$$

Figure 8. Equation. The Probability of Observing y_i Crashes.

Where, k is the number of failures, r is the number of successes, p is the probability of success, m is the explanatory variable, p(y) probability mass function, and Γ is gamma. The NB model's log-likelihood is computed as seen in Figure 9:

$$LL = \sum_{i=1}^{n} \ln\left(P(y_i)\right)$$

Figure 9. Equation. NB model's log-likelihood.

For most statistical software, twice the negative log-likelihood value, -2LL is reported. The NB models estimated were utilized to assess the shift in crash proportions due to an enhancement of barrier heights. This was done by predicting barrier crashes given that barrier heights have been adjusted to the recommended height ranges. A ratio of the predicted to the observed crashes was then estimated for both interstate and state highway system barriers. This ratio was then used to compute the shift in crash proportions attributed to changing barrier heights.

Optimization of Traffic Barriers

The final analysis involved optimization and ranking of barriers based on their estimated benefits of enhancing barrier height. Linear quantile models (LQM) and hurdle models were utilized to optimize and rank the traffic barriers based on changing barrier heights to the recommended heights specified in the RDG and other literature. The output of the optimization procedure was

crash costs relating the optimization of barrier heights to benefits attributed to a reduction in crash severity.

The optimization process relies on carefully weighting the costs and benefits of the prevailing policy on traffic barriers in the state. This study depended on using monetary costs or Equivalent Property Damage Only (EPDO) costs to assess the cost-effectiveness of optimizing barrier heights. The benefit-cost analysis, as applied in the context of traffic barriers, is considered as welfare maximization. (Elvik, 2001). The benefit-cost analysis uses the Pareto-criterion to assess whether a project improves the welfare of road users or not. This concept states that welfare is increased when a change makes nobody worse off while making some people better off. The cost-benefit analysis was conducted for a ten-year period as seen in Figure 10.

$$\sum_{i=1}^{10} predicted\ cost\ with\ no\ barrier\ enhancement_i\ - (Reset\ cost + predicted\ Future\ cost)_i$$

Figure 10. Equation. The cost-benefit analysis was conducted for a ten-year period

The LQM and hurdle models were estimated based on EPDO crashes. EPDO represents all crash costs converted to an equivalent cost of PDO crashes. Crash costs provided by the WYDOT Safety Office and used for the analysis are presented in Table 1.

Table 1. Crash Costs Based on WYDOT Estimates

Type crash	Cost
Fatality (F)	9,604,727
Suspected serious injury (SSI)	464,837
Unknown (U)	149,551
Suspected minor injury (SMI)	132,181
Possible injury (PI)	75,331
Property Damage Only (PDO)	34,612

Based on these crash costs, EPDO was computed as seen in Figure 11:

$$EPDO = 277.5(F) + 13.4(SSI) + 4.3(U) + 3.8(SMI) + 2.2(PI) + PDO$$

Figure 11. Equation. Estimate the EPDO

Linear Quantile Models

Quantile regression estimates functional relations between variables for all portions of a probability distribution. (Koenker & Bassett, 1978). Quantiles in a distribution or population rank and order values in that distribution. For instance, quartiles divide a distribution into four parts, quantiles into five, and deciles into ten parts. The use of quantile regression enables an estimation of regression models at different points in a distribution. For example, for highly skewed data, such as the income of a country, there might be an interest in predicting salaries at the highest or lowest quantiles. Also, predictions based on the median might not provide an accurate outlook of salaries due to the skewed nature of the data. Utilizing a quantile regression

approach that can predict salaries at different quantiles (eg. 25th or 75th quantile) would provide a holistic evaluation of salaries at different points in the distribution. The interpretation of parameter estimates from quantile regression is like interpreting estimates from the ordinary least squares approach. However, instead of predicting the mean of the dependent variable, as is done for the least-squares method, the quantile model predicts the dependent variable at different quantiles.

Quantile regression is conveniently defined as an optimization problem as seen in Figure 12, by minimizing the sum of absolute residuals as (Kroenker & Hallock, 2001).

$$min_{\mu \epsilon \Re} \sum_{i=1}^{n} (y_i - \mu^2)$$

Figure 12. Equation. The Optimization Problem of the Quantile Regression.

Where, y belongs to a random sample (y_1, y_2, …, y_n), and μ is a scalar. To obtain an estimate of the conditional expectation function E(Y|x) , μ is replaced by a parametric function $\mu(x, \beta)$ and the expression in Figure 12 is solved as set out in Figure 13.

$$min_{\mu \epsilon \Re} \sum_{i=1}^{n} (y_i - \mu(x_i, \beta))^{2}$$

Figure 13. Equation. Objective Function for the Quantile Model

To obtain estimates at different quantiles, equation in Figure 13 is rewritten as set out in Figure 14.

$$min_{\mu \epsilon \Re} \sum_{i=1}^{n} \rho_\tau (y_i - \mu(x_i, \beta))^{2}$$

Figure 14. Equation. Quantile Model Objective Function

Where, $\rho_\tau(.)$ represents a quantile or loss function. The resulting minimization problem is formulated as a linear function of parameters and can be solved efficiently using linear programming. (Kroenker & Hallock, 2001). The quantile model can be used to analyze the conditional mean of the clustered outcome variable as characteristic of the data used for this study. The methodology for performing the optimization and ranking of barriers using the LQM approach is shown in Figure 15.

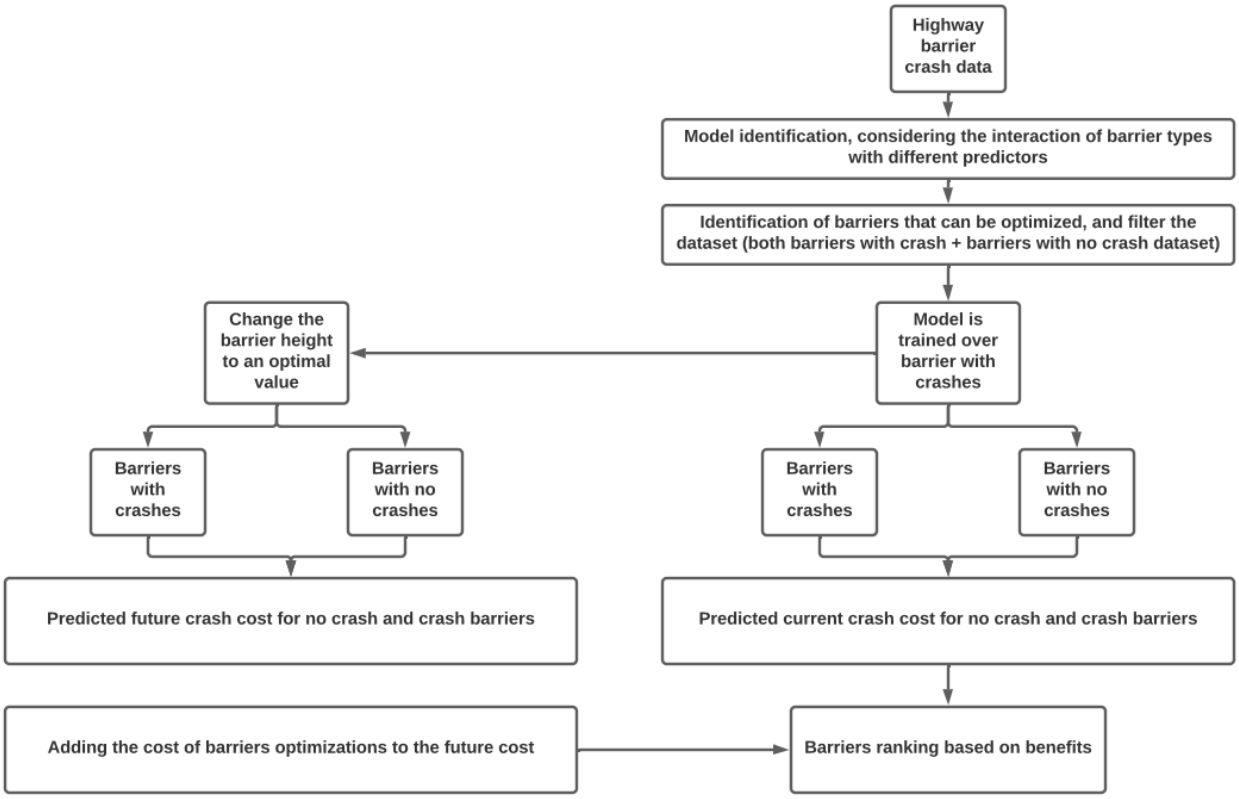


Figure 15. Chart. Linear Quantile Model Methodological Approach

Hurdle Models

Hurdle models are similar to zero-inflated models in that hurdle models adopt a dual regime data generating process. However, unlike the zero-inflated Poisson and NB models, which assume the zero-generating process to be structural, hurdle models consider zeros in the data to be due to sampling. For traffic safety, the structural zeros imply an inherently zero crash state by nature and the sampling zeros correspond to potential crash conditions implying zero crash observations only by chance. (Son, Kweon, & Park, 2011). The sampling zero assumption for the hurdle models is deemed to be appropriate for crash data analysis because road segments do not exist in a perfectly safe state. (Lord, Washington, & Ivan, 2007). Two models are usually estimated for zero-inflated and hurdle models. These models are for crash counts and zero crashes. Binary logistic or probit models are typically estimated for the zero-crash state, while Poisson, NB, or other count modeling structures are estimated for the crashes.

The hurdle model is expressed as seen in Figure 16:

$$\mathfrak{f}_{hurdle}(y;x,z,\beta,\gamma) = \begin{cases} \mathfrak{f}_{zero}(0;z,\gamma) & \text{, if y} = 0 \\ (1-\mathfrak{f}_{zero}(0;z,\gamma)).(\mathfrak{f}_{count}(y;x,\beta)/(1-(\mathfrak{f}_{count}(0;x,\beta)) & \text{, if y} > 0 \end{cases}$$

Figure 16. Equation. Hurdle Model.

Where, β, γ are model parameters, f_{count} is a count data model, f_{zero} is a zero-hurdle model. The term $\mathfrak{f}_{zero}(0;z,\gamma)$ accounts for the hurdle component of the model and predicts zero counts with

a probability of less than 0.5. The ($f_{count}(0; x, \beta)$ part of the model handles the prediction of crashes above a zero count and highlights the probability of crossing the hurdle.

For this study, the zero-crash state was modeled using a binary logistic regression to account for whether a barrier would experience any crash, and a truncated NB model to account for EPDO crashes. The hurdle model was implemented for this study using a machine learning approach. The data was split into two sets, training and validation dataset. This procedure is outlined in Figure 17.

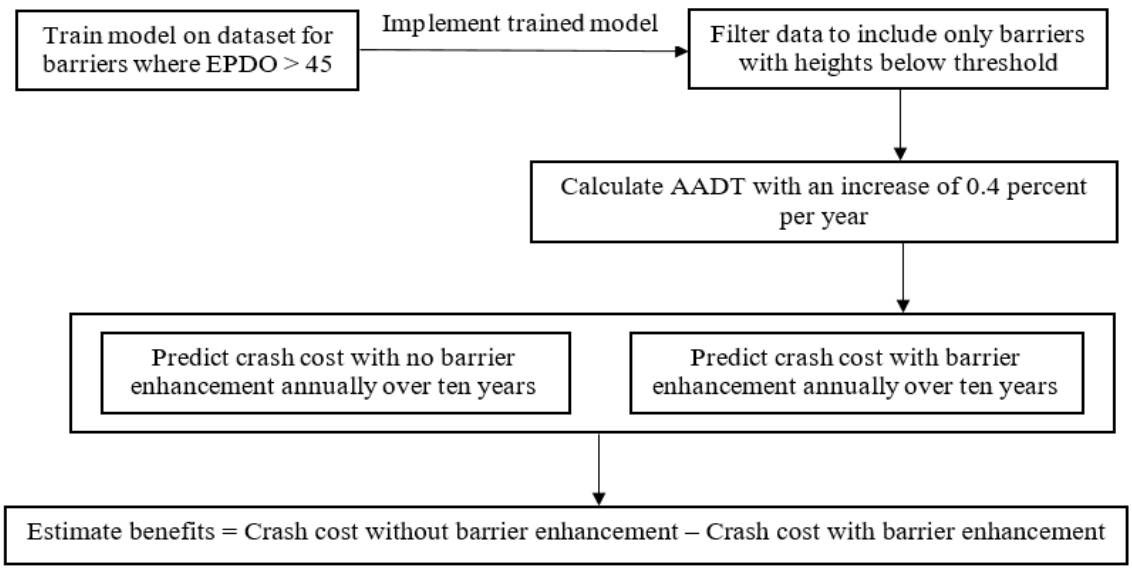


Figure 17. Chart. Machine Learning Approach for Hurdle Model

Several assumptions were made to conduct the analysis using the hurdle model. Key among them were:

- Traffic increased by a rate of 0.4 percent yearly.
- All predictors are kept constant for the cost analysis apart from barrier heights and traffic,
- The analysis period is 10 years.
- The reset/renewal cost will be implemented in the first year only. This implies that a reset/renewal cost is considered as a startup cost.
- No interest rate was considered for the benefits (savings from the reduction in crashes) accrued by optimizing barrier heights at the end of each year.
- The optimum barrier height was set at 27 inches for box-beam and W-beam barriers while a value of 40 inches was chosen for concrete barriers (AASHTO, 2011b).

Chapter Summary

Approaches adopted to achieve the goal of assessing, optimizing, and ranking traffic barriers were presented in this chapter. This chapter discussed a barrier condition rating system, the estimation of crash severity shifts, and optimization of traffic barrier height. The formulation of

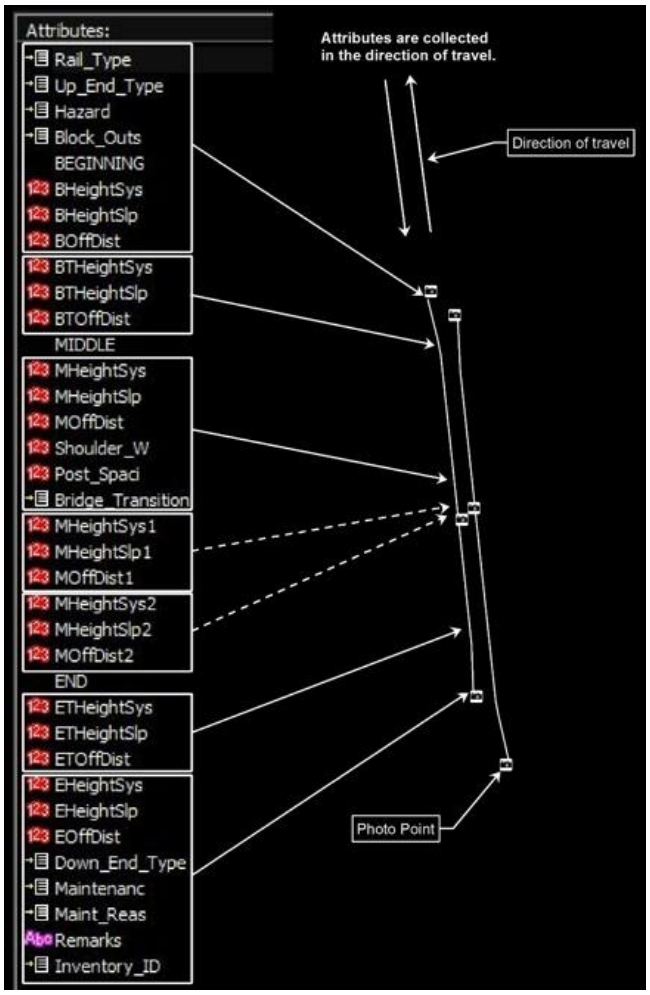
the NB, LQM, and hurdle models and how they are used to estimate crash severity shifts or utilized for barrier height optimization were presented in this chapter.

CHAPTER 4: DATA COLLECTION

A field survey was conducted between the summer of 2016 through the summer of 2018 to collect data for traffic barriers on Wyoming interstate and state highway systems. Based on the data collected, overall, 204 miles of median barriers exist on a total of 912 miles of interstate roads in Wyoming (0.22 miles median traffic barriers per mile) on all three interstate highways (I-90, I-80, and I-25). Side barriers on interstate highways accounting for 0.82 million linear feet (155 miles) were collected.

For the state highway system, 435 miles of barrier systems were inventoried for this study. The data related to geometric features and physical information collected included barrier type, system height, post-spacing, side-slope, lateral offset, shoulder width, segment width, hazard fixed-object behind traffic barriers, flare/parallel length, and bridge transition. Data from five geometric locations of the barrier was collected. Source: ***Trihydro/ WYDOT, 2018.***

Figure 18 and Figure 19 show the longitudinal and cross-sectional profiles of the geometric and physical variables collected.



Source: Trihydro/ WYDOT, 2018.

Figure 18. Illustration. Five Locations on Barriers Considered During Barrier Inventory

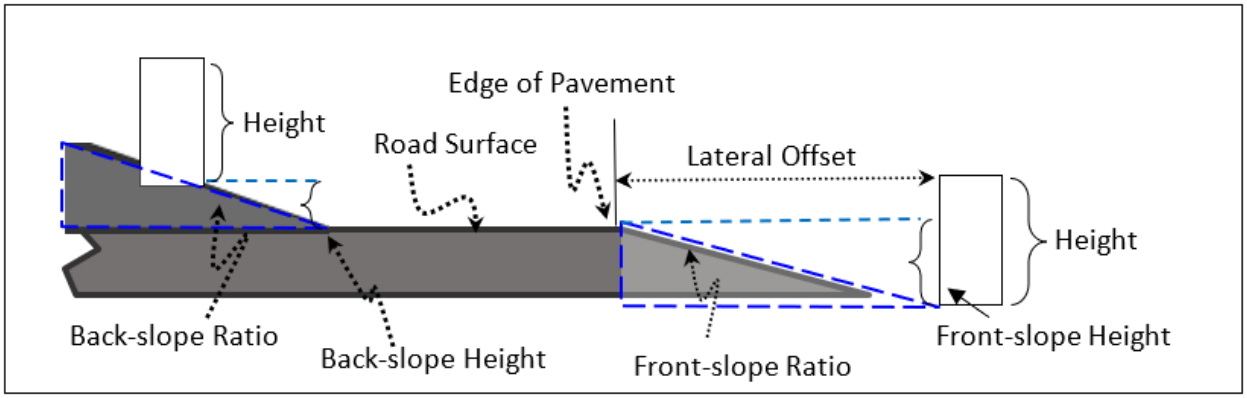


Figure 19. Illustration. The Cross-Sectional Profile of Some of the Variables Collected in the Field Survey

Based on the scope of this study, data collectors inventoried barriers on interstate and state highway system, in Wyoming, apart from locations that presented high safety risks to data collectors. Barriers considered for this study were installed either on the median or the right-hand side of the traveled way. Source: **Trihydro/ WYDOT, 2018.**

Figure 20 shows the routes on which barriers were inventoried for this study. Cable barrier systems were not collected statewide since they were mostly newly installed. Also, these new barrier systems were mostly designed based on recent design standards and policies. Additionally, cable barriers were previously identified in previous studies as being low risk compared to other barrier systems. (Alluri, Gan, Haleem, & Mauthner, 2015; Chimba, Emaasit, Allen, Hurst, & Nelson, 2014; Russo & Savolainen, 2018; Zou, Tarko, Chen, & Romero, 2014). For median barriers on interstate highways, 53.1, 27.6, 16.7, and 16.3 miles of box beam, W-beam, concrete, and cable systems were inventoried. For interstate side barriers, 67.6, 27.1, 11.7, and 11.2 miles of box beam, W-beam, concrete, and cable barrier systems, respectively were inventoried. On the state highway system, the inventory determined that there were 82.5, 21.4, 1.1, and 0.2 miles of W-beam, box beam, cable, and concrete barriers, respectively. Source: **Trihydro/WYDOT, 2018.**

Figure 21, Source: **Trihydro/WYDOT, 2018.**

Figure 22, Source: **Trihydro/WYDOT, 2018.**

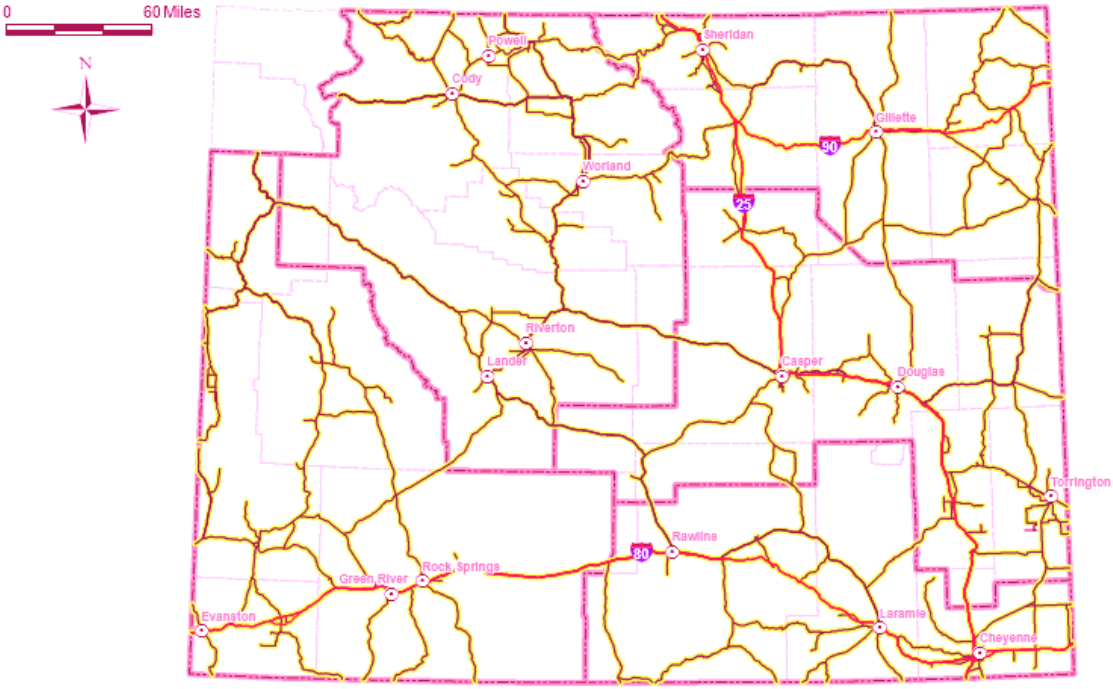
Figure 23, and Source: **Trihydro/WYDOT, 2018.**

Figure 24 show pictures of traffic barrier types inventoried.

The geometric data collected was merged with historical crash data collected from the CARE package. The CARE package contains historical crashes recorded from all over the state. Crashes reported between 2008 and 2017 were collected using the latest version of the CARE package, in

Wyoming. Crashes that involved work zone areas, multi-vehicle, and end terminals were not considered because the severity of crashes could not be directly linked with hitting the barriers. Based on the care package, a total of 7,622 barrier crashes were recorded during the reporting period, between 2008 and 2017. However, 66 work zone-related crashes, 295 multi-vehicle crashes, and 437 end-treatment crashes were removed from the dataset. The only crashes retained were those that had a direct impact on traffic barriers. Also, 315 crashes were removed due to possible coding errors by the police when recording the location of crashes. As a result, some of the crashes were recorded as traffic barrier-related while no barrier existed at the location. In summary, a total of 6,509 single-vehicle crashes were considered for the safety evaluation of traffic barriers in the state. For the state highway system, 1,343 crashes were recorded out of the 6,509 crashes. This indicates that 21 percent of all traffic barrier crashes occurred on state highway system roads. Also, only 82 (about 6 percent) were median barrier crashes. This is because most state highway systems are undivided two lane roads in Wyoming. Road geometric variables (radii, lane width, etc.), and traffic volume data were extracted from the WYDOT spreadsheets. Other road geometric features, including super elevation rates, the number of lanes, and longitudinal grades, were added by reviewing videos using the pathweb website (2018). Source: **Trihydro/WYDOT, 2018.**

Figure 25 shows a screenshot of the pathweb website. Average annual snowfall and average annual snow days were extracted from the National Oceanic and Atmospheric Administration (NOAA, 2018). From the weather data, an average of 39 snowy days and 64.15 inches of snowfall was recorded from the nearest weather station closest to the barrier location. A summary of the variables collected for the study is shown in Table 2 and Table 3.



Source: Trihydro/ WYDOT, 2018.

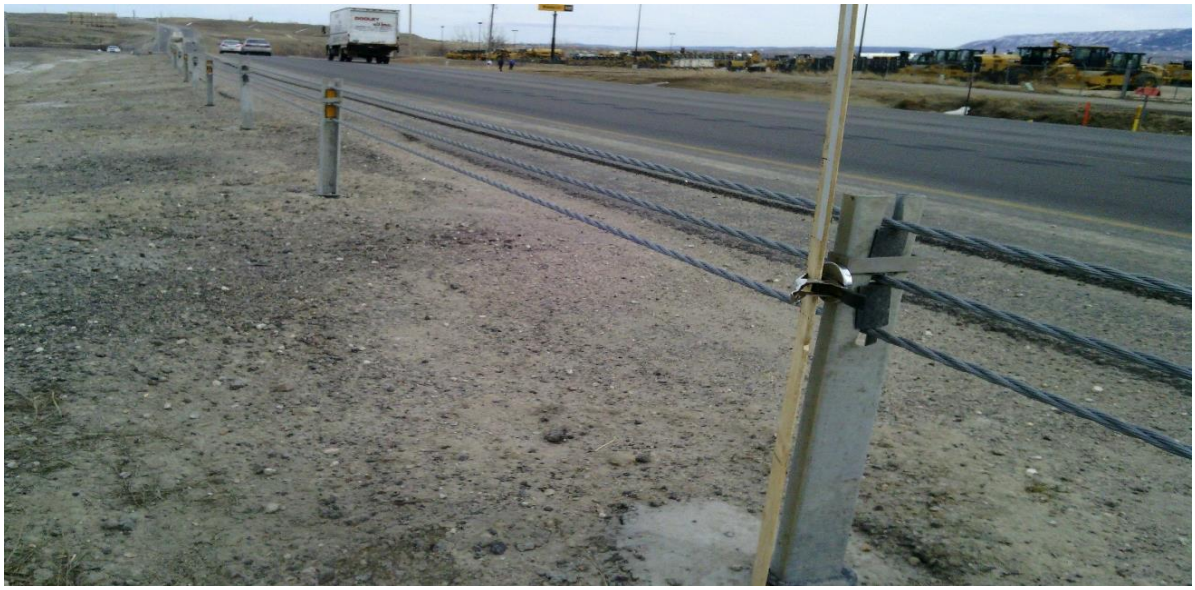
Figure 20. Map. Routes Inventoried for Study (Interstate Highways Highlighted Red, State highway system Highlighted Green)

Source: Trihydro/WYDOT, 2018.

Figure 21. Picture. W-beam Barrier

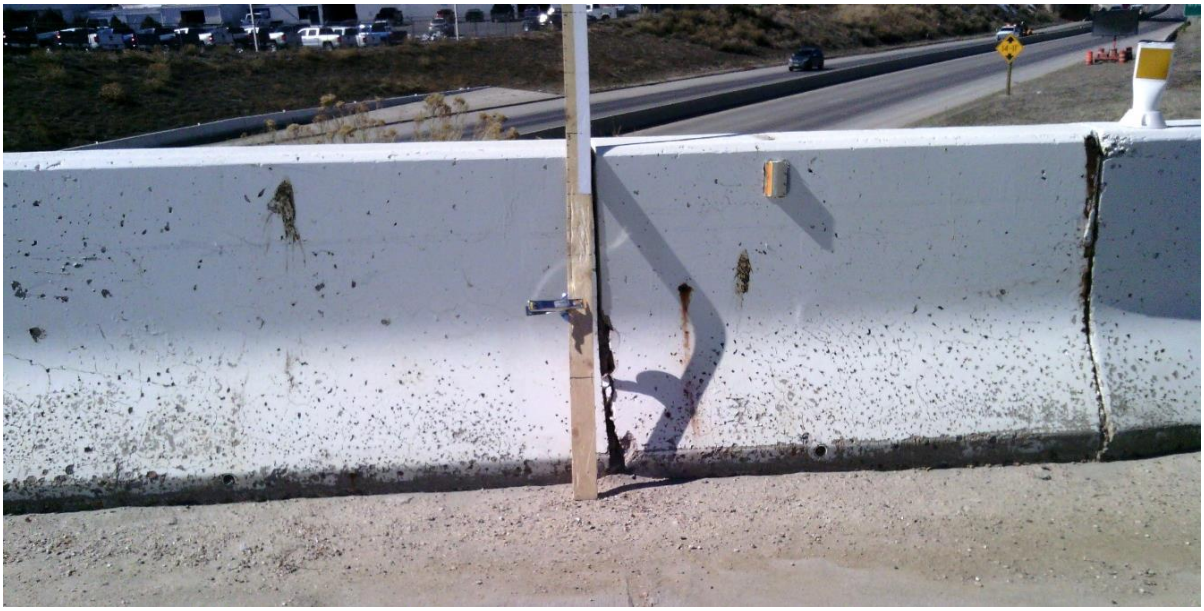
Source: Trihydro/WYDOT, 2018.

Figure 22. Picture. Box Beam Barrier



Source: Trihydro/WYDOT, 2018.

Figure 23. Picture. Cable Barrier



Source: Trihydro/WYDOT, 2018.

Figure 24. Picture. Concrete Barrier

Source: Trihydro/WYDOT, 2018.

Figure 25. Picture. Pathweb Screen Shot

Table 2. Summary of Variables Collected for Median Barriers (Interstate)

Road Features			Box Beam Barriers	W-Beam Barriers	Concrete Barriers	Cable Barriers
Traffic Barrier Geometric Features	Length (mile)	Mean	0.14	0.68	0.41	0.58
		Standard Deviation	0.17	0.53	0.67	0.67
		Maximum	0.93	2.20	1.94	1.92
		Minimum	0.01	0.01	0.01	0.11
	Shoulder Width (ft)	Mean	6.5	4.8	10.6	3.4
		Standard Deviation	3.6	2.9	7.4	0.6
		Maximum	22.1	13.0	25.4	5.1
		Minimum	0.0	0.0	0.0	2.7
	Lateral Offset (ft)	Mean	4.0	4.8	0.6	8.8
		Standard Deviation	5.6	5.0	2.1	1.7
		Maximum	23.5	26.0	12.7	20.7
		Minimum	0.0	0.0	0.0	7.3
	System Height (in)	Mean	29.4	29.2	35.1	29.9
		Standard Deviation	2.7	3.1	5.6	2.8
		Maximum	37.2	37.2	55.2	42.0
		Minimum	18.0	16.8	20.4	25.2
	Post-Spacing (ft)	Mean	6.0	6.4	-	16.2
		Standard Deviation	3.6	1.3	-	0.2
		Maximum	22.1	12.6	-	16.8
		Minimum	1.2	2.5	-	16.0
	Front-Slope[a] Ratio (V:H)	Mean	1:6	1:6	1:8	1:12
		Maximum	1:0.6	1:4	1:5	1:6
		Minimum	1:20	1:20	1:20	1:50
	Back-Slope Ratio (V:H)	Mean	1:5	1:8	1:10	-
		Maximum	1:2	1:6	1:10	-
		Minimum	1:20	1:8	1:20	-
Road Characteristics	Speed Limit (mph)	Mean	72	73	66	72
		Standard Deviation	5.5	6.4	6.6	6.4
		Maximum	75	75	75	75
		Minimum	50	50	50	50
	AADT (vehicle/day)	Mean	6,303	6,002	8,135	4,465
		Standard Deviation	2,567	1,676	1,913	950
		Maximum	12,903	12,903	10,995	7,208
		Minimum	749	1,624	3,388	3,432
	AADTT (truck/day)	Mean	2,037	2,488	1,892	898
		Standard Deviation	1,110	803	860	133
		Maximum	3,689	3,413	3,689	1,690
		Minimum	131	284	235	590

[a] Side-slopes flatter than 1:20 were considered as flat

Table 3. Summary of Variables Collected for Side Barriers (Interstate)

Road Features		Box Beam Barriers	W-Beam Barriers	Concrete Barriers	Cable Barriers
Length (ft)	Mean	650	1,374	2,543	4,357
	Standard Deviation	802	1,913	3,257	3,553
	Maximum	8,658	9,366	10,276	10,138
	Minimum	66	40	57	630
Shoulder Width (ft)	Mean	6.1	5.6	9.3	3.3
	Standard Deviation	3.2	3.2	7.6	0.4
	Maximum	22.1	13.0	25.4	4.7
	Minimum	0.0	0.0	1.4	2.7
Lateral Offset (ft)	Mean	3.1	4.8	0.4	8.5
	Standard Deviation	4.2	4.8	1.3	0.8
	Maximum	27.9	25.6	8.1	13.0
	Minimum	0.0	0.0	0.0	7.3
System Height (in)	Mean	29.6	28.7	33.9	33.3
	Standard Deviation	2.5	3.3	4.5	4.3
	Maximum	41.6	37.2	42.0	42.0
	Minimum	21.6	19.2	25.1	25.2
Post-Spacing (ft)	Mean	5.9	6.3	-	16.3
	Standard Deviation	0.3	1.2	-	0.2
	Maximum	9.2	12.6	-	16.8
	Minimum	2.7	2.4	-	16.0
Front-Slope Ratio (V:H)	Mean	1:7	1:6	1:10	1:10
	Maximum	1:1	1:0.3	1:10	1:6
	Minimum	1:10	1:10	1:10	1:10
Back-Slope Ratio (V:H)	Mean	1:6	1:18	1:18	-
	Maximum	1:2	1:6	1:20	-
	Minimum	1:10	1:10	1:10	-
Speed Limit (mph)	Mean	72.3	71.9	66.4	74.5
	Standard Deviation	6.9	8.5	9.9	2.2
	Maximum	75.0	75	75.0	75
	Minimum	55.0	55.0	55.0	55.0
AADT (vehicle/day)	Mean	5,175	4,749	8,119	3,914
	Standard Deviation	2,297	1,445	1,956	585
	Maximum	12,903	7,335	10,995	7,146
	Minimum	749	1,545	3,587	3,277
AADTT (truck/day)	Mean	1,596	1,610	2,075	744
	Standard Deviation	1.043	1,011	834	157
	Maximum	3,689	3,325	3,689	1,038
	Minimum	131	270	242	555
AAS [a] (in)	Mean	57.2	68.9	62.7	63.0
	Maximum	108.4	108.4	108.4	79.2
	Minimum	32.4	36.5	46.7	47.3
AASD [b] (No. of Days)	Mean	37	41	32	31
	Maximum	50	50	49	41
	Minimum	16	20	21	21

[a] Annual Average Snowfall
[b] Annual Average Snowy Days

Chapter Summary

This chapter discussed data collection and preparation procedures. A field survey was conducted to collect data for traffic barriers on interstate and state highway system from the summer of 2016 to 2018. A total of 912 miles of roads were inventoried for this study. Traffic barriers were inventoried for median and side barriers on interstate roads, and side barriers for the state highway system. For the interstate system, 204 miles and 155 miles were inventoried for median and side barriers. On the state highway system, 435 miles of mainly side barriers were inventoried for the study. The predominance of side barriers installed on the state highway system is attributed to the fact that most two-lane roads in the state are undivided. Traffic barrier geometric data collected included system height, post-spacing, side-slope, lateral offset, shoulder width, segment width, hazard fixed-object behind traffic barriers, flare/parallel length, and bridge transition. These were then merged with historical crash data from the CARE package. The crashes were recorded from 2008 to 2017. The inventory data was summarized and presented on tables found in this chapter.

CHAPTER 5: RESULTS

This chapter discusses the results of the study. The results of the impact of geometric factors of traffic barriers on crash severity are first presented. The analysis in the shifts in crash proportion due changes in barrier heights is then presented and discussed. The next results presented were the benefit-cost analysis and ranking of barriers based on barrier height improvement. The final discussion related to the use of the proposed BCI to assess the overall conditions of traffic barriers. Three cases were discussed to demonstrate the use of the BCI procedure.

The Effect of Geometric Dimensions of Median and Side Traffic Barriers on Crash Severity

This section discusses the effect of the geometric features of the median, side traffic barriers, and road variables on crash severity for interstate roads in Wyoming. A review of previous studies indicated that there are gaps with regard to evaluating the performance of traffic barriers in crashes. For example, despite several studies being conducted using simulation tools or statistical methods to assess barrier performance, the effect of variables, such as traffic barrier height, has not been investigated using a comprehensive crash dataset. The analysis conducted for this section aimed to fill this gap by evaluating the effect of variables related to traffic barriers' geometric dimensions (height, post-spacing, sideslope, lateral offset, etc.) on traffic barrier crashes. Statistical models are presented for crash severity analysis of median and side barriers on interstate highways. The focus of interstate highways was due to the higher frequency of barrier crashes on this highway functional class. Based on the CARE package, 42 percent of traffic barriers are located on interstate highways, in Wyoming, and account for approximately 70 percent of traffic barrier crashes.

Data Analysis

Ordinal logistic regression was selected for the statistical analysis. Three discrete categories were considered for crash severity (dependent variable) in the analysis based on the KABCO (K-Fatal, A-Incapacitating injury, B-Non-incapacitating injury, C-Possible injury, O-No injury) scale developed by the National Safety Council, 1970. However, data limitation crash types K (fatal), A (incapacitating injury), B (non-incapacitating injury), and C (possible injury), were combined to have higher frequencies in these discrete categories. The categories used for the analysis were:

- High severity (fatal and incapacitating injury)
- Moderate severity (non-incapacitating injury and possible injury)
- Low-severity or roperty damage only (no injury)

Only single-vehicle crashes were considered in the analysis because multi-vehicle crashes involving traffic barriers may be due to hitting other vehicles also involved in the crash. Table 2 and Table 3 in the data collection chapter shows the variables considered for the analysis.

Interstate Median Barrier Crash Severity Model

Table 4 presents the results of the random parameters (RP) ordered logit model developed for the severity of crashes involving median barriers on interstate highways.

Table 4. Ordered Logit RP Model for Crash Severity of Median Traffic Barriers (Interstate)

Variable		Estimate	Standard Error	P-Value
Constant		0.183	0.476	0.700
Traffic Barrier	Box Beam Barriers with a Front-slope Height of 0.1-1 ft	-0.762	0.126	<0.001
	Standard Deviation of Parameter Distribution	0.871	0.085	<0.001
	Box Beam Barriers Located on a Flat Slope	-0.473	0.157	<0.001
	Box Beam Barriers with a Lateral Offset Shorter than 2 ft	0.358	0.124	<0.001
	Cable Barriers with a Height of 30-42 in	-1.187	0.380	<0.001
	Concrete Barriers with a Height Shorter than 32 in	0.225	0.192	0.048
	W-Beam Barriers with a Height of 24-30 in	-0.27	0.155	0.040
	W-Beam Barriers with a Post-Spacing of 6.1-6.3 ft	-0.798	0.202	<0.001
	Standard Deviation of Parameter Distribution	1.583	0.160	<0.001
Traffic, Road, and Crash Environment	Dry Surface Conditions	0.208	0.094	0.027
	Standard Deviation of Parameter Distribution	0.588	0.074	<0.001
	Horizontal Curves with a Radius Shorter than 2000 ft	0.298	0.151	0.039
	Log (AADTT)	-0.500	0.143	<0.001
	Standard Deviation of Parameter Distribution	0.152	0.013	<0.001
	Motorcycles	3.884	0.565	<0.001
	Female Driver	0.446	0.083	<0.001
	Driver Improperly Restrained	0.892	0.110	<0.001
	Rollover Crash	1.629	0.135	<0.001
	Drivers with a Record of Alcohol Citation	0.758	0.178	<0.001

Restricted Log Likelihood = -1,067.20
Log Likelihood at Convergence (RP) = -897.63
Log Likelihood at Convergence (Fixed) = -905.89

The results of the log-likelihood test indicated that the RP model provides a superior fit to the traditional fixed-effects model. A variable is considered random if the standard deviation of the distribution of the random parameter is statistically significant. The standard deviations of the random parameters have been shown in Table 4.

Based on the modeling results in Table 4, cable barriers, with a minimum height of 30 inches and a maximum height of 42 inches, were found to be associated with the least probability of severe injury crashes for median barrier crashes. The superior performance of cable barriers in terms of crash severity is consistent with previous studies. (Russo & Savolainen, 2018; Zou et al., 2014). The finding indicates that taller cable barriers may be consistent with vehicle dimensions, or they may perform better in absorbing crash forces in comparison to short cable barriers. Concrete barriers with a height of less than 32 inches were found to increase the probability of severe crashes. The RDG recommends two heights of 32 and 42 inches for concrete barriers. The result from Table 4 is therefore expected, especially in Wyoming where taller concrete barriers are recommended mostly due to the high truck traffic volume. Truck traffic composition on some segments of I-80 in Wyoming is up 60 percent (Molan, Rezapour, & Ksaibati, 2019a). To present a clear view regarding the role of traffic barrier heights in crashes, Figure 26 compared the percentage of high severity and moderate severity crashes found in each traffic barrier type with respect to their height. Note that all the categories presented in Figure 26 had more than 100 observations, apart from the categories of cable barrier (< 30 inches), cable barrier (=> 30

inches), short concrete barrier (< 32 inches), short W-beam barrier (< 24 inches), and short box beam barrier (< 25 inches) with 43, 45, 64, 42, and 68 observations, respectively.

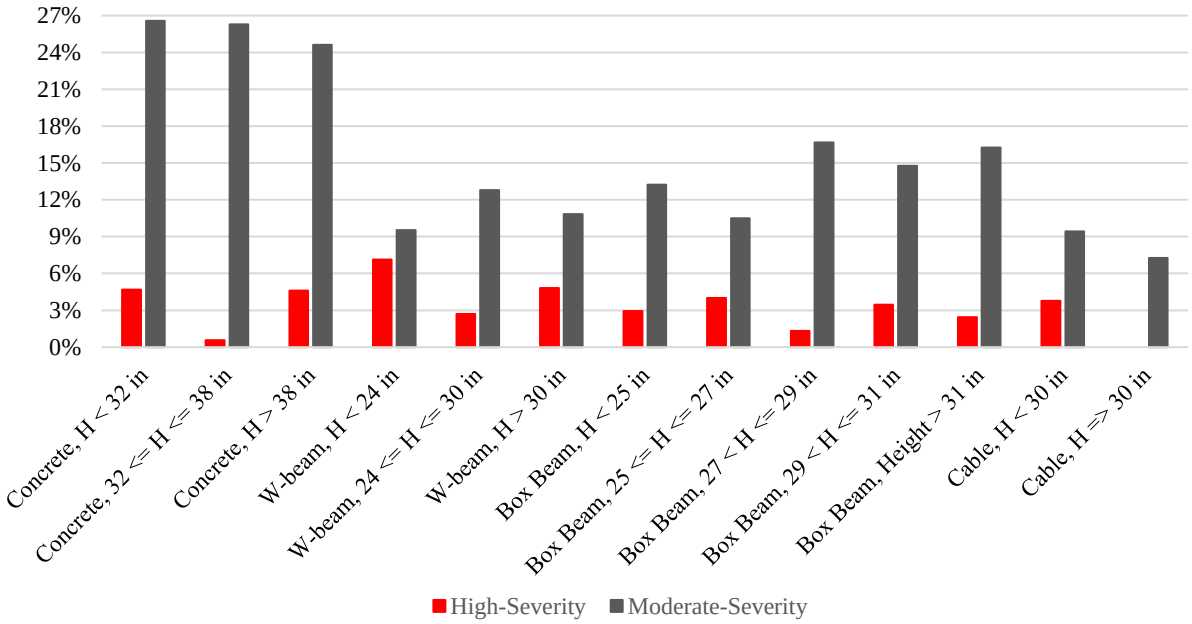


Figure 26. Chart. Percentage of Crash Severity Categories for Median Traffic Barriers

From Figure 26, W-beam barriers resulted in the highest probability of experiencing a severe crash. For moderate severity crashes, concrete barriers had the highest frequency of 25-27 percent. This rate of moderate-severity crashes was found to be considerably higher than all the other median traffic barriers considered in this study. On the other hand, both cable barrier categories had the lowest percentage of injury crashes. Another important point found was that box beam barriers with a height between 27 and 29 inches are the most appropriate to reduce high-severity crashes. Also, concrete barriers with a height of 32-38 were found to be less severe than taller concrete barriers (> 38 inches). This result might be related to the fact that the height of a car drivers' eye is about 42-51 inches (3.5-4.25 feet) based on the Green Book (AASHTO, 2011a). In other words, there might be a higher probability that a car driver's head may hit the concrete barrier when it has a height greater than 38 inches during a crash.

With regards to other geometric dimensions found to be significant in Table 4, box beam barriers located on a flat or a slight front side-slope (with a maximum height of one foot from the road surface) were more likely to be involved in low-severity crashes. Also, crash severity increased when there was a lateral offset shorter than 2 feet for box beam barriers. Similar to the recommendations provided regarding post-spacing by the RDG, W-beam barriers with a post-spacing between 6.1 and 6.3 feet resulted in lower crash severity.

Interstate roads with a higher annual average daily truck traffic (AADTT) were found to be less severe. This may be attributable to the fact that truck drivers are more experienced, and other drivers might tend to drive more cautiously when there are more trucks. As previous studies also found, female drivers, dry surface conditions, and motorcycles were more likely to increase the severity of crashes involving median traffic barriers (Russo & Savolainen, 2018; Zou et al.,

2014). Both unbelted drivers and drivers with a record of alcohol citation significantly increased the likelihood of high-severity crashes. As expected, crashes involving rollovers showed one of the highest parameter estimates (β= 1.629) among the variables related to the crash environment. Sharp horizontal curves (as opposed to tangent segments or horizontal curves with a radius larger than 2,000 feet) also had a higher probability of resulting in high-severity crashes.

Interstate Side Barrier Crash Severity Model

The results of the random parameters ordered logit model for side barriers on interstate highways are shown in Table 5. Just as was found with the log-likelihood test for the interstate median barrier model, the random parameter model was a better fit in comparison to the fixed-effects model.

Based on the results shown in Table 5, height, lateral offset, and post-spacing significantly affected the severity of crashes involving side box beam barriers. Meanwhile, the traffic types did not have a significant relationship with crash severity. A possible reason might be the higher number of side box beam crashes compared to the other side traffic barrier types included in the analysis. A similar study may be conducted with a lot more crashes involving other barrier types in the future as data becomes available. All side box beam barriers with a height from 25 to 31 inches were found to reduce crash severity, especially when they have a height between 29 and 31 inches. On the other hand, crash severity increased when the side box beam barrier had a height taller than 31 inches. The results show that the typical height of 27 inches recommended for side box beam barriers in the RDG could result in lower crash severity; however, a height of 29-31 should be more appropriate to minimize the severity of crashes hitting side box beam barriers.

Lateral offset and post-spacing were also found to impact the severity of crashes involving side box beam barriers. Side box beam barriers with a lateral offset shorter than two feet were more likely to result in higher crash severity. This outcome might be attributed to the fact that drivers have a shorter time to react compared to far side box beam barriers. Therefore, they might hit the box beam barriers with a sharper angle and a higher speed. In terms of post-spacing, it was found that side box beam barriers with a post-spacing of 6.1-6.3 feet tended to result in less severe crashes.

With respect to the vehicle, traffic, and environmental factors, side traffic barrier crashes involving motorcycles and rollovers had the highest estimates. These findings were expected as past studies also found similar results. (Russo & Savolainen, 2018; Zou et al., 2014). Drivers and passengers are subjected to more severe forces in rollover crashes compared to crashes with no rollover. Because of the lack of protection and safety equipment, such as seatbelts, and airbags, motorcyclists experience higher severity in traffic barrier crashes in comparison to other vehicle types. This finding may be due to other vehicle types (SUV, pickup, and trucks) having a stronger body to protect occupants. Passenger cars were also identified to be associated with higher injuries in crashes.

Table 5. Ordered Logit RP Model for Crash Severity of Side Traffic Barriers (State highway systems)

	Variable	Estimate	Standard Error	P-Value
	Constant	-2.382	0.251	<0.001
Traffic Barrier	Box Beam Barriers with a Height of 25-27 in	-0.546	0.219	0.012
	Standard Deviation of Parameter Distribution	0.705	0.176	<0.001
	Box Beam Barriers with a Height of 27-29 in	-0.517	0.204	0.011
	Standard Deviation of Parameter Distribution	0.756	0.130	<0.001
	Box Beam Barriers with a Height of 29-31 in	-1.482	0.218	<0.001
	Standard Deviation of Parameter Distribution	1.941	0.218	<0.001
	Box Beam Barriers with a Height Taller than 31 in	0.350	0.193	0.032
	Box Beam Barriers with a Lateral Offset Shorter than 2 ft	0.418	0.145	0.003
	Box Beam Barriers with a Post-Spacing of 6.1-6.3 ft	-0.583	0.210	0.045
	Standard Deviation of Parameter Distribution	1.788	0.194	<0.001
Traffic and Road Environment	Dry Surface Conditions	0.369	0.131	0.005
	Standard Deviation of Parameter Distribution	0.715	0.099	<0.001
	Winter Seasons (October-March)	-0.624	0.129	<0.001
	Standard Deviation of Parameter Distribution	0.701	0.074	<0.001
	Vertical Curves with a Length Shorter than 1000 ft	0.332	0.140	0.017
	Crashes Occurred in (lighted/unlighted) Darkness	0.271	0.112	0.016
	Interstate Roads with a ROW Wider than 400 ft	-0.394	0.112	<0.001
	Standard Deviation of Parameter Distribution	0.588	0.079	<0.001
	Rollover Occurred	2.569	0.209	<0.001
	Passenger Cars	0.362	0.116	<0.001
	Motorcycles	4.776	0.584	<0.001
	Female Drivers	0.211	0.126	0.047
	Standard Deviation of Parameter Distribution	1.307	0.115	<0.001
	Drivers Older than 55 Years	0.719	0.144	<0.001
	Drivers with a Record of Alcohol Citation	0.861	0.252	<0.001
	Standard Deviation of Parameter Distribution	0.720	0.249	<0.001
	Driver Improperly Restrained	1.811	0.164	<0.001
	Driver Improper Action	0.476	0.185	0.010
	Standard Deviation of Parameter Distribution	0.720	0.065	<0.001

Restricted Log Likelihood = -868.50
Log Likelihood at Convergence (RP) = -694.84
Log Likelihood at Convergence (Fixed) = -707.19

Dry surface conditions were more likely to cause a severe injury crash compared to other road surface conditions. Drivers may increase their speed and drive less cautiously on dry road surfaces (as opposed to wet, snowy, and icy surfaces). This could also be the reason for experiencing less severe crashes in winter seasons (October-March). Vertical curves with a length shorter than 1,000 feet had a higher probability of resulting in high-severity crashes compared to flatter curves. Also, crashes that occurred during darkness (lighted but dark/unlighted) were more likely to be severe. There might be a few possible reasons for this result. For example, sight distance of drivers could be negatively affected during dark conditions, or drivers might be tired when driving at night compared to the daytime. Roads with a right-of-way (ROW) of more than 400 feet were found to reduce the severity of side traffic barrier crashes. A possible reason may be that highway designers typically consider a wider ROW when roadsides are flatter with fewer challenges in terms of geometric features. Also, in this case, they can place the side traffic barriers further from the road edge.

An RP-ordered logit model was estimated to analyze the crash severity of barrier-related crashes on state highway systems highways. The results are presented in Appendix A. Additional injury severity analyses were conducted as part of this study. Ordered logistic regression models were estimated to evaluate the influence of barrier type, vehicle, and environmental factors on crash severity. These results are shown in Appendix A. The reader is referred to other analyses conducted with regards to the impact of traffic barriers on crash severity by the research team. Some have resulted in papers that have been published in peer-reviewed journals while others are under the review process (Molan & Ksaibati, 2020a, 2020b; Molan, Moomen, & Ksaibati, 2019, 2020a, 2020b; Molan, Rezapour, & Ksaibati, 2019b; M. Rezapour, Wulff, & Ksaibati, 2019; M Rezapour, Molan, et al., 2019).

Summary of Crash Severity Analyses

Ordered logit models with random parameters were utilized to analyze the geometric features of traffic barriers impacting crash severity for median and side barriers on interstate highways in Wyoming. For median barriers front slope, lateral offset, barrier height, and post spacing were found to influence barrier-related crash severity. With regard to side barriers, the geometric features of box beam barriers were found to impact crash severity. These again included barrier height, lateral offset, and post spacing. Other roads geometric and traffic factors were included in the ordered logit models. The results from the analyses will help policymakers modify some aspects of the features of traffic barriers to improve safety.

Shift in Crash Proportions

The installation of traffic barriers at a location is aimed at reducing the severity of crashes. Thus, traffic barriers prevent vehicles from crossing medians, entering opposing lanes, and crashing with oncoming traffic. Traffic barriers are installed by the side of the road to prevent collisions with fixed roadside objects and other hazards. Therefore, the barriers function by preventing high severity crashes, and instead, reduce crash impacts. However, the presence of a barrier may in turn lead to an increase in crashes at some locations though these crashes may not result in serious injuries. This is because the presence of a barrier may reduce the available space for a vehicle to maneuver and come to a safe stop. This implies that the presence of a traffic barrier may not necessarily reduce crash frequency. However, when barriers are properly built and installed to specifications operate they reduce the severity of crashes.

As previously discussed, the presence of exceedingly tall or very short barriers increase the risks of underride and override crashes, respectively, which may, in turn, increase the probability of severe injuries. As a result, an improvement of barrier heights to within the optimum range should lead to a shift in the proportion of injury categories. In other words, with a change in barrier heights to within the recommended range, predicted crashes should show a decrease in the high injury severity categories (fatal and serious injury), and an increase in PDO crashes. However, PDO crashes may also experience a decrease in frequency.

The analysis carried out for this section aimed to evaluate the shift in crash proportions with a change in barrier height to within the optimal height range. This was done by comparing the observed traffic barrier crashes at the current heights to predicted crashes at the barrier's optimum height. To achieve this, barriers that were found to be outside the recommended height range were set to the optimum height. Recommended lower and upper barrier height ranges were identified from the literature. (AASHTO, 2011b; Fang, Gutowski, Li, & DiSogra, 2013; Gabler

et al., 2005; Ray, Engstrand, Plaxico, & McGinnis, 1997). These height ranges are shown in Table 6, Table 7, and Table 8.

Table 6. Recommended Heights for Median Barriers (Interstate)

Barrier type	Recommended barrier height (Inches)	Percent below	Percent above	Percent within
Cable barrier	30-42	38	0	63
W-beam	27-31	40	20	40
Box beam barrier	25-31	3	29	68
	29-31	45	29	27
Concrete barrier	32-42	38	6	57

Table 7. Recommended Heights for Side Barriers (Interstate)

Barrier type	Recommended barrier height (Inches)	Percent below	Percent above	Percent within
Cable barrier	28-30	0	63	38
W-beam	27 -31	44	28	29
Box beam barrier	27-31	24	29	47
Concrete barrier	32-42	57	0	43

Table 8. Recommended Heights for Side Barriers (State highway system)

Barrier type	Recommended barrier height (Inches)	Percent below	Percent above	Percent within
Cable barrier	30-42	10	0	90
W-beam	27-31	37	36	27
Box beam barrier	27-31	18	46	36
Concrete barrier	32-42	42	0	58

To evaluate the shift in crash proportion, crash prediction models (SPFs) were estimated using NB regression modeling for each crash severity type (fatal/injury and PDO). Due to data limitations, models could not be estimated separately for median and side barriers. The models were therefore estimated for both median and side barriers. This was done for both interstate and state highway system highways. This evaluation was undertaken only for barriers with historical crashes. This was necessary because a comparison between historical and future crashes from the predictions was required. The prediction models are shown below in Table 9, Table 10,

Table ***11***, and

Table ***12***. Crashes predicted from the models using the crash data with the adjusted barrier heights were then compared to the observed crashes.

Table 9. Fatal/Injury Crash Prediction Model (Interstate)

	Estimate	Std. Error	Z-value	P-value
Constant	-0.1262	1.089	-0.166	0.9077
Length (feet)	0.00024	0.000	9.568	0.0000
Height (inches)	-0.00393	0.004	-1.0740	0.2827
Median (1 if median is present, 0 otherwise)	-1.375	1.182	-1.164	0.2445
Height* Median	-0.07387	0.0396	1.868	0.0618
Number of observations	1378			
Log-likelihood at convergence	-2111.877			

Table 10. PDO Crash Prediction Model (Interstate)

	Estimate	Std. Error	Z-value	P-value
Constant	-0.5826	0.303	-1.925	0.0258
Length (feet)	0.0003	0.001	16.328	0.0000
Height (inches)	0.0219	0.011	2.067	0.0387
Median (1 if median is present, 0 otherwise)	0.7911	0.059	13.335	0.0000
Shoulder Width (feet)	0.0837	0.038	2.190	0.0285
Height* Shoulder Width	-0.0026	0.001	-1.993	0.0463
Number of observations	1378			
Log-likelihood at convergence	-3951.392			

Table 11. Fatal/Injury Crash Prediction Model (State highway system)

	Estimate	Std. Error	Z-value	P-value
Constant	-0.258	0.614	-0.412	0.6805
AADT	0.0002	0.001	4.272	0.0000
Height (feet)	-0.0014	0.021	-0.666	0.5052
Shoulder Type (1 asphalt, 0 concrete)	-3.1120	0.867	-3.59	0.0003
Barrier length (feet)	0.0001	0.001	5.624	0.0000
Height: Shoulder Type	0.0929	0.029	3.168	0.00154
Number of observations	865			
Log-likelihood at convergence	-1665.505			

Table 12. PDO Crash Prediction Model (State highway system)

	Estimate	Std. Error	Z-value	P-value
Constant	0.8670	0.3876	2.237	0.0258
AADT	0.0001	0.00002	6.502	0.0000
Height (feet)	-0.0232	0.01333	-1.739	0.0829
Shoulder Type (1 asphalt, 0 concrete)	-1.4430	0.5437	-2.655	0.0079
Barrier length (feet)	0.0001	0.0001	6.305	0.0000
Height: Shoulder Type	0.0395	0.0857	2.125	0.0336
Number of observations	865			
Log-likelihood at convergence	-2515.536			

Heights were not adjusted for those barriers that fell within the recommended range. A ratio of the predicted to the observed crashes was then estimated. A ratio of less than one indicated that the predicted crashes were less than the observed crashes for that severity category. This is an indication that an increase in the barrier height led to a decrease in the frequency of crashes for that severity category. The results of the analysis are shown in Table 13, Table 14, and Table 15.

Table 13. Crash Shift Analysis for Median Interstate Barriers

Barrier Type	Observed Crashes		Predicted Crashes		Ratio = Predicted/Observed	
	F+I	PDO	F+I	PDO	F+I	PDO
W-beam	80	370	77.39	376	0.97	1.02
Box beam	360.10	1432	337	1544	0.94	1.08

Table 14. Crash Shift Analysis for Side Interstate Barriers

Barrier Type	Observed Crashes		Predicted Crashes		Ratio = Predicted/Observed	
	F+I	PDO	F+I	PDO	F+I	PDO
W-beam	30	83	21.11	81.47	0.70	0.98
Box beam	109.10	490	127	466.90	1.16	0.95

Table 15. Crash Shift Analysis for Side Interstate Barriers

Barrier Type	Observed Crashes		Predicted Crashes		Ratio = Predicted/Observed	
	F+I	PDO	F+I	PDO	F+I	PDO
W-beam	263	565	71.70	475.80	0.27	0.84
Box beam	473	1150	177.20	865	0.37	0.75

NB: F+I = Fatal + Injury crashes

Evaluation of Shift in Crash Proportions

There was an insufficient number of cable barrier crashes to conduct the crash shift analysis. This is because most cable barriers were recently installed on most highways, in Wyoming. Similarly, there was a limited number of crashes observed for concrete barriers installed as side barriers. Therefore, a crash shift analysis could not be conducted for this barrier type as well.

Turning to the specific results, the analysis indicates that W-beam barriers and box beam median barriers would decrease the proportion of crashes recorded as fatal and injury, if barrier height adjustments are done for interstate median barriers Table 13. In other words, the count of fatal and injury crashes that would occur given that treatment (height adjustment) has been implemented is lower compared to counts for when treatment has not been done. However, an increase in PDO was estimated for W-beam and box beam median barriers for enhanced barrier heights. The results are intuitive and indicate that setting barrier heights within the optimum ranges is beneficial. Similar results were found for interstate side barriers (Table 14). However, the results suggest that adjusting barrier height may lead to an increase in the proportion of fatal and serious injury crashes for box beam barriers. This may indicate that for box beam barriers installed on interstate highways other geometric factors, such as shoulder width, lane width, and barrier type, must be taken into account when providing safety improvement. Enhancing barrier height alone will not be enough to improve safety for side box beam barriers on interstate highways.

The greatest reduction in fatal and injury crashes was estimated for the side barriers (W-beam and box beam) on state highway system (Table 15). A higher reduction was also found for PDO crashes for the barriers installed on the state highway system. This is an indication that investing in improving the height of barriers on the state highway system will yield higher savings in terms of lives and property. This finding is intuitive as it is well-known crash severity is worse on rural highways due to a lower standard of design in comparison to interstate highways.

Benefit-Cost Analysis of Traffic Barrier Height Enhancement

The benefit-cost analysis was undertaken for traffic barriers on both interstate and state highway system. The benefit-cost analysis aimed at helping WYDOT to select barriers to upgrade under current budget constraints. Therefore, the barriers were prioritized and optimized to select the most cost-effective ones that would also decrease crash severity. Some of the barriers installed on both interstate and state highway system, in Wyoming, did not experience crashes over the analysis period due to low traffic volumes and the random nature of crashes. However, it is important to note that these barriers still have the potential to record crashes. Therefore, barriers without historical crashes were considered as candidates for optimization in instances where their heights fell outside the recommended range.

As mentioned previously, a machine learning approach was adopted for the benefit-cost analysis. For analyses using machine learning, the database is split into two, training and test datasets. The training dataset is used to train the model while the test dataset included under-design barriers. For this analysis, traffic barriers with historical crashes were considered as the training dataset. Models were estimated from this dataset from which predictions were made for traffic barriers with no historical crashes. The barrier crash cost estimated from EPDO was considered as the dependent

variable from the analysis. Though the crash cost is related to several variables, only predictors common to both barriers with and without historical crashes were considered for the analysis. Barrier optimization on interstate highways was done using hurdle models while the quantile model was utilized for state highway system barriers.

Recommended barrier heights from the literature served as the basis for optimizing the barrier heights and the benefit-cost calculations. Although the literature provided different recommended heights for W-beam barriers (27, 29, and 31 inches), a single value of 27 inches was recommended for box-beam barriers. (AASHTO, 2011b; Fang et al., 2013). For consistency, a value of 27 inches was chosen as the recommended height W-beam and box-beam barriers that would be optimized to this value. For concrete barriers, the literature recommends heights between 32 and 42 inches. (Elvik, 2001; Gabler et al., 2005). A height of 40 inches was chosen as the optimum for concrete barriers. Cable barriers were found to be within the recommended range and were incorporated into the model training process. However, they were not included in the optimization analysis.

Benefit-Cost Analysis of Traffic Barrier Height Optimization (Interstate Highways)

For interstate highways, the dataset was filtered to include only EPDO values greater than 45. The model was then trained and implemented on barriers that had heights outside the recommended range. An annual increase in traffic rate of 0.4 percent was considered. A comparison was then made across the sum of predicted costs with and without optimizations. It should be noted while considering traffic barrier enhancement, the cost spent on optimization should be considered. The cost-benefit was computed as:

(a): Predicted costs with no barrier enhancement: equal to sum of the predicted costs for every year when only the traffic volume changes, over 10 years.

(b): Predicted costs with barrier enhancement: equal to the sum of predicted costs for every year when traffic for every year and barrier heights would be changed only in the first year, over 10 years.

The benefit of barrier enhancement or optimization is then estimated as seen in Figure 27.

$$\text{Benefit-Cost} = \sum_{i=1}^{10}((a_i) - (b_i)) * 34{,}612$$

Figure 27. Equation. The Benefit of Barrier Enhancement Estimation.

The value of 34,612 is the cost of PDO based on WYDOT data. This value is multiplied by the estimated EPDO to derive crash costs.

The hurdle model was estimated for traffic barriers located on interstate highways. The first layer is a logistic regression that estimates the likelihood of a crash while the second layer presents the truncated component for crash counts. The binary logistic regression component of the model was first estimated. If the probability of a barrier crash was found to be higher than the cut-off value of 0.5, this was an indication that the crash count for that barrier is greater than zero. The

NB model was then estimated for those barriers. Table 16 shows the estimated coefficients for the two layers of the hurdle model.

Table 16. Estimation Results of Hurdle Model

	Estimate	Std. Error	z value	Pr(>|z|)
First layer, logistic regression model				
(Intercept)	1.16E+00	3.34E-01	3.468	0.000525
AADT, continuous	1.53E-04	7.37E-05	2.079	0.037646
Barrier length	1.26E-03	2.95E-04	4.262	2.03E-05
Shoulder width,0 as shoulder width >=4.5, 1 otherwise	5.93E-01	2.11E-01	2.809	0.004974
Offset distance, from the end of shoulder width to b	-3.12E-02	1.03E-02	-3.042	0.002352
Second layer, NB model				
(Intercept)	7.73E-01	1.02E+00	0.755	0.45014
Shoulder width,0 as shoulder width <=4.5, 1 otherwise	-9.56E-01	1.57E+00	-0.609	0.54262
Barrier height	-3.24E-02	3.25E-02	-0.998	0.31846
Length of a barrier	4.16E-04	3.13E-05	13.28	< 2e-16
Type of barrier as cable	1.30E+00	8.69E-01	1.491	0.13601
Type of barrier as concrete	7.18E-01	3.05E-01	2.355	0.01855
Type of barrier as box beam	1.44E-01	1.81E-01	0.795	0.42674
Restrain condition	6.99E-01	3.04E-01	2.300	0.02142
Speed compliance	1.05E+00	3.83E-01	2.739	0.00616
AADTT	3.17E-04	1.31E-04	2.412	0.01585
Shoulder width ×barrier height	2.62E-02	5.25E-02	0.499	0.61813
Log(theta)	-1.62E+00	3.18E-01	-5.086	3.65E-07
Root Mean Square Error = 9.5, log-likelihood = -2881 on 17 Degrees of freedom				

The results of the first layer indicate that as AADT and barrier length increase, the likelihood of crashes also increases. These are expected as AADT and barrier length are exposure variables and are expected to increase the probability of crashes. The results also have implications for the barriers with no crash counts. As the traffic volume increases, traffic barriers with no crashes are expected to record crashes. The results also indicate that when shoulder width and offset distance decrease, the likelihood of crashes increases. Again, the results are intuitive as decreasing these predictors indicates a reduction between vehicles and the barriers.

For the count model, roadway characteristics, such as barrier length, traffic volume, barrier type, and shoulder width were incorporated into the model. Driver actions were also included in the

count model. The results suggest that not having a restraint and not following the speed limit were associated with a higher EPDO, an indication of an increase in crash severity.

The analysis also indicated that the impact of barrier height should be considered as an interaction term impacting crash severity. This is also important for this analysis as barrier height is the only factor that would be changed in the optimization procedure. Therefore, accounting for the interaction term would improve the results and reduce bias. Barrier type was another factor considered to account for differences across the different barriers. It is also important to note that AADT was found to be statistically significant in the first layer while AADTT was significant for the second layer.

The parameter theta, included in the model results, represents the shape parameter of the NB model of the hurdle model. This value is an estimate of the skewness of the model and is a measure of the over-dispersion of the NB model in comparison to the Poisson distribution.

Table ***17*** presents a ranking of the first 25 barriers that were found to result in the highest enhancement benefit for the interstate system. The complete ranking of all barriers on interstate highways is shown in Table 38 of Appendix B. It is important to note that about half of the traffic barriers, ranked among the first 25 barriers with the highest benefit, has no historical crashes. However, based on a possible increase in traffic volume over the next 10 years on the highways they are located, those barriers have a high probability of recording crashes. Interestingly, the results of the optimization indicate that these barriers will have the highest benefit if their heights are enhanced.

Also, only four concrete barriers were included in the analysis with all of them being identified with the 25 barriers whose optimization would result in the highest benefit. This is expected based on the NB part of the hurdle model. This is because the highest change in the barrier height is related to this barrier type. The result for the concrete barrier highlights the importance of including exposure variables such as traffic and barrier length.

Table 17. Ranking of Interstate Barriers Based on the Highest Benefits

Interstate	Barrier ID	Shoulder width	Current	Barrier height	Type of barrier	Length of barrier (ft)	EPDO with no enhancement in 10 years	EPDO with enhancement in 10 years	Total benefit in 10 years	Rank
80I	6266	<4.5	14	51.6	box	266	62	30	1,102,578	1
80D	4960	>4.5	1	1.2	box	96	71	39	1,074,508	2
90D	7374	>4.5	0	4.8	box	313	50	31	650,118	3
90I	7294	<4.5	0	44.4	box	266	41	25	546,505	4
25I	5839	<4.5	4	37.2	w-beam	209	49	36	434,430	5
80I	5079	>4.5	1	26.4	concrete	63	48	36	417,952	6
90D	7798	>4.5	0	24.0	concrete	259	42	30	402,508	7
80D	6280	>4.5	2	26.4	concrete	195	46	35	397,666	8
80D	6282	>4.5	1	26.4	concrete	192	46	34	396,363	9
25D	6862	>4.5	4	22.8	w-beam	1514	117	105	388,144	10
90I	7101	<4.5	13	36.0	w-beam	1095	47	36	368,925	11
90I	7539	<4.5	0	36.0	box	362	41	32	311,260	12
90I	7270	<4.5	1	37.2	box	232	34	26	284,909	13
25I	6966	<4.5	0	36.0	w-beam	274	37	29	279,994	14
90I	7239	<4.5	5	36.0	box	387	37	29	271,885	15
80D	6527	>4.5	10	24.0	box	2236	117	108	268,597	16
25D	6953	<4.5	0	36.0	w-beam	238	35	28	267,896	17
90D	7450	<4.5	1	36.0	box	247	35	28	258,478	18
25D	6890	>4.5	0	21.6	w-beam	1502	64	57	243,725	19
90I	7031	<4.5	5	36.0	w-beam	304	32	25	237,050	20
80D	5962	>4.5	0	20.4	w-beam	115	45	39	208,203	21
25I	6891	>4.5	2	24.0	w-beam	1501	84	78	186,141	22
80I	5114	>4.5	0	19.2	box	144	35	29	176,747	23
25D	6861	>4.5	8	21.6	w-beam	425	45	40	170,862	24
25D	6872	>4.5	0	20.4	w-beam	216	37	32	164,605	25

Traffic Rate Increase Scenarios

The AADT and AADTT were increased at a rate of 0.4 percent a year, equivalent to 4 percent in 10 years. From the hurdle model, both variables are important in predicting crash costs. In considering a different scenario, it was assumed that traffic would increase at twice the current rate over a period of 10 years. The two scenarios were then compared. The analysis indicated that the number of EPDO would increase by 27 for an 8 percent increase in traffic volume over 10 years in comparison to the current rate of 4 percent over the same period. It should also be noted that an increase in an EPDO rate for crash with enhancement is slightly lower than EPDO with no enhancement. These scenarios, including an analysis done for a 10 percent increase in traffic volume are shown in Table 18.

Table 18. Predicted EPDO based on Different Scenarios for Traffic Volume Increase

Scenario	Traffic Increase in a Year	EPDO for 10 Years with No Optimization	EPDO for 10 years with Optimization
1	1.004	8917	8809
2	1.008	8941	8832
3	1.01	8989	8880

In summary, considering the traffic rate increase of 4 percent, based on the last 10 years, a reduction in EPDO of 108 would be expected. The savings are equivalent to $2,629,150 after reducing the cost of resetting for W-beam and box-beam. This will also include the removal and rebuilding of concrete barriers.

Benefit-Cost Analysis of Traffic Barrier Height Optimization (State highway system)

For this analysis, highway barriers with crashes were used for training a quantile regression model. Interaction terms were included in the model to account for the hierarchy of the dataset resulting from the different barrier types. Only predictors that were available for the barriers without historical crashes were retained in the trained model so it could be implemented on those barriers without crashes.

The model was trained on the whole dataset regardless of barrier height. However, testing was done on only those barriers that exceeded or were below the recommended heights. So in effect, only barriers above 35 inches and those below 27 inches were incorporated in the optimization process, as these barriers are likely to result in override and underride crashes. A value of 27 inches was chosen as the optimum height for all barriers. Predictions of crash costs were first made for barriers at their current heights. The trained model was then implemented on barriers with and without crashes with all the heights set at 27 inches. Recommendations were then made for barriers to be reset or newly installed. Barriers with wooden posts cannot be reset and must be replaced. This meant that almost all W-beam barriers in Wyoming were recommended for replacement because they are predominantly installed with wooden posts. The costs of these changes are shown in Table 19.

Table 19. Bid Prices for Barrier Optimization

Barrier Types	Brand New Installation Per Foot ($)	Reset Bid Price Per Foot ($)
Box beam	50.25	10.45
W beam	50.89	---

The optimization procedure consists of defining an objective function and constraints. The objective function of this study was to minimize the cost of barrier crashes over the next 10 years based on budget availability. Constraints included keeping all other factors constant over 10 years. Barriers outside the recommended range were set at 27 inches.

Results of the Linear Quantile Model

The linear quantile model (lqm) function in the statistical package R® was used to train the model on barriers with historical crashes. The significant predictors are shown in Table 20. The response variable for the model is a crash cost in dollars.

Table 20. Results of the Linear Quantile Model at 95 Percent Quantile

	Value	Std. Error	Lower bound	Upper bound	Pr(>|t|)
Intercept	8.81E+05	6.54E+05	-4.32E+05	2194828	0.183859
Barrier height	-22.8E+05	2.47E+05	-6.88E+05	302582.4	0.437842
AADT	2.34E+02	7.67E+01	7.99E+01	388.28	0.003672
Length of barrier	2.65E+02	1.56E+02	-4.89E+01	-578.76	0.052001
Side slope	-1.32E+05	8.25E+04	-2.98E+05	33666.75	0.11571
Shoulder width	-2.29E+06	9.45E+05	-4.19E+06	-393499	0.01899
Barrier type	-2.30E+05	4.55E+04	-3.22E+05	-138574	6.46E-06
Posted speed limit	-5.17E+03	3.74E+03	-1.27E+04	2355.46	0.173718
Side slope: type of barrier	6.26E+04	2.87E+04	5.06E+03	120226.2	0.033615
Barrier height: shoulder width	111E+05	3.94E+05	1.32E+05	1717153	0.023088
Barrier type: Posted speed limit	3.82E+03	1.37E+03	1.06E+03	6585.42	0.007661
Variance (real crash cost) = 2e+12, variance of predicted cost with no enhancement = 3.576208 e+11, Root Mean Square Error = 1.47e+06					

As previously discussed, crash cost predictions were done by keeping all other variables constant and changing only barrier height. This is due to limitations imposed by WYDOT with regards to changing other variables, such as shoulder width due to right of way limitations. Shoulder width was entered into the model as a categorical variable. Shoulder widths higher than 5.5 feet were coded as one, while all others below this width were coded as zero.

Barrier Ranking Criteria

Barriers were ranked based on the total benefit. The total benefit was calculated from the following equation (Figure 28):

$$Total\ benefit\ in\ 10\ years = benefit\ over\ the\ 1st\ year + 9 * benefit\ over\ 10\ consequtive\ year$$

Figure 28. Equation. The Total Benefit in 10 Years

On the other hand, the benefit over the first year was calculated as follows (Figure 29):

$$Benefit\ over\ the\ 1st\ year = predicted\ current\ cost - (Reset\ cost + predicted\ Future\ cost)$$

Figure 29. Equation. The Benefit over the First Year

Based on Equation 16, the barriers were ranked according to total benefits over 10 years. Installation and reset costs were estimated as a product of barrier length and the reset or installation costs are shown in Table 19. It should be noted that although the real crash costs were available for barriers with historical crashes, they could not be compared with the predicted costs after barrier height changes due to a difference in scales. This meant that the costs had to be estimated by implementing the trained model over the dataset. For predicted costs after barrier enhancement, only the barrier height was left unconstrained. Traffic volume on the state highway system was found to be constant over the previous 10 years (2004 to 2014). It was assumed the same trend would continue and the traffic volume would remain constant in the coming decade. This same procedure was adopted for traffic barriers without historical crashes.

Table ***21*** is the ranking of the first 25 of the most cost-effective barriers with historical crashes identified by the optimization procedure. Similarly, the ranking of the first 25 cost-effective barriers with no historical crashes is shown in Table 22. A complete ranking of all traffic barriers on the interstate system can be found in Table 38 in Appendix B.

Table 21. Ranking of Interstate Traffic Barriers Based on Estimated Benefits

Interstate	Barrier ID	Shoulder width	Current EPDO	Barrier height	Type of barrier	Length of barrier (ft)	EPDO with no enhancement in 10 years	EPDO with enhancement in 10	Total benefit in 10 years	Rank
80I	6266	<4.5	14	51.6	box	266	62	30	1,102,578	1
80D	4960	>4.5	1	1.2	box	96	71	39	1,074,508	2
90D	7374	>4.5	0	4.8	box	313	50	31	650,118	3
90I	7294	<4.5	0	44.4	box	266	41	25	546,505	4
25I	5839	<4.5	4	37.2	w-beam	209	49	36	434,430	5
80I	5079	>4.5	1	26.4	concrete	63	48	36	417,952	6
90D	7798	>4.5	0	24	concrete	259	42	30	402,508	7
80D	6280	>4.5	2	26.4	concrete	195	46	35	397,666	8
80D	6282	>4.5	1	26.4	concrete	192	46	34	396,363	9
25D	6862	>4.5	4	22.8	w-beam	1514	117	105	388,144	10
90I	7101	<4.5	13	36	w-beam	1095	47	36	368,925	11
90I	7539	<4.5	0	36	box	362	41	32	311,260	12
90I	7270	<4.5	1	37.2	box	232	34	26	284,909	13
25I	6966	<4.5	0	36	w-beam	274	37	29	279,994	14
90I	7239	<4.5	5	36	box	387	37	29	271,885	15
80D	6527	>4.5	10	24	box	2236	117	108	268,597	16
25D	6953	<4.5	0	36	w-beam	238	35	28	267,896	17
90D	7450	<4.5	1	36	box	247	35	28	258,478	18
25D	6890	>4.5	0	21.6	w-beam	1502	64	57	243,725	19
90I	7031	<4.5	5	36	w-beam	304	32	25	237,050	20
80D	5962	>4.5	0	20.4	w-beam	115	45	39	208,203	21
25I	6891	>4.5	2	24	w-beam	1501	84	78	186,141	22
80I	5114	>4.5	0	19.2	box	144	35	29	176,747	23
25D	6861	>4.5	8	21.6	w-beam	425	45	40	170,862	24
25D	6872	>4.5	0	20.4	w-beam	216	37	32	164,605	25

The estimated benefits of barriers with no historical crashes are marked red in Table 38. It may be observed from Table 22 that the first nine of the most economical barriers with crash histories are those above the height of 35 inches followed by barriers with a very low height. It may also be observed that those barriers above the height threshold are associated with wider shoulder widths while short barriers have narrower widths. These findings highlight the additional information that can be gained by including interaction terms in models.

Table 22. Ranking of State Highway system Traffic Barriers Based on Estimated Benefits

Barrier ID	Shoulder Width	AADT	Barrier Height	Type of Barrier	Length of Barrier (ft)	Predicted Crash cost without Barrier Enhancement	Predicted Crash Cost with Enhancement	Barrier Height Change Cost	Benefit in 10 Years	Rank
2744	1	1536	40.8	W Beam	152	-1,123,297	-342,233	7,712	7,802,925	1
4231	1	363	37.2	W Beam	66	-638,563	-61,255	3,372	5,769,706	2
5324	1	657	37.2	Box Beam	723	-714,252	-136,944	7,552	5,765,526	3
1443	1	2189	37.2	W Beam	665	-1,111,476	-534,168	33,851	5,739,228	4
3055	1	719	36	W Beam	312	-941,238	-431,848	15,878	5,078,015	5
3055	1	719	36	W Beam	312	-941,238	-431,848	15,878	5,078,015	6
3056	1	719	36	W Beam	712	-1,067,924	-558,534	36,245	5,057,648	7
3056	1	719	36	W Beam	712	-1,067,924	-558,534	36,245	5,057,648	8
3888	1	659	36	W Beam	884	-1,074,108	-564,718	45,005	5,048,888	9
576	0	955	<12	Box Beam	169	-667,164	-275,992	1,761	3,909,954	10
2745	0	588	<12	Box Beam	461	-1,988,261	-1,597,088	4,822	3,906,894	11
2745	0	588	<12	Box Beam	461	-1,988,261	-1,597,088	4,822	3,906,894	12
4739	0	5234	18	Box Beam	169	-818,620	-688,229	1,762	1,302,142	13
5453	0	1417	19.2	W Beam	901	-865,220	-752,215	45,866	1,084,184	14
5196	0	687	19.2	W Beam	1062	-969,475	-856,469	54,056	1,075,995	15
3847	0	4810	19.2	W Beam	1834	-1,160,352	-1,047,346	93,315	1,036,735	16
3678	0	4810	20.4	Box Beam	214	-1,551,362	-1,455,742	2,232	953,964	17
366	0	467	20.4	Box Beam	257	-685,951	-590,331	2,686	953,511	18
796	0	75	21.6	W Beam	87	-610,229	-531,994	4,451	777,891	19
1365	0	1264	21.6	Box Beam	492	-483,973	-405,738	5,140	777,202	20
1859	0	739	21.6	Box Beam	1204	-620,043	-541,809	12,586	769,757	21
3069	0	1045	21.6	Box Beam	1267	-590,369	-512,134	13,245	769,098	22
3993	0	659	21.6	W Beam	634	-539,124	-460,890	32,282	750,061	23
498	0	1677	21.6	W Beam	1088	-1,026,365	-948,130	55,357	726,986	24
5453	0	1417	21.6	W Beam	1201	-675,170	-596,935	61,116	721,226	25

Similar to the results in

Table ***21***, despite the higher initial cost of W-beam barriers, it was found in Table 22 that this barrier type had higher benefits when enhanced compared to box beam barriers with no crashes.

Again, the highest impact/benefit is observed for the lowest barrier heights when they are located on narrower shoulder widths. As explained previously, the model was trained to include variables common to datasets of barriers with and without historical crashes. Barrier length and traffic volume were also included to normalize the data. After the model was trained on barriers with crashes, it was implemented on barriers with no crashes. Table 23 presents the summary of optimization done across all barriers both with and without crashes.

Table 23. Summary Statistics of Benefit-Cost Analyses across Barrier Types

Barrier Types		Number of Barriers	Total Length (miles)	Number of Economical Barriers	Length of Economic Barriers (Miles)	Number of Non-Economic Barriers	Length of Non-Economic -Barriers	Reset/New Installation Cost for the 1st Year ($)	Total Benefit
Barriers with Crashes	W-beam	87	19	60	8	27	11	5,165,219	37,951,532
	Box-beam	62	6.5	44	4	18	2.5	358,664	14,676,278
	Sum	149	26	104	12.3	45	13.4	5.523,884	52,627,809
Barriers without Crashes	W-beam	251	19	207	16	43	3	5,210,783	8,851,006
	Box-beam	123	10	59	5	64	5	543,742	No benefit
	Sum	374	29	266	21	107	8	5,754,526	8,851,006
Total Benefit across All Barriers		1046	55	370	33	152	21	10,987,410	61,478,815

From the results in Table 23, it was found that while W-beam height adjustment was found to be cost-effective, simply changing barrier heights for box-beam barriers was not found to be cost-effective. This might be because of other confounding factors resulting in a high predicted cost, which cannot be addressed only by changing the barrier height. Another reason is that for this category, shoulder width needs to be changed along with barrier height as the interaction between these two predictors indicated in Table 20. As can be seen from Table 23, for barriers with crashes, WYDOT could save about 61 million dollars. In summary, by investing about 10

million dollars to upgrade barriers below the recommended height within 10 years, WYDOT can accrue benefits estimated at 61 million dollars only through the optimization of barrier heights.

The two previous analyses were related to highway and interstate systems separately. Those two optimization processes were conducted separately due to severe heterogeneity across the two state highway systems. That is due to differences in terms of design and traffic characteristics of the two highways. However, the third cost-benefit analysis was also conducted by considering a combination of the two highway systems. Bayesian hierarchical finite mixture that is similar to the second layer of the hurdle model was conducted. The results indicated that considering resetting the barriers in the state, the optimization process would result in more than 3 million dollars. The results are presented in Table 24. As can be seen from Table 24, the top barriers all belong to the state highway system. This is due to the fact that the shortest barriers are in the state highway system.

It is recommended to use the two separate state highway cost-benefit analyses due to the aforementioned points. It is worth mentioning optimizing only cost-benefit barriers would increase the benefit to more than 7 million dollars. A complete list of those barriers is presented in Table 40 in the appendix.

Table 24. The Top Critical Barriers, Sorted Based On Highest Benefits

Row	Barrier ID	Highway ID	Highway system	Barrier length	Barrier height	Shoulder width	Type of barrier	Saving cost in 10 years by barriers enhancem
1	109	ML22B	State highway	97	<12	4	W-beam	327,485
2	575	ML22B	State highway	102	<12	4	W-beam	327,433
3	576	ML22B	State highway	169	<12	2	W-beam	326,740
4	112	ML22B	State highway	361	<12	3	W-beam	324,728
5	1048	ML601B	State highway	64	<12	4	Box beam	316,254
6	1047	ML601B	State highway	65	<12	4	Box beam	316,243
7	2745	ML1900B	State highway	461	<12	3	W-beam	313,653
8	2745	ML1900B	State highway	461	<12	3	W-beam	313,653
9	15	ML104B	State highway	364	13.2	3	Box beam	78,985
10	5200	ML36B	State highway	2087	12	3	Box beam	77,829
11	7771	ML19353B	State highway	124	14.4	0	Box beam	76,948
12	5454	ML13B	State highway	631	14.4	3	Box beam	73,261
13	5202	ML36B	State highway	201	14.4	4	Box beam	72,974
14	5198	ML36B	State highway	725	14.4	4	Box beam	67,499
15	4739	ML254B	State highway	169	18	4	W-beam	65,480
16	4573	ML1002B	State highway	201	15.6	0	Box beam	59,391
17	5197	ML36B	State highway	913	15.6	4	Box beam	54,857
18	5462	ML13B	State highway	338	16.8	2	Box beam	54,605
19	5201	ML36B	State highway	201	16.8	4	Box beam	52,565
20	3614	ML319B	State highway	127	16.8	1	Box beam	51,256
21	5199	ML36B	State highway	537	16.8	3	Box beam	49,048
22	1205	ML5649B	State highway	159	18	2	W-beam	46,065
23	5204	ML36B	State highway	249	18	4	Box beam	43,183
24	3615	ML319B	State highway	126	18	1	Box beam	42,726
25	5205	ML36B	State highway	300	18	3	Box beam	42,657
26	852	ML85B	State highway	324	18	2	W-beam	42,606
27	62	ML103B	State highway	338	18	3	Box beam	41,735
28	4572	ML1002B	State highway	202	18	0	Box beam	41,617
29	3678	ML2000B	State highway	214	20.4	4	W-beam	40,736
30	21	ML104B	State highway	299	18	1	Box beam	40,553
31	818	ML1400B	State highway	800	18	0	Box beam	36,364
32	693	ML103B	State highway	102	19	1	Box beam	36,059
33	90	ML211B	State highway	75	19	1	Box beam	35,019
34	5455	ML13B	State highway	501	19	3	Box beam	34,862
35	825	ML1400B	State highway	213	19	1	Box beam	34,597
36	64	ML103B	State highway	274	19	1	Box beam	34,404
37	824	ML1400B	State highway	237	19	0	Box beam	34,341
38	3847	ML2000B	State highway	1834	19	3	Box beam	34,253
39	821	ML1400B	State highway	326	19	1	Box beam	33,416
40	4847	ML507B	State highway	315	19	0	Box beam	33,163
41	2001	ML94B	State highway	299	19	3	Box beam	32,896
42	4475	ML1006B	State highway	326	19	1	Box beam	32,285
43	4476	ML1006B	State highway	327	19	0	Box beam	32,274
44	2096	ML202B	State highway	476	19	3	Box beam	31,457

Summary on Crash Barrier Optimization

The majority of the previous studies conducted on traffic barriers aimed to identify factors influencing barrier-related crash severity and frequency. However, relatively fewer studies have been undertaken to analyze the improvement of traffic barrier features. With monetary value assigned to these improvements, policymakers can make informed decisions on benefits to be gained from investing in roadside object enhancement such as for traffic barriers. This will in turn lead to a greater potential for road safety improvement, and a general benefit for society.

For interstate barriers, it was found that savings of over two million dollars in crash costs will be accrued from resetting W-beam and box beam barriers, and the rebuilding of concrete barriers over a 10-year period. An increase in traffic volume by four percent was used for the analysis period. From the benefit-cost analysis, it was apparent that the benefits of optimizing barrier heights on interstate highways outweigh the costs. The results indicated that it is possible to prevent over 100 EPDO crashes for over 10 years. This justifies investing in crash barrier enhancement on interstate highways.

For the state highway system, it was found that by improving barrier height, benefits to be gained due to a reduction in crash severity amounted to over 60 million dollars for a 10-million-dollar investment over a 10-year period. The analysis for the state highway system also proposed height enhancement to barriers with no historical crashes. These barriers also indicated that savings would be accrued in terms of crash costs, if their heights are enhanced.

From the benefit-cost analysis, it may generally be observed that those barriers whose height were extreme (for above 31 inches and far below 27 inches) had the highest benefit for both interstate and state highway system. This finding is intuitive as these barrier heights did not conform to the recommended barrier height range from the RDG and the analysis conducted for this report. Similarly, it may be seen that those barriers with heights close to the recommended height ranges had lower benefit-costs associated with them. This again is an indication that those barriers had lower crash severities due to the better performance of the barriers based on height. Also, some barriers without crashes were ranked high in terms of the benefit-cost analysis. Again, from the analysis, it was shown that by applying models estimated using traffic barriers with historical crashes, it is possible to predict crashes for those barriers without any crashes. An attempt was made to jointly rank traffic barriers on the interstate and state highway system based on the benefit-cost analysis. However, due to the differences in the highway class, geometric features, traffic volumes, and other features, this was not possible. Separate rankings were therefore presented for these barriers. The findings of this analysis have been presented in two papers that have been submitted to a peer-reviewed journal. (M. Rezapour & Ksaibati, 2020; M. M. Rezapour & Ksaibati, 2020).

Proposed Barrier Condition Index (BCI)

A case study of barrier condition assessment is presented in this section on how the BCI is estimated for traffic barriers. For this assessment, the conditions of barriers located on three sites in Wind River Indian Reservation (WRIR), Wyoming will be presented. Afterward, the improvement assessment recommendations will be provided for each site to upgrade the barrier features as a means to improve performance. For this reason, a barrier condition assessment

(BCA) worksheet has been prepared by reviewing previous literature. (AASHTO, 2011b; Gabler et al., 2010).

Table **25** shows the barrier condition assessment worksheet.

Table 25. Barrier Condition Assessment Worksheet

2017

BARRIER CONDITION ASSESSMENT
WYOMING-WASHAKIE

Revised. 10/30/2017
By Wyoming Technology Transfer Center (T2)

STATE ROUTE:		BEGINNING COORDINATE:		BARRIER TYPE:		BRIDGE?	YES/NO
SEGMENT #:		ENDING COORDINATE:		END TREATMENT TYPE:		H CURVE?	YES/NO
SURVEY DATI	/ /	SEGMENT LENGTH:	FT	OFFSET FROM THE LAN	FT	ADT:	VEH/DAY
OBSERVER:	BART & AMIR	DIRECTION:		SPEED LIMIT:	MPH	CLEAR ZONE CONDITION:	

	CATEGORY	LENGTH	VALUE	UNIT	GPS COORDINATE (X,Y)		SEVERITY
HEIGHT							
From the Ground Level to the Top	Cable System	N/A	30.0	Inches	N/A	N/A	None
From the Ground Level to the Top	W-Beam System	N/A	32.0	Inches	N/A	N/A	None
Vertical Face of the Base	Concrete Barrier	N/A	32.0	Inches	N/A	N/A	None
Height of Rail Cross-Section (Flattening & Crust	W-Beam System		12.0	Inches			None
	W-Beam System		12.0	Inches			None
	W-Beam System		12.0	Inches			None
			12.0	Inches			None
DEFLECTION							
Vertical	Cable & W-Beam		-	Degree			None
	Cable & W-Beam		-	Degree			None
	Cable & W-Beam		-	Degree			None
	Cable & W-Beam		-	Degree			None
Lateral	W-Beam System		-	Inches			None
	W-Beam System		-	Inches			None
	W-Beam System		-	Inches			None
	W-Beam System		-	Inches			None
Cable Sag							
	Cable System		-	Inches			None
	Cable System		-	Inches			None
	Cable System		-	Inches			None
	Cable System		-	Inches			None
Panels Condtion							
Vertical Tear	W-Beam System		-	No. In a Panel			None
	W-Beam System		-	No. In a Panel			None
	W-Beam System		-	No. In a Panel			None
	W-Beam System		-	No. In a Panel			None
Horizontal Tear (Add the height instead of length	W-Beam System		-	No. In a Panel			None
	W-Beam System		-	No. In a Panel			None
	W-Beam System		-	No. In a Panel			None
	W-Beam System		-	No. In a Panel			None
Deterioration (Any Rotted, Rusted?)	Any Type		YES/NO	Eng Judgement			
	Any Type		YES/NO	Eng Judgement			
	Any Type		YES/NO	Eng Judgement			
	Any Type		YES/NO	Eng Judgement			
Hardware (Any Missing Panel, Nuts, Bolts?)	Any Type		YES/NO	Eng Judgement			
	Any Type		YES/NO	Eng Judgement			
	Any Type		YES/NO	Eng Judgement			
	Any Type		YES/NO	Eng Judgement			
Posts Condition							
Separated From Guardrail	Cable & W-Beam		-	No. In a Panel			None
	Cable & W-Beam		-	No. In a Panel			None
	Cable & W-Beam		-	No. In a Panel			None
	Cable & W-Beam		-	No. In a Panel			None
Post Failure (Any Missing/Broken?)	Cable & W-Beam	N/A	YES/NO	Eng Judgement			Med
	Cable & W-Beam	N/A	YES/NO	Eng Judgement			Med
	Cable & W-Beam	N/A	YES/NO	Eng Judgement			Med
	Cable & W-Beam	N/A	YES/NO	Eng Judgement			
Soil Erosion (Depth)							
	Any Type		-	Inches			None
	Any Type		-	Inches			None
	Any Type		-	Inches			None
	Any Type		-	Inches			None
End-Terminal Condition							
Loosing Cable (Slack)	Cable & W-Beam	N/A	-	Inches			None
	Cable & W-Beam	N/A	-	Inches			None
Stub Height	Cable & W-Beam	N/A	-	Inches			None
	Cable & W-Beam	N/A	-	Inches			None
Alignment Condition (Any Misaligned or Missing screws?)		N/A	YES/NO	Eng Judgement			
End-Post Condiiton (Any Damaged, Severly Cracked, Rotted?)		N/A	YES/NO	Eng Judgement			
Extra Points							
Any Section is Candidate for Removal?			YES/NO	Eng Judgement			
			YES/NO	Eng Judgement			
			YES/NO	Eng Judgement			
			YES/NO	Eng Judgement			
Any Side Dozing is Required?			YES/NO	Eng Judgement			
			YES/NO	Eng Judgement			
			YES/NO	Eng Judgement			
			YES/NO	Eng Judgement			

The main categories in the worksheet are height (from the ground to the top, rail cross-section), deflection (vertical, lateral, cable sag), panel conditions (vertical tear, horizontal tear,

deterioration, hardware condition), post condition (separated from guardrail, posts condition), soil erosion, and the end-treatment condition (losing cable, sub height, end-post condition).

Barriers were rated on a scale of one to four to prioritize sites with severe damage in improvement works. Table 26 presents the criteria for these ratings. It should be noted that some of the variables inside the worksheet should be rated based on the engineering judgment and these variables are excluded from Table 26. Damages such as deterioration need to be graded based on observations since there is no other way to use any measurements to estimate the level of the deterioration. The criteria for each type of damage, in Table 26, are different based on their role in the severity of crashes. Also, damages received different weightings based on their impacts on the performance of barriers found from previous studies. (AASHTO, 2011b; Gabler et al., 2010; Pennsylvania Department of Transportation, 2017).

A score of four indicates an ideal barrier condition with no damage, while a rating of one shows a high-severity damage that worsens safety. The index of two and three refer to medium and low conditions, respectively. Barriers with ratings of one and four are shown, in Figure 30 and Figure 31.

Table 26. Criteria for Rating Barrier Damage (Gabler et al., 2010)

Variables	Barrier Type	Unit	High-Severity	Medium-Severity	Low-Severity	None (No Damage)
Height from the Ground Level to the Top	Cable System	cm	x =<66	71>x>66	-	x>= 71
	Rigid System	cm	x =<71	76>x>71	-	x>= 76
	W-Beam Guardrail	cm	x =<2871	78>x>71	-	x>= 76
Height of Rail Cross-Section	W-Beam Guardrail	cm	-	43<x<23	x= 23 or 30	x=23
Vertical Deflection	W-Beam Guardrail	Degree	x>= 30	15=<x<30	0<x<15	x=0
Lateral Deflection	W-Beam Guardrail	cm	x>23	15<x<23	0<x<15	x=0
Cable Sag	Cable System	cm	x>12	15<x<23	0<x<15	x=0
Panel Vertical Tear	W-Beam Guardrail	Number	x>= 1	-	-	x=0
Panel Horizontal Tear	W-Beam Guardrail	Number	x>= 3	x= 2	x= 2	x=0
Post Separated from Guardrail	Any Type	Number	-	x>= 3	-	x=0
End-Terminal Loosing Cable	Any Type	cm	-	x>= 4	2.5<x<4	x =<2.5
End-Terminal Stub Height	Any Type	cm	x>= 23	10<x<23	-	x =<10

Figure 30. Picture. BCI Rating of Approximately One

Figure 31. Picture. BCI Rating of Approximately Four

Site Description

Comprehensive information regarding the three sites evaluated comprising their GPS coordinates, segment length, AADT, and the speed limit has been provided in Table 27.

Table 27. Geographic and Traffic Information of Sites Evaluated

Site		GPS Coordinate		Length	Speed Limit (mph)		ADT
No.	Name	Latitude	Longitudinal	(ft)	NB/EB	SB/WB	(veh/day)
1	Little Wind & Blue Cloud	42.96695	-108.49938	205	55	-	< 400
2	Northern Arapahoe Rd	42.98244	-108.51877	130	55	55	< 400
3	South Fork Rd	42.99903	-108.93186	50	55	55	< 400

Site No. 1

Site No. 1 has a semi-rigid W-beam traffic barrier with wooden posts (without blockouts). The poor condition of end-treatments was determined to be the main problem for this segment. As shown in Figure 32 and Figure 33, the second end-treatment seems to be a "trailing end W-Beam guardrail anchorage" type while a part of the end-post is missing. The existing end-post can cause serious damages to vehicles impacting the traffic barrier. In other words, it would perform as a sharp blade in the event of a collision. The first end treatment was also missing the end terminal portion. Additionally, the offset from the edge of pavement was measured as 1 foot, which is not acceptable based on the recommended offset of 4 feet in the RDG. (AASHTO, 2011b).

Figure 32. Picture. First End-Treatment

Figure 33. Picture. Second-End Treatment

The height of the barrier was the second significant problem for this segment. Low-height barriers raise the propensity of vehicle rollover and override, while very tall-barriers promote vehicle underride. (Julin et al., 2017). According to Wiebelhaus et al., 2013, low heights of 24 and 26 inches increase vehicle override while heights of 27, 29, and 30 inches will redirect the impacting vehicle. According to the RDG, a height of 30 to 32 inches is suggested for semi-rigid W-Beam guardrails. The Federal Highway Administration (FHWA) has also categorized barriers with a height lower than 24 inches as no longer reasonably function. (Fitzgerald, 2008). One of the reasons for this difference in the height was attributed to shoulder drop-off and the soil erosion (5 inches) in the location of posts. Almost all the posts were not in good condition because of their extended time of service. Figure 34 illustrates one of the posts' situations.

Figure 34. Picture. Deteriorated Barrier Post

Other damages found during the assessment were that 25 feet of the barrier had a severe lateral deflection, severe deterioration was observed on the panels, and there was a missing bolt in the connection of two panels. Also, as shown in Figure 35, the traffic signs were not placed behind the barrier and this could affect barrier performance in the event of a crash.

Figure 35. Picture. Improper Placement of Traffic Signs at Site No. 1

Table 28 shows the score of Site No. 1 based on the established rating system of this study. Note should also be made that weights were assigned to damages based on a previous study to account for the various levels of significance for different types of damages (Gabler et al., 2010). The score was estimated as 1.83 for site No. 1, which represents a high-severity condition.

Table 28. Summary of Assessment and Estimated Score on Site No. 1

	High	Med	Low	None	Sig Coefficient	SCORE (1-4)	Weighted SCORE	AVE SCORE
Height	*				3.0	1	3	**1.83**
Rail Flattening & Crush				*	0.5	4	2	
Deflection								
Vertical			*		1.0	3	3	
Lateral	*				1.0	1	1	
Cable Sag	N/A	N/A	N/A	N/A				
Panels Condition								
Vertical Tear				*	1.0	4	4	
Horizontal Tear				*	0.5	4	2	
Deterioraton				*	1.0	4	4	
Hardware			*		0.5	3	2	
Posts Condition								
Separated From Guardrail				*	0.5	4	2	
Posts Condition		*			2.0	2	4	
Soil Erosion		*			2.0	2	4	
End-Terminal Condition								
End-Post #1 Condiiton	*				3.0	1	3	
End-Post #2 Condiiton	*				3.0	1	3	
Extra Points								
Removal Section				*				
Side Dozing				*				

Site No. 2

The barrier system for this site is a Wyoming two-tube bridge railing on a bridge with W-beam barriers as end-treatments. No serious problem was observed for the barrier segment on the bridge apart from some minor deterioration due to weather effects over time. Figure 36 shows this deterioration.

Figure 36. Picture. Minor Rail Deterioration Observed for Site No. 2

With regard to the end-treatment, the hardware condition had no problem since all the end-treatments were new. Despite the good shape of the barriers, there was a serious problem regarding the height of the end-treatments, due to an installation error. In fact, the existing end-treatments have a turned-down terminal that became popular, in early 1960. However, this type of terminal was failed based on tests done by FHWA. As a result, the FHWA in 1994 discouraged the use of turned-down terminals. (Wiebelhaus et al., 2013). Based on the recent category of the barriers, the existing end-treatment can be referred to as a “W-beam guardrail anchored (buried) in back slope” with the wrong installation. An ideal back slope of 1V:2H is suggested for this type of end-treatment although the topography of the location has no back slope. (AASHTO, 2011b). In this situation, another type of end-treatment would be more appropriate. The existing end treatment at the site is predicted to exacerbate crashes by making vehicles bounce after impact thereby increasing the severity of crashes instead of alleviating them. Figure 37 and Figure 38 shows a comparison between the existing end-treatments and what is acceptable based on the RDG.

Another concern regarding the existing end-treatments at the site is that the bridge transition is not well designed. Bridge transitions are very important because they are used to mostly join two barrier types (usually a rigid barrier on the bridge and a guardrail system as the end-treatments) with different stiffness, strengths, and geometric features. In such cases, it is required to use adequate blockouts, additional posts, or rail elements to provide a proper stiffness transition to remove potential vehicles snagging or pocketing near the bridge end. (Wiebelhaus et al., 2013). Due to its weak wooden posts, the existing end-treatment would perform poorly in the transition during crashes.

Figure 37. Picture. Existing End-Treatment at Site No. 2

Figure 38. Picture. Approved End-Treatment According to the RDG (TEA , 2021)

Side dozing was seen as essential on site No. 2. Approximately, 30 feet on southbound (SB) and 20 feet on northbound (NB) sections had an averagely 5 inches of accumulated dirt at the bottom of the end-treatment posts. For this reason, the height of the end-treatment guardrail was measured as 26 inches at its highest level (at the start point and the end point of the bridge's barrier), thereby reducing the effective barrier height. This point is clearly seen in Figure 39.

The summary of barrier assessment in site No. 2 is presented in Table 29. Both the SB and NB sections had the same condition and received the same score of 2.55. This means that the whole barrier system on-site No. 3 places in the category of a medium-severity condition.

Figure 39. Picture. Accumulated Dirt at the Bottom of Posts at Site No. 2

Table 29. Summary of Assessment and Estimated Score on Site No. 2

Percentage of Severity	High	Med	Low	None	Sig Coefficient	SCORE (1-4)	Weighted SCORE	AVE SCORE
Height		*			3.0	2	6	**2.55**
Rail Flattening & Crush				*	0.5	4	2	
Deflection								
Vertical				*	1.0	4	4	
Lateral				*	1.0	4	4	
Cable Sag	N/A	N/A	N/A	N/A				
Panels Condition								
Vertical Tear				*	1.0	4	4	
Horizontal Tear				*	0.5	4	2	
Deterioraton			*		1.0	3	3	
Hardware				*	0.5	4	2	
Posts Condition								
Separated From Guardrail				*	0.5	4	2	
Post Failure				*	2.0	4	8	
Soil Erosion				*	2.0	4	8	
End-Terminal Condition								
End-Post #1 Condiiton	*				3.0	1	3	
End-Post #2 Condiiton	*				3.0	1	3	
Extra Points								
Removal Section				*				
Side Dozing		*						

Site No. 3

Site No. 3 was the only site with no barrier system. Figure 40 shows the general view of the site. Based on the recommendations of the RDG, fill section height, and the sideslope rate are the two main parameters to determine whether a barrier system is needed. Site No. 3 was located on a river with a fill section of height 10 feet and the sideslopes about 2H:1V on each side. A barrier system was therefore warranted for both directions of site No. 3 based on recommendations of the RDG. Therefore, this research scored the site as 1 which means it has the highest priority for installing a barrier system.

Figure 40. Picture. A General View of Site No. 3

Some important considerations that were noted for the traffic barrier design phase are listed below:

- The existing road had a pavement width of 24 feet. This width seems enough for two proper traffic lanes. Minimum width of 2 feet is required on each side to install a new barrier system. The road width is therefore adequate.
- Soil erosion (or shoulder drop-off) with a height of approximately 5 inches was seen all along the bridge on each side. This defect should be considered with regard to providing a proper height for the barrier system.
- Four adjacent access points (to farmlands) were observed that may limit the length of the barrier system.

Summary of Evaluation

Table 30 shows the condition assessment conducted for the sites in this study. The summary of improvement costs, crash statistics, and the BCI at each site is provided by Table 31 to present a prioritized ranking for the improvement phase. From Table 31, Site No. 3 with no barrier received the lowest BCI and was prioritized as the site requiring urgent improvement among all the sites evaluated. Site No. 1 and Site No. 2 with an average BCI of 1.83 and 2.55 respectively were categorized as sites with high and medium severity damages.

In terms of crashes recorded at the sites, Site No. 3 was the only location with recorded crashes and is again ranked as a high-priority site needing improvement. Moreover, there was no barrier system at site No. 3. Since the rest of the sites did not have any crashes recorded, the benefits after the improvement phase were assumed to be the same in each damage-severity category, for example, the same benefits will be received for improving any of the high-severity sites. The prioritized ranking was then provided by comparing the improvement costs in each damage-

severity level. Note that the crash information was provided by the Department of Transportation of WRIR for the research team in this work. This research aimed to provide an initial cost estimate for the improvements based on prices provided by the WYDOT website. It should be noted that the costs of mobilization and installation are not included in the cost estimations. Regarding the cost estimation, a total budget of $49,900 is estimated for the materials to meet all the recommended improvements in the study. The cost of the installation and the mobilization should be investigated and added to this budget to predict an estimate regarding the whole improvement budget.

Table 30. Summary of the Condition Assessment

Site	Score		Severity Category	Main Problems
	NB/EB	SB/WB		
1	1.83	-	High	Short height, Deflection, Poor end-treatment
2	2.55	2.55	Medium	Poor end-treatment
3	1	1	High	There is no barrier even though it is warranted

Table 31. Summary of Estimated Improvement Costs

Site	Score		Number of Crashes	Estimated Improvement Costs ($)	Prioritized Ranking for the Improvement
	NB/EB	SB/WB			
1	1.83	-	0	14,400	2
2	2.55	2.55	0	15,400	3
3	1	1	3	20,100	1
Total Costs				**49,900**	

Summary of BCI Assessment

This research was the first effort regarding establishing a new rating system called Barrier Condition Index (BCI), which will be useful in unifying barrier assessment studies. The new BCI included different variables either from the viewpoint of the geometry (height, offset) or the variables related to the hardware condition (deflection damages, panel condition, posts condition, soil erosion, and the end-treatment condition). The procedure of the barrier assessment was demonstrated by a case study conducted in WRIR. As a summary of the procedure, surveyors need to record all the damages and information related to the condition of the barrier using the proposed BCA worksheet (

Table **25**). Then, the input of each category (each variable) will be rated based on the defined criteria presented in Table 26. Finally, an average BCI score will be given to each barrier system considering different coefficients for each variable according to their impact on the condition extracted from previous studies. The developed BCI can be implemented in different states to optimize the barrier improvements based on a prioritized ranking. The benefits of using the BCI to obtain prioritized ranking can be clearer and more significant in large-scale projects with

several barrier segments. The analysis conducted for the BCI has been published in a paper titled ‘Developing the new barrier condition index (BCI) to Unify barrier assessments-a case study in Wind River Indian Reservation, Wyoming (Molan & Ksaibati, 2018).

CHAPTER 6: OVERALL SUMMARY AND RECOMMENDATIONS

Fatalities attributed to roadside objects and hazards are a continuing challenge in the United States. Traffic barriers are protective devices installed to prevent collision with roadside objects and to reduce the risk of cross-median crashes. Traffic barriers also change the characteristics of crashes thereby reducing crash severity.

The main objectives of this study were to evaluate the main geometric factors of traffic barriers that impact crash severity, estimate the shift in crash proportions due to the enhancement of barrier height, and rank barriers based on benefits derived from optimizing barrier heights. The final objective was to propose a barrier condition rating index that provides a uniform reference for rating barrier systems.

Data collection was done from the summer of 2016 through the summer of 2018 for both interstate and state highway system. Over 204 miles of barriers on the interstate system while for state highway systems, 435 miles of barriers systems were inventoried. The barriers considered for this study were either installed on the median or roadside. Data collected included barrier type, system height, post-spacing, side-slope, lateral offset, shoulder width, segment width, hazard fixed-object behind traffic barriers, flare/parallel length, and bridge transition. The barrier data collected was merged with historical crash data from the CARE package. A total of 7,622 barrier-related crashes were recorded during the reporting period between 2008 and 2017.

Statistical analyses using RP ordered logit models were then conducted to assess the impact of barrier geometric factors on crash severity for median and side barriers on interstate highways. Crashes were categorized into three: high-severity, moderate-severity, and low severity. The analysis indicated that the RP ordered logit model provided a good fit to the data. Barrier height, front slope conditions, post spacing, and lateral offset were the main variables impacting crash severity. It was also found that taller barriers generally decreased crash severity. This was attributed to taller barriers being consistent with vehicle dimensions and absorbing crash energy better than shorter barrier heights. Other factors that were found to significantly affect crash severity were road surface condition, AADTT, motorcycles, driver restraint, driver gender, crash type, alcohol or drug citation, and driver action.

The next evaluation investigated the shift in the crash proportion given that barrier heights have been adjusted to an optimal range. The reasoning behind this analysis was that traffic barriers are generally meant to reduce crash severity and improve safety. Therefore, an improvement in barrier height should result in a decrease in the proportion of severe injury crashes. For this analysis, fatalities, and injuries were grouped together and PDO was also grouped as a separate category. NB models were estimated to predict crash frequency for the two categories for both interstate and state highway system. This was done for only barriers that had recorded crashes. Crashes predicted from the models using the crash data were then compared to the observed crashes by estimating a ratio. A ratio of less than one indicated that the crash severity had decreased the proportion of that severity category. The results indicated that adjusting barrier heights decreased the proportion of fatal and injury crashes for median, W-beam, and box beam barriers installed on interstates. However, for side barrier crashes, it was found that changing

barrier heights for the box beam barrier did not decrease the proportion of fatal and injury crashes. This indicated that additional variables must be optimized for safety to be improved for side box beam barriers on interstate highways. Fatal and injury crashes for W-beam and box beam barriers on state highway system recorded the largest change in crash proportions. This indicated that barriers on state highway system will accrue the highest benefits if those barriers with heights below the recommended ranges are enhanced.

The next analysis conducted was the benefit-cost analysis for adjusting barrier heights to the recommended ranges. A machine learning approach was adopted for the analysis. This required data to be split into training and testing datasets. The training dataset was used to estimate a model that was then tested on a test dataset. Crashes were converted to EPDO costs based on data provided by WYDOT. The approach was to estimate the difference in crash costs for barriers with and without height adjustments over a 10-year period. This difference would be the estimated benefit of improving barrier height. Afterward, the barriers were ranked according to the estimated benefit.

For interstate barriers, a hurdle model was estimated using barriers with historical crashes. The hurdle model estimates both a probability and a count model together. A binary logistic regression model was therefore estimated along with an NB regression model. The results of the hurdle model suggested that barrier height should be considered as an interaction term with shoulder width. The ranking indicated that among the 25 barriers with the highest benefit, almost half had no historical crashes. This was an indication that traffic volume growth over the next decade may increase the risk of those barriers recording crashes. However, improving the heights of barriers without crashes to within the recommended range will result in the highest benefit.

For state highway system, a quantile model was estimated to evaluate the benefit-cost analysis for enhancing barrier height. Interaction terms were included in the dataset to account for the hierarchy present in the data due to the different barrier types. The model was trained on the whole dataset regardless of barrier height. Testing was done on only barriers with heights either above or below the recommended height range. All barriers were optimized to a value of 27 inches. Again, barriers were ranked on estimated benefits to be derived from optimizing barrier height. This entailed computing the difference in EPDO crash costs between barriers with heights optimized and barriers without their heights optimized over a 10-year period. Ranking was done separately for barriers with and without historical crash data based on the estimated highest benefits. The ranking indicated that barriers with heights above 35 inches and those with very low heights had the highest benefits. For those barriers without historical crashes, it was found that W-beam barriers had higher estimated benefits in comparison to box beam barriers despite the initial higher costs of resetting W-beam barriers. Overall, an estimated savings of over 60 million dollars in crash costs could be realized for a 10-million-dollar investment over a 10 year period if traffic barrier heights are enhanced on state highway system.

Next, a barrier condition index was proposed. The BCI is a proposed approach to qualitatively assess barrier conditions. To demonstrate this assessment, the conditions of barriers located on three sites in the WRIR in Wyoming were presented. For the BCI, barriers are rated on a scale of 1 to 4. A rating of 4 represents an ideal barrier condition with no damage while a rating of 1

indicates high-severity damage. The ratings of 2 and 3 refer to medium and poor barrier conditions respectively. The first site assessed had a semi-rigid W-beam barrier with wooden posts. The barrier was given an index of 1.83 which is a poor rating. This rating was given due to the barrier's missing end treatment, low height, severe lateral deflection, panel deterioration, and missing bolts. The barrier was therefore given an index reflecting a poor condition. The second barrier assessed was a tube railing on a bridge and W-beam barriers as the end-treatments. Minor deterioration and problems with end-treatments were observed. Due to the problems identified, this barrier was given a condition index of 2.55 which indicates a medium-severity condition. The third site had no barrier system even though the conditions indicated the need for a side barrier. The site was assigned an index of 1.0 indicating a very poor condition. This also meant that this site had the highest priority for installing a barrier.

Recommendations

Based on the findings of this research, the following conclusions were made:

- The statistical analyses of geometric factors indicated that barrier height, post-spacing, side slope, and lateral offset impact crash severity. Efforts should be made to conform to the guidelines set out in the RDG and MASH Reports. Adhering to the guidelines will improve safety on the State's highways.
- The shift in crash proportion analysis shows that adjusting barrier heights to within the recommended height ranges will result in a general decrease in crash severity. This suggests that enhancing barrier height will lead to an improvement in safety by reducing the incidence of high severity crashes.
- The benefit-cost analyses suggested that substantial benefits would be gained if barrier heights are optimized on both interstate and state highway system. The crash cost savings are significant for barriers installed on state highway system with an estimated benefit of over 60 million dollars for a 10-million-dollar investment over a 10 year period. With these results, it is beneficial to invest in improving barrier heights to improve safety.
- Three cost-benefit analyses were considered: state highway, interstate, and a combined version. The results would provide the WYDOT with the resources to target first those under-design barriers with the highest benefit and then others under design barriers.
- Due to high heterogeneity across highway and interstate, a separate version of the two highway systems are recommended.
- In general, a combined analysis assigns more importance to highway system barriers as the barriers in this highway suffer from the lowest heights.
- For this study, apart from barrier height, all other barriers and geometric factors were constrained. Future optimization should be conducted with more flexibility. In addition to barrier heights, the analyses indicated that other factors including shoulder width, post spacing, barrier length, and barrier type may be altered to improve the overall safety.

- The proposed methodology for BCI provides a simple procedure to efficiently provide a qualitative rating of barrier conditions. The adoption of the BCI procedure will provide a

uniform rating approach that can be applied to all barriers in the state. This index may also be used to optimize barriers or locations for improvement.

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APPENDIX A

Table 32. Random-Parameters Ordered Logit Model for Crash Severity of Traffic Barriers on State highway system

	Variable	Estimate	Standard Error	P-Value
	Constant	-1.345	0.093	<0.001
	Standard Deviation of Parameter Distribution	0.099	0.040	0.014
Traffic Barrier	Box Beam Barriers with a Height of 27-29 in	-0.378	0.170	0.025
Traffic Barrier	Box Beam Barriers with a Height Taller than 31 in	0.493	0.172	0.004
Traffic Barrier	Box Beam Barriers with a Post-Spacing of 6.1-6.3 ft	-0.824	0.204	<0.001
Traffic Barrier	Standard Deviation of Parameter Distribution	0.723	0.181	<0.001
Traffic Barrier	W-Beam Barriers with a Front-slope Height higher than 1 ft	1.186	0.354	<0.001
Traffic Barrier	W-Beam Barriers with a Post-Spacing of 6.1-6.3 ft	-0.337	0.107	<0.001
Traffic Barrier	Standard Deviation of Parameter Distribution	0.476	0.067	<0.001
Traffic Barrier	W-Beam Barriers with a Lateral Offset Shorter than 2 ft	0.286	0.112	0.010
Traffic and Road Environment	Dry Surface Conditions	0.576	0.088	<0.001
Traffic and Road Environment	Negotiating Horizontal Curves	0.868	0.276	0.001
Traffic and Road Environment	Rollover Occurred	1.378	0.149	<0.001
Traffic and Road Environment	Passenger Cars	0.123	0.088	0.042
Traffic and Road Environment	Motorcycles	2.949	0.218	<0.001
Traffic and Road Environment	Trucks	-0.273	0.228	0.046
Traffic and Road Environment	Standard Deviation of Parameter Distribution	0.531	0.196	0.006
Traffic and Road Environment	Female Drivers	0.241	0.091	0.008
Traffic and Road Environment	Standard Deviation of Parameter Distribution	0.389	0.069	<0.001
Traffic and Road Environment	Drivers with a Record of Alcohol Citation	0.467	0.123	<0.001
Traffic and Road Environment	Driver Improper Restraint	0.577	0.122	<0.001
Traffic and Road Environment	Standard Deviation of Parameter Distribution	0.794	0.119	<0.001

Table 33. Ordered Logistic Regression for Severity of Crashes Involving Traffic Barriers

Variable		Categories	Reference Category	Estimates	Standard Error	Wald Chi-Sq	P-Value	Odds Ratio
Intercept 2		-	-	-4.138	0.8056	26.387	<.0001	-
Intercept 1		-	-	-1.244	0.7667	2.635	0.1045	-
Environmental	Vehicle Type	SUV	Passenger Car	-0.239	0.2901	0.682	0.4086	0.787
		Pickup	Passenger Car	0.151	0.2366	0.410	0.5219	1.164
		Truck	Passenger Car	-0.467	0.6183	0.572	0.4494	0.626
		Motorcycle	Passenger Car	5.023	0.5161	94.725	<.0001	151.86
		Other	Passenger Car	0.219	0.4795	0.209	0.6474	1.245
	Surface Condition	Wet	Dry	-0.059	0.3481	0.028	0.8650	0.943
		Snow	Dry	-1.074	0.3407	9.935	<.0001	0.342
		Ice	Dry	-1.019	0.2498	16.649	<.0001	0.361
		Other (slush, sand)	Dry	-0.574	0.4340	1.753	0.1854	0.563
	Rollover	Yes	No	2.094	0.3173	43.562	<.0001	8.119
	Road Class	Rural	Urban	0.546	0.2288	5.699	0.0170	1.727
Driver	Gender	Female	Male	0.815	0.2103	15.043	<.0001	2.261
	Improper Restraint	Yes	No	1.064	0.2476	18.463	<.0001	2.898
	Alcohol Involved	Yes	No	0.791	0.2671	8.789	<.0001	2.208
Traffic Barrier	Type	W-Beam	Concrete	-0.231	0.4377	0.280	0.5966	0.793
		Box Beam	Concrete	-0.301	0.6982	0.186	0.0481	0.740
	System Height	28 inch < Height <= 31 inch	<= 28 inch	-0.350	0.2129	2.713	0.0395	0.704
		Height > 31 inch	<= 28 inch	0.029	0.3371	0.007	0.9293	1.030
	Side slope Height	0 (Flat) < Height <= 1 ft	Flat or Higher than Surface	0.246	0.2248	1.203	0.1727	1.280
		Height > 1 ft	Flat or Higher than Surface	0.559	0.3496	2.560	0.0306	1.750
	Post-Spacing	5.5 ft < Spacing <= 6 ft	<= 5.5 ft	-0.118	0.4158	0.081	0.7758	0.888
		6 ft < Spacing <= 6.5 ft	<= 5.5 ft	-0.8141	0.4414	3.4012	0.0451	0.443
		> 6.5 ft	<= 5.5 ft	-2.1312	1.1354	3.5232	0.0605	0.119

Table 34. Ordered Logistic Regression for Severity of Crashes Involving Cable Barriers

Variable		Categories	Reference Category	Estimates	Standard Error	Wald Chi-Square	P-Value	Odds Ratio
Intercept 2		-	-	-4.1646	0.00668	389253.507	<.0001	-
Intercept 1		-	-	-1.8453	0.00245	565442.228	<.0001	-
Environmental	Vehicle Type [a]	SUV	Passenger Car	0.6202	0.00573	11718.2415	<.0001	1.859
		Van	Passenger Car	0.8721	0.00712	14983.6892	<.0001	2.392
		Pick Up	Passenger Car	-0.0732	0.00587	155.5231	<.0001	0.929
		Truck	Passenger Car	0.9611	0.00979	9641.8985	<.0001	2.614
	Road Conditions	Wet	Dry	0.4714	0.00678	4839.8777	<.0001	1.602
		Snow	Dry	-0.6975	0.0113	3821.4830	<.0001	0.498
		Ice	Dry	-0.7563	0.00494	23472.9826	<.0001	0.469
		Other (slush, sand)	Dry	-0.3359	0.0148	513.6890	<.0001	0.715
	Highway Speed Limit	Speed Limit > 55 mph	Speed Limit <= 55 mph	-0.5622	0.00264	45291.5631	<.0001	0.570
Driver	Driver Gender	Male	Female	-0.5710	0.00334	29236.4846	<.0001	0.565
	Driver Residency	Wyoming Resident	Non-Resident	-0.2449	0.00379	4185.1773	<.0001	0.783
	Driver Conditions	Non-Normal (Alcohol Use, Angry, etc.)	Normal	0.8809	0.00408	46568.6217	<.0001	2.413
	Driver Alcohol Citation (Record)	Yes	No	0.8174	0.00702	13553.6809	<.0001	2.265
	Driver Improper Restrain	Yes	No	0.7517	0.00716	11018.3210	<.0001	2.121
Number of Observations				1593				
Log-Likelihood (Fixed Model)				-416.18				
Log-Likelihood (Random Parameter Model)				-424.68				

Table 35. Ordered Logistic Regression for Severity of Crashes Involving Guardrail Barriers

Variable		Categories	Reference Category	Estimates	Standard Error	Wald Chi-Square	P-Value	Odds Ratio
Intercept 2		-	-	-3.6993	0.2067	320.1913	<.0001	-
Intercept 1		-	-	-1.2896	0.1761	53.5984	<.0001	-
Environmental	Vehicle Type	SUV	Passenger Car	0.0557	0.1343	0.1723	0.6781	1.057
		Van	Passenger Car	-0.0489	0.2680	0.0334	0.8551	0.952
		Pick Up	Passenger Car	0.1285	0.1201	1.1448	0.2846	1.137
		Truck	Passenger Car	0.4052	0.1763	5.2853	0.0215	1.500
		Motorcycle	Passenger Car	4.0832	0.3302	152.9064	<.0001	59.336
		Other	Passenger Car	-0.1606	0.7884	0.0415	0.8385	0.852
	Road Conditions	Wet	Dry	0.00665	0.1625	0.0017	0.9674	1.007
		Snow	Dry	-0.8277	0.1928	18.4306	<.0001	0.437
		Ice	Dry	-0.7713	0.2687	8.2407	0.0041	0.560
		Other (slush, sand)	Dry	-0.5798	0.1234	22.0686	<.0001	0.462
	Highway Speed Limit	Speed Limit > 55 mph	Speed Limit <= 55 mph	0.2280	0.1278	3.1813	0.0445	1.256
	Negotiating Horizontal Curve	Yes	No	0.2732	0.1211	5.0885	0.0241	1.314
Driver	Driver Gender	Male	Female	-0.4869	0.1027	22.4853	<.0001	0.615
	Driver Residency	Wyoming Resident	Non-Resident	-0.2167	0.0996	4.7395	0.0295	0.805
	Driver Conditions	Non-Normal (Alcohol Use, Angry, etc.)	Normal	0.5979	0.1378	18.8236	<.0001	1.818
	Driver Alcohol Citation	Yes	No	0.4948	0.2096	5.5720	0.0182	1.640
	Driver Improper Restrain	Yes	No	1.1523	0.1306	77.8976	<.0001	3.166
Number of Observations				5138				
Log-Likelihood (Fixed Model)				-2776.21				
Log-Likelihood (Random Parameter Model)				-2831.091				

Table 36. Ordered Logistic Regression for Severity of Non-Truck (Light Vehicles) Crashes Involving Traffic Barriers

Variable		Categories	Reference Category	Estimates	Standard Error	Wald Chi-Square	P-Value	Odds Ratio
Intercept 2		-	-	-4.7400	0.2116	501.8156	<.0001	
Intercept 1		-	-	-2.4451	0.1921	162.0454	<.0001	
Environmental	Traffic Barrier Type	Rigid	Cable	1.5046	0.1524	97.4322	<.0001	4.503
		Guardrail	Cable	1.2108	0.1208	100.4931	<.0001	3.356
	Road Conditions	Wet	Dry	-0.1894	0.1352	1.9623	0.1613	0.827
		Snow	Dry	-1.0138	0.1598	40.2518	<.0001	0.363
		Ice	Dry	-0.7829	0.1019	59.0835	<.0001	0.457
		Other (slush, sand)	Dry	-1.0877	0.2303	22.3052	<.0001	0.337
	Highway Speed Limit	Speed Limit > 55 mph	Speed Limit <= 55 mph	0.2047	0.1141	3.2182	0.0428	1.227
	Number of Lanes	Number of Lanes > 2	Number of Lanes <= 2	0.2361	0.1118	4.4602	0.0347	1.266
	Negotiating Horizontal Curve	Yes	No	0.3623	0.0958	14.3055	0.0002	1.437
Driver	Driver Age	Age > 35 Years	Age <= 35 Years	0.2464	0.0792	9.6826	0.0019	1.279
	Driver Gender	Male	Female	-0.4648	0.0812	32.7397	<.0001	0.628
	Driver Residency	Wyoming Resident	Non-Resident	-0.1992	0.0825	5.8245	0.0158	0.819
	Driver Condition	Non-Normal (Alcohol Use, Angry, etc.)	Normal	0.5380	0.1173	21.0491	<.0001	1.713
	Driver Alcohol Citation (Record)	Yes	No	0.3056	0.1632	3.5071	0.0411	1.357
	Driver Citation (Record)	Driver cited	Driver not cited	0.1802	0.0841	4.5959	0.0320	1.197
	Driver Improper Restraint	Yes	No	1.1490	0.1132	102.9890	<.0001	3.155
Number of Observations				6863				
Log-Likelihood (Fixed Model)				-2225.42				
Log-Likelihood (Random Parameter Model)				-3150.90				

Table 37. Ordered Logistic Regression for Severity of Truck Crashes Involving Traffic Barriers

Variable		Categories	Reference Category	Estimates	Standard Error	Wald Chi-Square	P-Value	Odds Ratio
Intercept 2		-	-	-4.5041	0.6986	41.5733	<.0001	
Intercept 1		-	-	-2.4955	0.6580	14.3836	0.0001	
Environmental	Traffic Barrier Type	Rigid	Cable	0.9305	0.5005	3.4565	0.0730	2.536
		Guardrail	Cable	1.1325	0.3335	11.5292	0.0007	3.103
	Road Conditions	Wet	Dry	0.1262	0.3810	0.1097	0.7405	1.134
		Snow	Dry	-1.7728	0.6408	7.6540	0.0057	0.170
		Ice	Dry	-0.7405	0.2964	6.2407	0.0125	0.477
		Other (slush, sand)	Dry	-0.6668	0.8632	0.5968	0.4398	0.513
	Negotiating Horizontal Curve	Yes	No	0.8350	0.2874	8.4412	0.0037	2.305
Driver	Driver Age	Age > 35 Years	Age <= 35 Years	0.6760	0.2999	5.0801	0.0242	1.966
	Driver Gender	Male	Female	-1.0204	0.4191	5.9294	0.0149	0.360
	Driver Residency	Wyoming Resident	Non-Resident	0.8143	0.4122	3.9028	0.0482	2.258
	Driver Conditions	Non-Normal (Alcohol Use, Angry, etc.)	Normal	1.1990	0.3103	14.9339	0.0001	3.317
	Driver Alcohol Citation (Record)	Yes	No	2.1779	1.1394	3.6540	0.0459	8.828
Number of Observations				658				
Log-Likelihood (Fixed Model)				-304.81				
Log-Likelihood (Random Parameter Model)				-352.587				

APPENDIX B

Table 38. Ranking of Interstate Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
6266	4	14	52	266	62	30	1,102,578	1
4960	8	1	1	96	71	39	1,074,508	2
7374	9	0	5	313	50	31	650,118	3
7294	2	0	44	266	41	25	546,505	4
5839	3	4	37	209	49	36	434,430	5
5079	7	1	26	63	48	36	417,952	6
7798	7	0	24	259	42	30	402,508	7
6280	10	2	26	195	46	35	397,666	8
6282	11	1	26	192	46	34	396,363	9
6862	10	4	23	1514	117	105	388,144	10
7101	3	13	36	1095	47	36	368,925	11
7539	4	0	36	362	41	32	311,260	12
7270	2	1	37	232	34	26	284,909	13
6966	3	0	36	274	37	29	279,994	14
7239	3	5	36	387	37	29	271,885	15
6527	9	10	24	2236	117	108	268,597	16
6953	2	0	36	238	35	28	267,896	17
7450	3	1	36	247	35	28	258,478	18
6890	11	0	22	1502	64	57	243,725	19
7031	3	5	36	304	32	25	237,050	20
5962	9	0	20	115	45	39	208,203	21
6891	11	2	24	1501	84	78	186,141	22
5114	9	0	19	144	35	29	176,747	23
6861	9	8	22	425	45	40	170,862	24
6872	9	0	20	216	37	32	164,605	25
6386	7	2	23	291	53	48	160,292	26
6866	6	0	20	227	36	31	157,340	27
7726	9	1	23	1295	51	46	142,387	28
6236	11	15	25	2894	107	102	130,810	29
6865	10	0	22	252	33	30	120,702	30
6393	17	2	24	270	52	49	115,054	31
6889	11	1	23	352	37	34	103,692	32
7548	7	37	24	877	49	46	100,361	33
6535	9	14	25	956	74	71	96,442	34
5836	10	5	23	203	34	31	94,971	35
7550	7	6	24	858	46	43	93,840	36

Table 38 Continued. Ranking of Interstate Barriers According to Total Benefits

Barrier ID	Shoulder width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement in 10 years	EPDO with Enhancement in 10 years	Total Benefit in 10 Years ($)	Rank
6133	10	3	25	1212	64	61	76,880	37
5078	6	0	24	244	37	35	75,622	38
6390	9	51	25	1129	60	57	71,849	39
5722	10	0	24	138	34	32	67,533	40
6962	10	4	24	177	33	31	65,400	41
7659	9	0	24	452	30	29	57,457	42
6379	10	19	25	151	42	40	53,913	43
7549	7	1	24	230	27	25	51,505	44
7647	8	0	24	489	27	26	51,373	45
4357	8	3	25	315	41	40	50,679	46
6494	8	0	25	213	40	39	49,941	47
5030	8	8	25	168	39	38	49,841	48
6495	10	0	25	219	40	38	49,360	49
6231	12	1	25	324	40	38	48,453	50
6509	9	0	25	215	38	36	46,296	51
6404	6	0	25	244	36	35	44,180	52
5092	7	2	25	254	36	35	43,344	53
6878	10	5	25	329	36	35	42,971	54
7633	10	1	25	451	37	36	42,901	55
5045	9	0	25	152	34	33	40,889	56
5053	10	0	25	163	34	32	40,658	57
5752	10	0	25	602	37	35	40,482	58
5039	8	0	25	150	33	32	40,295	59
7712	10	1	25	685	37	36	40,208	60
6409	9	0	25	259	32	31	37,850	61
5868	10	4	25	215	32	31	37,841	62
5826	10	0	25	510	34	33	37,748	63
5863	10	0	25	213	32	31	37,503	64
7756	9	0	25	335	33	31	37,466	65
5633	10	0	25	228	32	31	37,299	66
6281	10	0	25	64	29	28	35,365	67
4204	9	0	25	301	29	28	32,770	68
7142	10	0	25	217	27	26	30,798	69
7601	6	0	25	544	29	28	30,615	70
6545	7	17	26	241	67	66	30,226	71
7629	9	1	26	471	67	66	28,060	72

Table 38 Continued. Ranking of Interstate Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
6475	6	11	26	269	62	62	27,372	73
6524	10	287	26	208	52	51	21,903	74
6233	12	14	26	1877	83	82	21,615	75
6392	9	4	26	841	62	61	20,765	76
5098	12	20	26	826	59	59	19,291	77
6526	9	16	26	507	53	52	19,083	78
6874	12	14	26	127	44	44	18,897	79
4319	11	4	26	470	49	49	18,753	80
6884	10	18	26	476	46	45	15,710	81
6663	10	1	26	873	54	53	15,661	82
5227	12	3	26	814	52	52	15,592	83
5097	5	0	26	755	51	50	15,516	84
5101	10	0	26	403	43	42	14,937	85
6162	10	0	26	127	37	36	14,672	86
6491	6	0	26	262	39	38	14,145	87
6514	9	0	26	217	37	37	13,971	88
6406	10	0	26	259	35	35	12,697	89
6726	9	15	26	241	34	34	12,457	90
5055	12	0	26	202	34	34	12,426	91
6401	7	0	26	221	34	34	12,416	92
6855	8	0	26	259	35	35	12,176	93
5041	10	0	26	248	35	34	12,174	94
5678	9	0	26	273	34	33	11,916	95
5625	7	6	26	275	35	35	11,875	96
5043	18	0	26	249	34	34	11,854	97
6318	7	0	26	224	33	32	11,435	98
6856	8	0	26	250	33	33	11,432	99
6421	10	0	26	859	45	45	11,336	100
6870	9	0	26	703	42	42	11,320	101
6363	9	3	26	256	33	33	11,230	102
6759	5	0	26	212	32	32	11,182	103
6668	10	0	26	180	31	31	11,162	104
6279	9	0	26	63	28	28	11,122	105
6892	12	0	26	514	38	37	11,101	106
7510	9	0	26	583	40	39	11,090	107
6362	10	0	26	255	33	32	11,086	108
5877	11	1	26	215	32	31	10,992	109
6338	6	0	26	253	32	32	10,938	110

Table 38 Continued. Ranking of Interstate Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
6338	6	0	26	253	32	32	10,938	111
7540	11	0	26	209	31	30	10,643	112
6278	10	0	26	277	31	31	10,209	113
6289	10	0	26	187	29	28	10,057	114
6339	9	0	26	1250	51	50	10,022	115
7648	10	0	26	296	31	31	9,781	116
7640	9	0	26	472	34	34	9,652	117
7695	11	0	26	216	29	28	9,487	118
7624	8	0	26	471	33	33	9,415	119
7230	11	1	26	208	28	28	9,357	120
4181	9	0	26	301	30	30	9,215	121
7693	9	0	26	290	29	29	9,205	122
5895	8	0	26	379	31	31	9,123	123
5779	8	0	26	340	28	28	8,031	124
6973	9	0	26	425	30	29	7,857	125
3812	9	0	26	762	36	36	7,643	126
5809	7	14	26	835	37	37	7,465	127
7645	7	0	26	453	29	29	7,459	128
7660	7	0	26	451	29	29	7,316	129
7661	9	0	26	452	29	28	7,187	130
7574	6	0	26	500	29	29	6,988	131
7448	6	1	26	1272	44	44	6,390	132

Table 39. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
2744	7	41	W-beam	-1123297	-342,233.71	7,712	7,802,925	1
4231	11	37	W-beam	-638563	-61,255.19	3,372	5,769,707	2
5324	6	37	Box-beam	-714252	-136,944.24	7,552	5,765,527	3
1443	9	37	W-beam	-1111476	-534,168.18	33,852	5,739,228	4
3055	8	36	W-beam	-941238	-431,848.82	15,878	5,078,016	5
3055	8	36	W-beam	-941238	-431,848.82	15,878	5,078,016	6
3056	8	36	W-beam	-1067924	-558,534.15	36,246	5,057,648	7
3056	8	36	W-beam	-1067924	-558,534.15	36,246	5,057,648	8
3888	7	36	W-beam	-1074108	-564,718.25	45,005	5,048,889	9
109	4	0	Box-beam	-584529	-193,357.51	1,016	3,910,700	10
575	4	0	Box-beam	-650957	-259,785.76	1,068	3,910,648	11
576	2	0	Box-beam	-667164	-275,992.34	1,762	3,909,955	12
1048	4	0	W-beam	-423022	-31,850.21	3,245	3,908,471	13
1047	4	0	W-beam	-423323	-32,151.51	3,302	3,908,415	14
112	3	0	Box-beam	-718907	-327,735.73	3,774	3,907,943	15
2745	3	0	Box-beam	-1988261	-1,597,088.88	4,822	3,906,894	16
2745	3	0	Box-beam	-1988261	-1,597,088.88	4,822	3,906,894	17
5200	3	12	W-beam	-1344888	-1,127,570.48	106,212	2,066,963	18
15	3	13	W-beam	-522201	-322,269.24	18,504	1,980,818	19
7771	0	14	W-beam	-760922	-578,375.12	6,308	1,819,160	20
5202	4	14	W-beam	-798679	-616,132.31	10,224	1,815,244	21
5454	3	14	W-beam	-706157	-523,610.64	32,100	1,793,367	22
5198	4	14	W-beam	-940739	-758,192.26	36,886	1,788,582	23
4573	0	16	W-beam	-681109	-515,947.84	10,240	1,641,373	24
5197	4	16	W-beam	-974317	-809,155.25	46,451	1,605,163	25
3614	1	17	W-beam	-703060	-555,284.16	6,450	1,471,309	26
5201	4	17	W-beam	-763834	-616,058.07	10,210	1,467,550	27
5462	2	17	W-beam	-710382	-562,605.70	17,222	1,460,537	28
5199	3	17	W-beam	-855078	-707,301.65	27,335	1,450,425	29
1205	2	18	Box-beam	-287212	-156,821.06	1,657	1,302,248	30
4739	4	18	Box-beam	-818620	-688,229.91	1,763	1,302,143	31
852	2	18	Box-beam	-291908	-161,517.61	3,384	1,300,521	32
3615	1	18	W-beam	-685550	-555,159.76	6,427	1,297,479	33
4572	0	18	W-beam	-646482	-516,091.92	10,267	1,293,638	34
5204	4	18	W-beam	-759662	-629,271.31	12,690	1,291,216	35

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
21	1	18	W-beam	-671647	-541,256.80	15,210	1,288,695	36
5205	3	18	W-beam	-773295	-642,904.70	15,248	1,288,657	37
62	3	18	W-beam	-379416	-249,025.58	17,189	1,286,716	38
109	0	18	W-beam	-832214	-701,823.85	40,694	1,263,212	39
575	5	18	W-beam	-994269	-863,878.47	64,368	1,239,537	40
1048	0	18	W-beam	-1032381	-901,990.60	82,694	1,221,211	41
1047	1	19	W-beam	-248539	-135,533.99	3,806	1,126,245	42
112	1	19	W-beam	-634154	-521,149.07	5,177	1,124,875	43
5200	1	19	W-beam	-655700	-542,694.77	10,828	1,119,224	44
15	0	19	W-beam	-662346	-549,340.58	12,075	1,117,976	45
7771	1	19	W-beam	-581319	-468,314.18	13,952	1,116,099	46
5202	3	19	W-beam	-174633	-61,627.65	15,212	1,114,839	47
5454	0	19	W-beam	-569253	-456,248.34	16,036	1,114,016	48
5198	1	19	W-beam	-653472	-540,466.54	16,568	1,113,484	49
4573	1	19	W-beam	-686347	-573,341.71	16,580	1,113,472	50
5197	0	19	W-beam	-535490	-422,484.95	16,622	1,113,430	51
3614	3	19	W-beam	-715999	-602,994.35	24,231	1,105,820	52
5201	3	19	W-beam	-719752	-606,747.35	25,507	1,104,545	53
5462	5	19	W-beam	-936814	-823,809.20	26,668	1,103,384	54
5199	0	19	W-beam	-764078	-651,072.79	31,169	1,098,883	55
1205	0	19	W-beam	-738038	-625,032.85	32,440	1,097,612	56
852	1	19	W-beam	-515621	-402,616.13	35,089	1,094,962	57
5453	3	19	W-beam	-865220	-752,215.21	45,867	1,084,185	58
5196	3	19	W-beam	-969475	-856,469.69	54,056	1,075,995	59
3847	3	19	W-beam	-1160352	-1,047,346.79	93,316	1,036,735	60
3678	4	20	Box-beam	-1551362	-1,455,742.33	2,233	953,965	61
366	0	20	Box-beam	-685951	-590,331.30	2,686	953,511	62
3615	1	20	W-beam	-467257	-371,637.11	3,725	952,472	63
4572	0	20	W-beam	-648658	-553,038.44	12,769	943,428	64
5204	2	20	W-beam	-655350	-559,730.32	14,025	942,172	65
21	5	20	W-beam	-651659	-556,038.97	15,990	940,208	66
5205	0	20	W-beam	-551969	-456,349.62	16,055	940,143	67
62	1	20	W-beam	-642849	-547,229.05	16,331	939,866	68
818	3	20	W-beam	-772395	-676,775.76	21,605	934,592	69
3610	2	20	W-beam	-861147	-765,527.59	21,770	934,428	70
4571	1	20	W-beam	-673555	-577,935.12	23,600	932,597	71
90	2	20	W-beam	-888287	-792,667.12	26,864	929,334	72

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
693	4	20	W-beam	-526374	-430,754.07	29,100	927,098	73
825	5	20	W-beam	-721648	-626,028.33	29,126	927,072	74
824	4	20	W-beam	-623983	-528,363.06	30,034	926,163	75
64	3	20	W-beam	-813373	-717,753.52	34,947	921,251	76
2001	5	20	W-beam	-847472	-751,852.73	43,343	912,854	77
4847	0	22	W-beam	-360392	-282,157.76	754	781,589	78
4475	2	22	Box-beam	-582241	-504,007.01	1,403	780,940	79
821	1	22	Box-beam	-210935	-132,700.25	3,202	779,141	80
4476	0	22	W-beam	-479404	-401,169.84	3,262	779,081	81
796	1	22	W-beam	-610229	-531,994.58	4,451	777,892	82
2096	0	22	W-beam	-598310	-520,075.57	4,975	777,368	83
5455	0	22	W-beam	-598375	-520,140.18	4,988	777,356	84
1365	2	22	Box-beam	-483973	-405,738.82	5,141	777,203	85
489	4	22	W-beam	-747471	-669,236.96	5,751	776,593	86
826	0	22	W-beam	-420205	-341,970.54	6,332	776,011	87
3981	4	22	W-beam	-989336	-911,101.51	6,460	775,883	88
4474	0	22	W-beam	-607567	-529,333.06	8,320	774,023	89
95	2	22	Box-beam	-374225	-295,991.11	8,567	773,776	90
819	0	22	W-beam	-614317	-536,082.51	9,587	772,756	91
820	2	22	W-beam	-578466	-500,232.05	10,432	771,911	92
5499	5	22	W-beam	-660885	-582,650.43	11,607	770,737	93
1859	2	22	Box-beam	-620043	-541,809.08	12,586	769,757	94
4846	5	22	W-beam	-677986	-599,751.94	12,800	769,544	95
3069	0	22	Box-beam	-590369	-512,134.37	13,245	769,098	96
22	4	22	W-beam	-843457	-765,222.82	21,713	760,631	97
5203	4	22	W-beam	-495104	-416,869.79	22,941	759,402	98
500	2	22	W-beam	-857153	-778,918.55	24,283	758,060	99
4497	2	22	W-beam	-742574	-664,339.59	27,392	754,951	100
492	4	22	W-beam	-776165	-697,930.97	28,747	753,597	101
53	2	22	W-beam	-897758	-819,523.36	31,904	750,439	102
3993	4	22	W-beam	-539124	-460,890.15	32,282	750,061	103
5446	2	22	W-beam	-883671	-805,436.30	45,753	736,590	104
498	2	22	W-beam	-1026365	-948,130.61	55,357	726,986	105
5465	4	22	W-beam	-675170	-596,935.52	61,117	721,226	106
4882	4	22	W-beam	-941623	-863,389.05	64,277	718,067	107
5193	4	22	W-beam	-1280170	-1,201,935.97	118,895	663,449	108
2245	0	23	Box-beam	-171385	-110,536.07	1,043	607,446	109

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
3609	5	23	W-beam	-183765	-122,915.71	2,432	606,058	110
2084	0	23	Box-beam	-319641	-258,792.02	3,079	605,410	111
5723	0	23	W-beam	-572139	-511,290.22	3,883	604,606	112
367	1	23	W-beam	-600287	-539,438.32	3,950	604,539	113
2767	1	23	W-beam	-579584	-518,735.02	4,724	603,765	114
694	2	23	Box-beam	-301244	-240,394.67	4,878	603,611	115
220	2	23	Box-beam	-301519	-240,670.38	4,889	603,600	116
4110	3	23	W-beam	-1714014	-1,653,165.44	5,071	603,418	117
898	3	23	Box-beam	-889647	-828,798.25	5,097	603,393	118
901	5	23	W-beam	-730712	-669,862.83	5,868	602,621	119
434	3	23	Box-beam	-1129589	-1,068,740.49	5,971	602,518	120
4029	2	23	Box-beam	-250669	-189,819.73	6,124	602,366	121
7773	0	23	Box-beam	-240535	-179,685.79	6,216	602,273	122
6894	4	23	Box-beam	-280695	-219,846.01	6,368	602,122	123
822	4	23	Box-beam	-288770	-227,920.70	6,679	601,810	124
842	0	23	W-beam	-566705	-505,855.65	9,371	599,119	125
823	4	23	W-beam	-990669	-929,819.64	9,973	598,516	126
4722	3	23	W-beam	-559766	-498,916.93	10,185	598,304	127
4167	5	23	W-beam	-904169	-843,319.81	10,325	598,164	128
2038	2	23	Box-beam	-439780	-378,931.55	11,764	596,726	129
2244	2	23	W-beam	-660910	-600,061.02	12,153	596,337	130
493	1	23	W-beam	-523694	-462,845.57	12,926	595,563	131
6059	5	23	W-beam	-535157	-474,308.54	15,077	593,412	132
499	1	23	W-beam	-795529	-734,679.77	15,980	592,509	133
2639	4	23	W-beam	-677685	-616,836.41	16,006	592,483	134
4881	5	23	W-beam	-651657	-590,808.07	17,811	590,678	135
3989	5	23	W-beam	-472227	-411,378.47	22,990	585,500	136
491	1	23	W-beam	-964100	-903,250.78	24,663	583,827	137
5207	1	23	W-beam	-711069	-650,219.62	33,094	575,395	138
5448	4	23	W-beam	-774097	-713,248.34	40,901	567,588	139
3611	3	23	W-beam	-791281	-730,431.59	41,869	566,620	140
4065	1	23	W-beam	-794203	-733,353.76	50,943	557,547	141
5371	4	23	W-beam	-1215608	-1,154,758.95	111,315	497,174	142
4853	2	24	Box-beam	-1698012	-1,654,548.13	404	434,231	143
2481	0	24	Box-beam	-245672	-202,208.11	601	434,034	144
4736	0	24	W-beam	-418353	-374,889.93	771	433,864	145

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
3609	5	23	W-beam	-183765	-122,915.71	2,432	606,058	110
2084	0	23	Box-beam	-319641	-258,792.02	3,079	605,410	111
5723	0	23	W-beam	-572139	-511,290.22	3,883	604,606	112
367	1	23	W-beam	-600287	-539,438.32	3,950	604,539	113
2767	1	23	W-beam	-579584	-518,735.02	4,724	603,765	114
694	2	23	Box-beam	-301244	-240,394.67	4,878	603,611	115
220	2	23	Box-beam	-301519	-240,670.38	4,889	603,600	116
4110	3	23	W-beam	-1714014	-1,653,165.44	5,071	603,418	117
898	3	23	Box-beam	-889647	-828,798.25	5,097	603,393	118
901	5	23	W-beam	-730712	-669,862.83	5,868	602,621	119
434	3	23	Box-beam	-1129589	-1,068,740.49	5,971	602,518	120
4029	2	23	Box-beam	-250669	-189,819.73	6,124	602,366	121
7773	0	23	Box-beam	-240535	-179,685.79	6,216	602,273	122
6894	4	23	Box-beam	-280695	-219,846.01	6,368	602,122	123
822	4	23	Box-beam	-288770	-227,920.70	6,679	601,810	124
842	0	23	W-beam	-566705	-505,855.65	9,371	599,119	125
823	4	23	W-beam	-990669	-929,819.64	9,973	598,516	126
4722	3	23	W-beam	-559766	-498,916.93	10,185	598,304	127
4167	5	23	W-beam	-904169	-843,319.81	10,325	598,164	128
2038	2	23	Box-beam	-439780	-378,931.55	11,764	596,726	129
2244	2	23	W-beam	-660910	-600,061.02	12,153	596,337	130
493	1	23	W-beam	-523694	-462,845.57	12,926	595,563	131
6059	5	23	W-beam	-535157	-474,308.54	15,077	593,412	132
499	1	23	W-beam	-795529	-734,679.77	15,980	592,509	133
2639	4	23	W-beam	-677685	-616,836.41	16,006	592,483	134
4881	5	23	W-beam	-651657	-590,808.07	17,811	590,678	135
3989	5	23	W-beam	-472227	-411,378.47	22,990	585,500	136
491	1	23	W-beam	-964100	-903,250.78	24,663	583,827	137
5207	1	23	W-beam	-711069	-650,219.62	33,094	575,395	138
5448	4	23	W-beam	-774097	-713,248.34	40,901	567,588	139
3611	3	23	W-beam	-791281	-730,431.59	41,869	566,620	140
4065	1	23	W-beam	-794203	-733,353.76	50,943	557,547	141
5371	4	23	W-beam	-1215608	-1,154,758.95	111,315	497,174	142
4853	2	24	Box-beam	-1698012	-1,654,548.13	404	434,231	143
2481	0	24	Box-beam	-245672	-202,208.11	601	434,034	144
4736	0	24	W-beam	-418353	-374,889.93	771	433,864	145

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
2646	0	24	Box-beam	-108629	-65,165.05	774	433,861	146
219	5	24	Box-beam	-172710	-129,246.89	1,054	433,582	147
303	0	24	Box-beam	-1014367	-970,903.66	1,070	433,565	148
301	0	24	Box-beam	-1072098	-1,028,634.67	1,073	433,562	149
421	1	24	Box-beam	-266565	-223,101.11	1,150	433,486	150
420	4	24	W-beam	-501739	-458,275.37	1,373	433,262	151
892	3	24	Box-beam	-180380	-136,916.62	1,389	433,246	152
3605	4	24	Box-beam	-548752	-505,288.79	2,227	432,408	153
267	3	24	Box-beam	-158040	-114,576.82	2,238	432,398	154
711	4	24	Box-beam	-158104	-114,640.95	2,240	432,395	155
4097	0	24	W-beam	-364281	-320,817.33	2,362	432,273	156
5852	3	24	Box-beam	-150253	-106,789.97	2,368	432,267	157
4724	1	24	Box-beam	-145645	-102,181.97	2,606	432,029	158
585	1	24	Box-beam	-146539	-103,075.97	2,613	432,022	159
843	3	24	Box-beam	-223206	-179,742.04	2,671	431,964	160
4415	0	24	W-beam	-603309	-559,845.38	2,830	431,805	161
60	3	24	Box-beam	-328797	-285,333.77	2,917	431,718	162
61	4	24	Box-beam	-173519	-130,055.29	3,060	431,575	163
501	2	24	W-beam	-511744	-468,280.52	3,251	431,384	164
2243	4	24	Box-beam	-446107	-402,643.82	3,287	431,348	165
1055	0	24	W-beam	-444920	-401,456.74	3,316	431,319	166
3877	0	24	Box-beam	-310126	-266,662.17	3,438	431,197	167
2095	0	24	W-beam	-584635	-541,171.98	3,802	430,834	168
4008	1	24	W-beam	-583040	-539,576.18	3,976	430,659	169
1995	1	24	W-beam	-583086	-539,622.57	3,984	430,651	170
4888	0	24	W-beam	-420111	-376,647.96	5,004	429,631	171
5192	1	24	Box-beam	-367758	-324,294.45	5,050	429,586	172
89	1	24	W-beam	-621302	-577,838.77	5,229	429,406	173
1761	0	24	W-beam	-486958	-443,494.78	5,741	428,894	174
1765	0	24	Box-beam	-1197122	-1,153,658.58	6,585	428,050	175
4104	4	24	Box-beam	-261881	-218,417.72	6,637	427,998	176
3636	5	24	Box-beam	-434558	-391,094.02	7,705	426,930	177
4767	2	24	W-beam	-263418	-219,954.37	8,180	426,455	178
111	5	24	W-beam	-634790	-591,326.01	8,444	426,191	179
1364	3	24	W-beam	-634840	-591,376.93	8,453	426,182	180
4634	0	24	Box-beam	-461251	-417,787.43	9,207	425,429	181

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
3078	5	24	W-beam	-971788	-928,324.89	9,693	424,943	182
28	2	24	Box-beam	-373440	-329,976.04	9,877	424,758	183
4822	4	24	W-beam	-726251	-682,787.90	10,279	424,356	184
4824	5	24	Box-beam	-391392	-347,928.58	10,395	424,240	185
6789	4	24	W-beam	-978399	-934,935.89	10,933	423,702	186
3254	2	24	W-beam	-910089	-866,625.30	10,964	423,671	187
3318	1	24	W-beam	-649489	-606,025.77	10,981	423,654	188
224	3	24	Box-beam	-407802	-364,338.01	11,201	423,434	189
3253	3	24	W-beam	-379746	-336,282.04	11,369	423,266	190
4536	2	24	W-beam	-633892	-590,428.98	11,606	423,029	191
6790	2	24	Box-beam	-438588	-395,124.39	12,388	422,248	192
6771	4	24	Box-beam	-507465	-464,001.89	12,715	421,921	193
414	2	24	W-beam	-782576	-739,112.07	12,828	421,808	194
4632	5	24	W-beam	-767801	-724,337.18	14,039	420,596	195
562	3	24	W-beam	-395721	-352,257.89	14,367	420,268	196
2765	3	24	Box-beam	-514646	-471,182.63	15,319	419,316	197
149	0	24	W-beam	-581714	-538,250.58	15,814	418,822	198
3617	1	24	W-beam	-613469	-570,005.55	15,954	418,682	199
2645	2	24	W-beam	-622220	-578,756.08	16,015	418,620	200
2664	0	24	W-beam	-667551	-624,087.48	16,555	418,081	201
1366	3	24	W-beam	-365242	-321,778.07	16,629	418,006	202
4640	0	24	W-beam	-623922	-580,458.46	17,915	416,720	203
2622	2	24	W-beam	-365875	-322,411.70	18,531	416,105	204
6055	4	24	W-beam	-706691	-663,227.97	19,063	415,572	205
2632	3	24	W-beam	-827235	-783,771.08	19,153	415,482	206
2631	2	24	W-beam	-795163	-751,699.95	19,175	415,461	207
6012	2	24	Box-beam	-620013	-576,549.74	19,380	415,255	208
6864	0	24	W-beam	-626661	-583,197.24	20,409	414,226	209
1860	4	24	W-beam	-912122	-868,658.72	21,746	412,889	210
593	1	24	W-beam	-621755	-578,291.17	23,667	410,968	211
3850	4	24	W-beam	-936336	-892,872.25	23,976	410,659	212
2105	5	24	W-beam	-676598	-633,134.44	29,941	404,694	213
6050	4	24	W-beam	-644058	-600,594.74	30,398	404,237	214
3924	5	24	W-beam	-713550	-670,086.81	30,543	404,092	215
3984	5	24	W-beam	-747334	-703,870.91	34,391	400,244	216
5830	1	24	W-beam	-819943	-776,479.71	40,166	394,470	217

Table 39 Continued. Ranking of State highway system Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
557	4	24	W-beam	-920081	-876,617.84	43,234	391,401	218
5929	3	24	W-beam	-785657	-742,193.53	48,286	386,349	219
1862	4	24	W-beam	-801421	-757,957.24	48,658	385,977	220
57	0	24	W-beam	-113759	-70,295.37	57,829	376,806	221
851	5	24	W-beam	-967432	-923,968.76	68,000	366,636	222
2927	2	24	W-beam	-913424	-869,960.78	111,532	323,103	223
4854	2	25	Box-beam	-1511323	-1,485,245.06	408	260,373	224
1760	0	25	Box-beam	-2528546	-2,502,468.33	427	260,354	225
3738	0	25	W-beam	-484364	-458,286.02	772	260,009	226
4766	0	25	Box-beam	-91485	-65,407.32	804	259,977	227
496	5	25	Box-beam	-103712	-77,634.28	1,121	259,660	228
59	0	25	Box-beam	-166724	-140,645.87	1,217	259,564	229
849	0	25	Box-beam	-101809	-75,731.01	1,223	259,558	230
3790	2	25	W-beam	-551752	-525,673.56	1,366	259,415	231
828	4	25	Box-beam	-405972	-379,893.58	1,636	259,145	232
7016	3	25	Box-beam	-224908	-198,829.74	1,971	258,810	233
4066	2	25	W-beam	-344829	-318,751.30	1,975	258,807	234
3591	3	25	Box-beam	-315938	-289,860.24	2,009	258,772	235
827	0	25	W-beam	-495086	-469,007.59	2,073	258,708	236
16	3	25	Box-beam	-416101	-390,022.83	2,388	258,393	237
5206	2	25	Box-beam	-162940	-136,862.22	2,499	258,282	238
490	2	25	W-beam	-420319	-394,240.55	2,591	258,190	239
2785	5	25	Box-beam	-438989	-412,910.93	2,603	258,178	240
495	4	25	W-beam	-913718	-887,639.86	2,646	258,135	241
1858	0	25	W-beam	-347974	-321,895.80	2,683	258,099	242
830	2	25	Box-beam	-174258	-148,179.90	2,870	257,911	243
5751	1	25	W-beam	-468567	-442,488.98	3,001	257,780	244
4496	2	25	Box-beam	-306204	-280,126.37	3,004	257,777	245
3992	1	25	W-beam	-586852	-560,773.75	3,004	257,777	246
1916	4	25	W-beam	-556553	-530,474.89	3,147	257,634	247
3356	2	25	W-beam	-351110	-325,032.21	3,153	257,628	248
3202	2	25	W-beam	-563971	-537,893.21	3,186	257,595	249
816	0	25	W-beam	-353237	-327,158.56	3,552	257,229	250
5208	0	25	W-beam	-506751	-480,673.13	3,620	257,161	251
52	0	25	W-beam	-330738	-304,660.28	3,806	256,975	252
857	2	25	W-beam	-269376	-243,298.20	3,818	256,964	253

Table 39 Continued. Ranking of State Highway System Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
4645	3	25	W-beam	-586160	-560,082.14	3,883	256,899	254
313	1	25	W-beam	-652074	-625,996.15	3,926	256,855	255
723	0	25	W-beam	-621324	-595,245.52	3,951	256,830	256
2659	4	25	Box-beam	-225311	-199,232.47	4,371	256,410	257
5242	3	25	Box-beam	-225722	-199,643.74	4,387	256,394	258
2511	3	25	W-beam	-594926	-568,847.96	4,520	256,261	259
6767	4	25	W-beam	-476992	-450,914.32	4,582	256,199	260
7730	3	25	Box-beam	-613542	-587,463.98	4,914	255,867	261
3604	0	25	W-beam	-213426	-187,347.85	5,140	255,641	262
8044	0	25	W-beam	-505215	-479,136.77	5,226	255,555	263
560	3	25	Box-beam	-323306	-297,227.49	5,577	255,204	264
3249	3	25	Box-beam	-515750	-489,671.73	5,776	255,005	265
6395	0	25	W-beam	-509218	-483,139.65	5,808	254,973	266
3068	1	25	Box-beam	-350031	-323,953.14	6,065	254,716	267
281	3	25	W-beam	-366767	-340,688.66	6,092	254,689	268
1857	0	25	W-beam	-570202	-544,123.75	6,335	254,446	269
6774	0	25	W-beam	-570523	-544,444.96	6,395	254,386	270
10	0	25	W-beam	-570598	-544,519.87	6,409	254,372	271
6773	0	25	W-beam	-368914	-342,835.93	6,495	254,286	272
4818	4	25	W-beam	-361759	-335,681.13	7,703	253,078	273
7162	3	25	Box-beam	-285295	-259,217.03	8,210	252,571	274
3607	4	25	W-beam	-264109	-238,030.89	8,448	252,333	275
2500	4.7	25	Box-beam	-521,781	-495,702.57	8,640	252,141	276
5952	0	25	Box-beam	-781826	-755,748.32	8,856	251,925	277
4589	3.8	25	W-beam	-635,021	-608,943.30	8,874	251,907	278
4053	0.2	25	W-beam	-535,366	-509,288.34	9,210	251,571	279
4709	2	25	W-beam	-639,492	-613,414.19	10,238	250,543	280
2792	2.9	25	W-beam	-525,395	-499,316.47	10,260	250,521	281
2390	1.7	25	W-beam	-712,183	-686,104.79	10,902	249,879	282
2414	4	25	W-beam	-471788	-445,710.04	10,954	249,827	283
4098	3.5	25	W-beam	-975,679	-949,600.73	10,986	249,795	284
3692	3.9	25	Box-beam	-406,322	-380,243.88	11,641	249,140	285
3690	3.8	25	W-beam	-600,558	-574,480.37	12,149	248,632	286
2501	4.4	25	W-beam	-593,245	-567,166.73	12,849	247,932	287
4919	2.4	25	W-beam	-472,118	-446,039.86	13,303	247,478	288
3994	1	25	W-beam	-626485	-600,407.13	14,073	246,708	289

Table 39 Continued. Ranking of State Highway System Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
5679	1.6	25	W-beam	-619,683	-593,604.82	14,116	246,665	290
4131	0	25	W-beam	-520,069	-493,991.07	15,219	245,562	291
650	0.6	25	W-beam	-590,636	-564,557.61	15,371	245,410	292
4932	0.6	25	W-beam	-629,805	-603,726.91	16,016	244,765	293
7696	1.7	25	W-beam	-509,449	-483,371.26	17,246	243,535	294
4498	2.8	25	W-beam	-732,599	-706,520.42	17,448	243,333	295
202	0	25	W-beam	-626399	-600,320.59	17,928	242,853	296
4916	0.8	25	W-beam	-640,229	-614,150.97	17,972	242,809	297
4726	0	25	W-beam	-589,503	-563,425.06	19,151	241,630	298
4727	0.5	25	W-beam	-503,498	-477,419.59	19,193	241,588	299
4728	3.7	25	W-beam	-503,618	-477,539.87	19,215	241,566	300
7772	5	25	W-beam	-887,483	-861,405.16	20,501	240,280	301
4635	0.5	25	W-beam	-590,410	-564,331.80	21,047	239,734	302
3680	3	25	W-beam	-913774	-887,695.80	23,005	237,776	303
2620	0.8	25	W-beam	-677,179	-651,101.37	24,907	235,874	304
1610	2.2	25	W-beam	-555,544	-529,465.50	25,429	235,352	305
6098	0	25	W-beam	-606,428	-580,349.59	25,435	235,346	306
5209	0.2	25	W-beam	-516,892	-490,813.71	26,093	234,688	307
20	4.9	25	W-beam	-564,448	-538,370.12	28,019	232,762	308
3158	2.9	25	W-beam	-580,768	-554,690.30	30,164	230,617	309
4723	3.6	25	W-beam	-765,334	-739,255.57	33,179	227,602	310
594	1.8	25	W-beam	-606,687	-580,608.54	35,028	225,753	311
5831	1.2	25	W-beam	-751,729	-725,651.17	37,007	223,774	312
3923	4.3	25	W-beam	-811,195	-785,117.04	40,820	219,961	313
258	4.6	25	W-beam	-753,594	-727,515.65	41,322	219,459	314
3208	5.4	25	W-beam	-648,427	-622,348.99	42,862	217,919	315
4009	1	25	W-beam	-821925	-795,846.93	50,754	210,027	316
5281	0	25	W-beam	-802,810	-776,731.85	52,181	208,600	317
3751	6	25	W-beam	-744549	-718,470.64	54,137	206,644	318
4552	4	24	W-beam	-2054656	-2,011,192.33	229,820	204,815	319
2658	3.2	25	W-beam	-746,965	-720,887.00	57,405	203,376	320
5194	4	25	W-beam	-916850	-890,772.24	60,494	200,287	321
3272	2	24	W-beam	-1174413	-1,130,949.46	243,635	191,000	322
4638	0	25	W-beam	-852,948	-826,869.50	69,949	190,832	323
2171	5.5	25	W-beam	-1,086,822	-1,060,743.57	73,193	187,588	324
2642	2.6	25	W-beam	-978,539	-952,461.13	73,194	187,587	325
259	4.8	25	W-beam	-929,815	-903,737.05	81,247	179,534	326

Table 39 Continued. Ranking of State Highway System Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
2106	2.3	25	W-beam	-567,074	-540,995.57	81,669	179,113	327
2641	4.6	25	W-beam	-864,361	-838,283.18	83,390	177,392	328
4569	3.8	25		-1,098,033	-1,071,955.32	127,246	133,535	329
4704	5	26	Box-beam	-127928	-119,235.33	904	86,023	330
2491	3	26	Box-beam	-573838	-565,145.71	1,150	85,777	331
4701	2	26	Box-beam	-275426	-266,732.96	1,841	85,086	332
2509	4	26	Box-beam	-209678	-200,985.50	2,049	84,878	333
773	5	26	Box-beam	-302118	-293,425.36	2,505	84,422	334
4115	5	26	Box-beam	-760868	-752,175.52	2,522	84,405	335
1764	0	26	Box-beam	-1205896	-1,197,203.33	2,722	84,205	336
5390	3	26	Box-beam	-302147	-293,454.63	3,693	83,234	337
921	3	26	W-beam	-404411	-395,718.54	3,765	83,162	338
2643	0	26	W-beam	-311421	-302,728.57	3,947	82,981	339
516	5	26	Box-beam	-414521	-405,828.64	4,329	82,598	340
4063	4	26	Box-beam	-312756	-304,063.11	4,351	82,576	341
275	0	26	Box-beam	-594667	-585,974.31	4,722	82,205	342
2484	0	26	W-beam	-692732	-684,039.11	5,285	81,642	343
274	0	26	Box-beam	-614035	-605,342.67	5,744	81,183	344
1766	0	26	Box-beam	-842252	-833,558.84	5,837	81,090	345
1982	4	26	Box-beam	-414059	-405,366.38	6,207	80,720	346
848	3	26	Box-beam	-398436	-389,742.91	6,682	80,245	347
3875	0	26	W-beam	-435104	-426,411.07	6,761	80,166	348
1717	2	26	Box-beam	-575983	-567,289.91	6,895	80,032	349
3635	4	26	Box-beam	-383484	-374,791.52	7,077	79,850	350
554	4	26	W-beam	-483172	-474,479.62	12,536	74,391	351
3922	4	26	Box-beam	-545421	-536,728.55	12,720	74,207	352
7499	4	26	W-beam	-506455	-497,762.08	15,357	71,570	353
5592	3	26	W-beam	-487539	-478,845.83	16,619	70,308	354
6054	2	26	W-beam	-221912	-213,218.91	16,690	70,237	355
3734	6	26	W-beam	-648916	-640,222.82	17,255	69,672	356
4416	3	26	W-beam	-867763	-859,070.01	17,632	69,295	357
4114	3	26	W-beam	-1027971	-1,019,278.74	25,504	61,423	358
3854	2	26	W-beam	-794653	-785,960.29	26,107	60,820	359
413	4	26	Box-beam	-789897	-781,204.12	28,177	58,750	360
168	3	26	W-beam	-321686	-312,993.07	30,613	56,314	361

Table 39 Continued. Ranking of State Highway System Barriers According to Total Benefits

Barrier ID	Shoulder Width	Barrier Height	Type of Barrier	Predicted Crash Cost (No Height Adjustment)	Predicted Crash Cost (Height Adjusted)	Barrier Height Change Cost ($)	Benefit in 10 Years ($)	Ranking
3749	2	26	W-beam	-743936	-735,242.96	35,088	51,839	362
6999	4	26	W-beam	-79415	-70,722.05	35,672	51,255	363
1705	4	26	W-beam	-808607	-799,914.59	36,393	50,534	364
3995	5	26	W-beam	-622131	-613,438.28	38,716	48,211	365
3706	4	26	W-beam	-755086	-746,393.80	38,917	48,010	366
1096	3	26	W-beam	-734116	-725,422.95	40,834	46,093	367
4733	2	26	W-beam	-556686	-547,993.39	44,914	42,013	368
3843	5	26	W-beam	-1069471	-1,060,778.07	51,443	35,484	369
6033	4	26	W-beam	-847173	-838,479.81	62,353	24,575	370

Table 40 Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
109	4	0	0	97	10.8	1.3	327,485	1
575	4	0	0	102	10.8	1.3	327,433	2
576	2	1	0	169	10.8	1.3	326,740	3
112	3	0	0	361	10.8	1.3	324,728	4
1048	4	0	0	64	10.5	1.3	316,254	5
1047	4	0	0	65	10.5	1.3	316,243	6
2745	3	7	0	461	10.5	1.3	313,653	7
2745	3	7	0	461	10.5	1.3	313,653	8
15	3	0	0	364	3.7	1.3	78,985	9
5200	3	0	12	2087	4.2	1.3	77,829	10
7771	0	0	14	124	3.6	1.4	76,948	11
5454	3	0	14	631	3.7	1.4	73,261	12
5202	4	0	14	201	3.5	1.3	72,974	13
5198	4	0	14	725	3.5	1.3	67,499	14
4739	4	2	18	169	3.9	1.9	65,480	15
4573	0	0	16	201	3.0	1.3	59,391	16
5197	4	0	16	913	3.2	1.3	54,857	17
5462	2	0	17	338	3.1	1.4	54,605	18
5201	4	0	17	201	2.9	1.3	52,565	19
3614	1	0	17	127	2.8	1.3	51,256	20
5199	3	0	17	537	2.9	1.3	49,048	21
1205	2	0	18	159	2.8	1.4	46,065	22
5204	4	0	18	249	2.6	1.3	43,183	23
3615	1	0	18	126	2.5	1.3	42,726	24
5205	3	0	18	300	2.6	1.3	42,657	25
852	2	0	18	324	2.7	1.3	42,606	26
62	3	0	18	338	2.6	1.3	41,735	27
4572	0	0	18	202	2.5	1.3	41,617	28
3678	4	9	20	214	3.1	1.9	40,736	29
21	1	0	18	299	2.5	1.3	40,553	30
818	0	0	18	800	2.6	1.3	36,364	31
693	1	0	19	102	2.4	1.3	36,059	32
90	1	0	19	75	2.3	1.3	35,019	33
5455	3	0	19	501	2.6	1.4	34,862	34
825	1	0	19	213	2.4	1.3	34,597	35
64	1	0	19	274	2.4	1.3	34,404	36

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement in 10 years	EPDO with Enhancement in 10 years	Total Benefit in 10 Years ($)	Rank
824	0	0	19	237	2.4	1.3	34,341	37
3847	3	1	19	1834	3.4	1.9	34,253	38
821	1	0	19	326	2.4	1.3	33,416	39
4847	0	0	19	315	2.3	1.3	33,163	40
2001	3	0	19	299	2.3	1.3	32,896	41
4475	1	0	19	326	2.3	1.2	32,285	42
4476	0	0	19	327	2.3	1.2	32,274	43
2096	3	0	19	476	2.3	1.3	31,457	44
5453	3	1	19	901	2.6	1.4	30,682	45
826	0	0	19	612	2.4	1.3	30,420	46
6894	4	0	22	127	2.7	1.8	30,000	47
3981	0	0	19	637	2.3	1.2	29,026	48
6239	3	0	22	139	2.6	1.7	28,889	49
5723	2	6	22	134	2.6	1.7	28,842	50
5723	2	0	22	134	2.6	1.7	28,842	51
6894	4	0	22	127	2.6	1.7	28,805	52
500	2	0	20	428	2.4	1.4	28,505	53
4474	1	0	19	690	2.3	1.2	28,482	54
95	1	0	20	73	2.1	1.3	28,034	55
492	2	0	20	528	2.4	1.4	27,459	56
366	0	4	20	257	2.2	1.3	27,084	57
819	0	0	20	251	2.1	1.3	26,997	58
4571	0	0	18	1625	2.5	1.3	26,744	59
820	2	0	20	276	2.1	1.3	26,739	60
5196	3	1	19	1062	2.4	1.3	26,600	61
5446	5	0	20	572	2.3	1.4	26,277	62
4846	0	0	20	315	2.1	1.3	26,029	63
5203	3	0	20	425	2.2	1.3	25,891	64
22	1	0	20	321	2.1	1.3	25,575	65
4882	4	0	20	590	2.2	1.3	24,571	66
901	4	0	22	113	2.2	1.4	24,220	67
53	4	0	20	572	2.2	1.3	24,005	68
4497	1	0	20	464	2.1	1.2	23,862	69
4110	3	4	23	100	2.6	1.9	23,725	70
7773	0	0	22	124	2.1	1.4	23,303	71
2084	0	0	22	15	2.0	1.3	22,914	72

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
2767	0	0	22	64	2.0	1.3	22,441	73
2245	3	0	20	687	2.1	1.3	22,294	74
4415	2	0	23	239	2.6	1.9	22,271	75
694	0	0	22	98	2.0	1.3	22,223	76
220	0	0	22	98	2.0	1.3	22,220	77
796	1	1	22	87	1.9	1.3	21,503	78
822	0	0	22	163	2.0	1.3	21,347	79
493	4	0	22	427	2.2	1.4	21,209	80
5852	4	0	23	196	2.4	1.8	21,149	81
823	0	0	22	188	2.0	1.3	21,087	82
4097	0	0	23	184	2.4	1.7	21,038	83
499	2	0	22	477	2.2	1.4	20,681	84
2038	5	0	22	228	1.9	1.3	20,322	85
2244	5	0	22	252	1.9	1.3	20,311	86
5852	4	0	23	196	2.3	1.7	20,263	87
4722	2	0	22	205	1.9	1.2	20,223	88
367	1	0	22	306	2.0	1.3	19,971	89
3877	1	0	23	485	2.6	1.9	19,702	90
1365	2	278	22	492	2.1	1.4	19,646	91
491	2	0	22	627	2.2	1.4	19,116	92
6059	4	0	22	451	2.0	1.3	19,050	93
4881	4	0	22	565	2.1	1.4	18,700	94
892	5	0	23	115	2.0	1.4	17,604	95
5371	5	0	23	48	1.9	1.4	17,481	96
2639	2	0	22	538	1.9	1.3	17,028	97
3993	4	2	22	634	2.0	1.3	16,922	98
4736	0	0	23	76	1.8	1.3	16,366	99
219	1	0	23	93	1.8	1.3	16,242	100
4853	2	31	24	39	2.3	1.8	16,206	101
6969	5	0	23	115	1.8	1.3	16,006	102
2646	1	0	23	78	1.8	1.3	15,963	103
501	1	0	23	314	2.0	1.4	15,724	104
4065	0	0	23	100	1.7	1.3	15,595	105
4104	0	0	24	15	2.2	1.7	15,313	106
842	2	0	22	820	2.0	1.3	15,143	107
2481	0	0	23	295	1.9	1.4	15,139	108
60	1	0	23	254	1.8	1.3	14,626	109
4536	2	1	24	228	2.4	1.9	14,470	110

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
4724	3	0	23	200	1.7	1.2	14,469	111
498	2	1	22	1088	2.2	1.4	14,300	112
5207	2	0	22	899	2.0	1.3	14,211	113
61	5	0	23	296	1.8	1.3	14,184	114
6864	5	0	24	190	2.2	1.8	13,795	115
2243	4	0	23	315	1.8	1.3	13,699	116
1055	5	0	23	350	1.8	1.3	13,593	117
5830	4	0	24	215	2.2	1.8	13,540	118
4066	0	0	24	325	2.4	1.9	13,463	119
421	2	0	23	467	1.9	1.4	13,340	120
420	2	0	23	468	1.9	1.4	13,329	121
6864	5	0	24	190	2.1	1.7	13,193	122
5830	4	0	24	215	2.1	1.7	12,938	123
28	4	0	24	213	2.1	1.7	12,842	124
434	3	1	23	571	2.0	1.4	12,810	125
3738	2	0	24	252	2.1	1.7	12,672	126
5465	4	1	22	1201	2.1	1.4	12,559	127
5065	4	0	24	307	2.2	1.7	12,521	128
3829	3	14	24	206	2.1	1.6	12,515	129
898	3	3	23	488	1.8	1.3	12,397	130
3850	4	5	24	471	2.4	1.9	11,930	131
6789	0	0	24	46	1.7	1.4	11,912	132
6790	0	0	24	56	1.7	1.4	11,816	133
1761	0	0	24	58	1.7	1.4	11,796	134
562	4	0	24	315	2.1	1.7	11,781	135
4888	0	1	24	98	1.8	1.4	11,753	136
1364	1	0	24	110	1.7	1.4	11,340	137
5929	2	0	24	215	1.9	1.5	11,321	138
5929	2	5	24	215	1.9	1.5	11,321	139
1859	2	1	22	1204	2.0	1.3	11,124	140
3069	0	2	22	1267	2.1	1.4	11,087	141
4634	4	0	24	27	1.6	1.3	11,056	142
2765	0	0	24	65	1.6	1.3	10,965	143
3078	3	0	24	133	1.7	1.4	10,872	144
267	4	0	23	609	1.8	1.3	10,855	145
4767	0	0	24	74	1.6	1.3	10,814	146
4640	0	0	24	113	1.7	1.3	10,794	147
4632	2	0	24	64	1.6	1.3	10,670	148

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
3617	0	0	24	75	1.6	1.3	10,662	149
6771	3	0	24	279	1.9	1.5	10,655	150
6771	3	1	24	279	1.9	1.5	10,655	151
2645	1	0	24	78	1.6	1.3	10,599	152
2664	1	0	24	78	1.6	1.3	10,597	153
593	4	0	24	202	1.8	1.4	10,561	154
711	4	0	23	639	1.8	1.3	10,543	155
6459	4	1	24	263	1.8	1.5	10,478	156
4029	2	1	23	586	1.7	1.2	10,423	157
3605	0	0	23	595	1.7	1.3	10,421	158
89	1	1	24	103	1.6	1.3	10,406	159
6055	2	0	24	161	1.7	1.3	10,293	160
303	0	5	24	102	1.6	1.3	10,256	161
301	0	1	24	103	1.6	1.3	10,253	162
5448	4	1	23	804	1.9	1.4	10,194	163
2095	1	0	23	650	1.8	1.3	10,096	164
496	5	0	24	276	1.8	1.4	10,051	165
2632	5	0	24	166	1.6	1.3	9,989	166
2631	3	0	24	166	1.6	1.3	9,987	167
3611	4	0	22	1263	1.9	1.3	9,509	168
4822	3	0	24	214	1.6	1.3	9,503	169
4824	4	0	24	214	1.6	1.3	9,501	170
57	3	0	24	223	1.6	1.3	9,425	171
490	3	0	24	376	1.9	1.5	9,403	172
3254	3	0	24	227	1.6	1.3	9,249	173
3318	1	4	24	216	1.6	1.3	9,195	174
4854	2	8	25	39	2.1	1.8	9,094	175
495	2	0	24	377	1.8	1.4	8,996	176
3253	3	0	24	256	1.6	1.3	8,945	177
224	1	0	24	249	1.6	1.3	8,905	178
585	1	1	24	250	1.6	1.3	8,898	179
4008	3	0	23	823	1.8	1.3	8,842	180
59	3	0	24	282	1.6	1.3	8,809	181
5751	4	0	24	427	1.8	1.5	8,655	182
414	4	0	24	293	1.6	1.3	8,628	183
6395	4	0	25	52	2.0	1.7	8,457	184
5751	4	0	24	427	1.8	1.4	8,423	185
7016	2	0	24	315	1.6	1.3	8,423	186

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
828	1	0	24	313	1.6	1.3	8,342	187
3591	3	0	24	327	1.6	1.3	8,286	188
4098	0	0	25	78	2.0	1.7	8,127	189
6395	4	0	25	52	1.9	1.7	8,117	190
149	0	0	24	329	1.6	1.3	8,112	191
3790	0	0	24	311	1.6	1.3	8,032	192
5206	4	0	24	375	1.7	1.3	7,981	193
827	0	0	24	352	1.6	1.3	7,939	194
281	0	0	25	53	1.8	1.6	7,603	195
16	2	0	24	364	1.6	1.3	7,541	196
1366	1	0	24	483	1.7	1.4	7,440	197
5242	4	0	25	157	2.0	1.8	7,432	198
830	0	0	24	401	1.6	1.3	7,311	199
4809	4	2	25	259	2.2	1.9	7,105	200
5242	4	0	25	157	1.9	1.7	7,082	201
5831	4	0	25	216	2.0	1.8	6,912	202
1760	0	8	25	41	1.6	1.4	6,884	203
3158	2	0	25	201	2.0	1.7	6,830	204
5044	4	0	25	213	2.0	1.7	6,774	205
5052	3	1	25	201	2.0	1.7	6,771	206
6767	2	0	25	39	1.6	1.4	6,686	207
8044	3	0	25	229	2.0	1.7	6,623	208
5054	4	7	25	201	1.9	1.7	6,565	209
5831	4	0	25	216	2.0	1.7	6,547	210
6774	1	0	25	59	1.6	1.4	6,476	211
6773	1	0	25	59	1.6	1.4	6,475	212
7162	2	0	25	62	1.6	1.4	6,444	213
4496	1	0	24	465	1.6	1.2	6,400	214
2500	0	0	25	70	1.6	1.4	6,362	215
2105	5	1	24	588	1.7	1.4	6,350	216
857	0	0	25	15	1.4	1.3	6,295	217
2390	1	0	25	77	1.6	1.4	6,286	218
8044	3	0	25	229	1.9	1.7	6,281	219
3249	2	0	25	51	1.5	1.3	6,255	220
2659	2	0	25	27	1.5	1.3	6,249	221
1995	1	0	23	1001	1.7	1.3	6,240	222
1765	0	1	24	630	1.8	1.4	6,196	223
7730	3	0	25	192	1.8	1.6	6,185	224

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
2501	3	0	25	89	1.6	1.4	6,164	225
4919	4	0	25	90	1.6	1.4	6,151	226
3604	0	0	25	41	1.4	1.3	6,051	227
7730	3	0	25	192	1.8	1.5	5,960	228
3607	2	0	25	63	1.5	1.3	5,891	229
2792	3	0	25	76	1.5	1.3	5,864	230
4818	4	0	25	62	1.4	1.3	5,854	231
1610	4	0	25	166	1.7	1.5	5,841	232
4916	3	0	25	120	1.6	1.4	5,841	233
4766	0	1	25	77	1.5	1.3	5,825	234
843	2	0	23	1126	1.8	1.3	5,793	235
4053	0	0	25	75	1.5	1.3	5,764	236
7772	0	0	25	128	1.6	1.4	5,758	237
4589	0	0	25	71	1.4	1.3	5,755	238
6050	4	1	24	597	1.7	1.3	5,731	239
4709	2	0	25	75	1.4	1.3	5,702	240
4131	0	0	25	101	1.5	1.3	5,687	241
3992	5	0	24	600	1.7	1.3	5,596	242
4645	5	0	25	107	1.5	1.3	5,509	243
5679	3	0	25	470	2.3	2.0	5,439	244
313	0	0	25	116	1.5	1.3	5,420	245
723	0	0	25	117	1.5	1.3	5,413	246
650	0	0	25	103	1.4	1.2	5,362	247
2511	3	0	25	189	1.6	1.4	5,338	248
4635	4	0	25	151	1.5	1.3	5,267	249
4498	0	0	25	114	1.4	1.2	5,248	250
4726	0	0	25	124	1.4	1.3	5,179	251
4727	0	0	25	126	1.4	1.3	5,167	252
4728	0	0	25	126	1.4	1.3	5,164	253
2414	4	3	25	215	1.6	1.4	5,062	254
594	2	0	25	214	1.6	1.4	5,010	255
2622	4	0	24	635	1.6	1.3	5,001	256
5209	4	0	25	174	1.5	1.3	4,982	257
3680	3	1	25	452	2.1	1.9	4,917	258
5679	3	0	25	470	2.2	1.9	4,889	259
3984	5	4	24	676	1.7	1.3	4,806	260
258	4	0	25	239	1.6	1.4	4,754	261
20	0	0	25	181	1.4	1.3	4,599	262

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
3722	5	0	25	403	1.9	1.7	4,362	263
4723	3	0	25	202	1.4	1.2	4,340	264
560	2	0	25	239	1.5	1.3	4,317	265
202	0	15	25	352	1.8	1.5	4,244	266
3208	4	0	25	252	1.5	1.3	4,149	267
5281	2	0	25	261	1.5	1.3	3,967	268
1857	2	0	25	275	1.5	1.3	3,964	269
3994	1	1	25	277	1.5	1.3	3,899	270
10	2	0	25	287	1.5	1.3	3,812	271
4638	0	0	25	299	1.5	1.3	3,724	272
259	2	0	25	339	1.6	1.4	3,707	273
1916	1	0	24	789	1.7	1.3	3,657	274
2658	2	0	25	277	1.5	1.3	3,631	275
2106	3	0	25	343	1.6	1.4	3,566	276
2171	1	0	25	302	1.5	1.3	3,475	277
4220	3	1	25	338	1.5	1.3	3,298	278
2642	1	0	25	315	1.5	1.3	3,241	279
6012	0	0	24	881	1.7	1.4	3,191	280
557	4	5	24	850	1.7	1.3	3,121	281
2641	1	0	25	353	1.5	1.3	2,839	282
5276	1	0	25	377	1.5	1.3	2,758	283
5275	4	0	25	378	1.5	1.3	2,753	284
4569	0	0	25	376	1.4	1.3	2,565	285
3692	4	0	25	418	1.5	1.3	2,542	286
3690	3	0	25	420	1.5	1.3	2,527	287
4491	1	0	25	414	1.4	1.2	2,119	288
1860	2	0	24	945	1.7	1.3	2,071	289
7696	3	2	25	553	1.7	1.5	1,988	290
7696	3	0	25	553	1.7	1.5	1,988	291
3202	4	0	24	956	1.7	1.3	1,874	292
4932	3	0	25	534	1.6	1.4	1,782	293
3356	3	0	24	949	1.6	1.3	1,701	294
3924	5	0	24	995	1.7	1.3	1,603	295
4960	8	0	1	96	1.5	1.4	1,525	296
4960	8	1	1	96	1.5	1.4	1,525	297
6511	4	0	26	167	2.1	2.0	1,520	298
66	2	0	25	500	1.5	1.3	1,505	299
4880	4	0	26	199	2.3	2.2	1,504	300

Table 40 Continued. Ranking of all State Barriers According to Total Benefits

Barrier ID	Shoulder Width	Current EPDO	Barrier Height	Length of Barrier (ft)	EPDO with No Enhancement	EPDO with Enhancement	Total Benefit in 10 Years ($)	Rank
2665	1	0	25	489	1.5	1.3	1,415	301
921	3	1	26	74	1.3	1.3	1,337	302
6540	4	1	26	170	2.0	1.9	1,317	303
2643	0	1	26	78	1.3	1.3	1,266	304
2484	0	2	26	104	1.5	1.4	1,240	305
311	0	0	25	500	1.4	1.3	1,225	306
6948	3	0	26	140	1.7	1.6	1,145	307
93	0	0	25	513	1.4	1.3	1,104	308
3986	5	0	25	551	1.5	1.3	1,035	309
3068	1	9	25	580	1.6	1.4	997	310
6909	3	1	26	169	1.8	1.7	994	311
6863	4	0	26	190	1.9	1.8	934	312
5088	3	0	26	192	1.9	1.8	928	313
2491	3	1	26	110	1.3	1.2	898	314
5698	5	1	26	181	1.8	1.7	883	315
5855	5	0	26	196	1.9	1.8	865	316
5217	2	0	26	204	1.8	1.8	753	317
1862	3	0	24	1072	1.7	1.3	746	318
5042	4	0	26	211	1.9	1.8	729	319
3875	0	4	26	133	1.3	1.3	662	320
5945	4	6	25	663	1.7	1.5	642	321
6504	5	0	26	256	2.1	2.0	595	322
4115	5	13	26	241	2.0	1.9	544	323
50	3	0	25	593	1.5	1.3	533	324
5840	3	0	26	226	1.8	1.8	510	325
5064	4	0	25	836	2.1	1.8	504	326
5930	2	0	26	203	1.7	1.6	488	327
4335	3	2	25	674	1.7	1.5	462	328
6493	3	8	26	261	2.0	1.9	391	329
5833	3	0	26	238	1.8	1.8	380	330
4701	2	1	26	176	1.4	1.3	368	331
6499	2	1	26	267	2.0	1.9	310	332
2509	4	4	26	196	1.5	1.4	276	333
6407	2	1	26	281	2.0	1.9	192	334
3321	8	0	23	20	0.9	0.9	45	335
3322	8	0	23	20	0.9	0.9	43	336
7196	4	5	26	229	1.5	1.5	20	337
6505	4	4	26	229	1.5	1.5	9	338