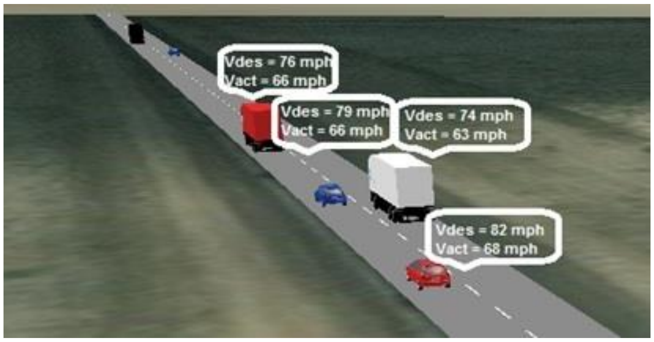
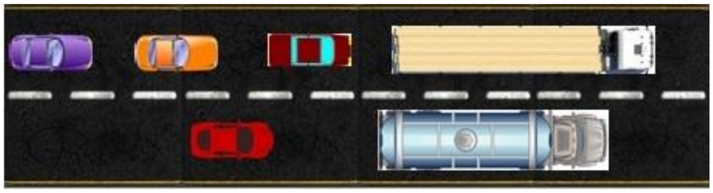
FINAL REPORT WY-2002F

SAFETY AND OPERATIONAL ANALYSIS WITH MITIGATION STRATEGIES FOR FREEWAY TRUCK TRAFFIC IN WYOMING





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16. Abstract

Interstate 80, in Wyoming, is characterized by heavy truck traffic, with an average of 47 percent of heavy trucks in the traffic flow. Trucks have significantly different physical and driving characteristics than passenger cars, especially on grades, which has impacts on operational efficiency and safety. The presence of heavy vehicles reduces the capacity of freeway segments, with the reduction being more significant along specific grades. This study explores safety and operational performance along I-80, with a focus on the benefits of climbing lanes along steep grades. Crash rate analysis indicated that the truck crash rates are higher than all vehicle crash rates. The analysis of major contributing factors showed that 54 percent of truck crashes occurred during icy road condition, snowy weather condition contributed to about 46 percent, and driving too fast and driving in improper lane contributed to approximately 45 percent of total truck related crashes. The maximum percentage of truck crashes occurred within a 4000-6000 ft curve radius range, however, this was not found to be significant. The results show that the addition of climbing lanes reduces delays and increases overall traffic speeds on upgrades, and can reduce the total crashes and truck-related crashes 6 to 34 percent, and 1 to 16 percent, respectively, depending on the analyzed location and applied methodology. The 20-year benefit-cost ratio for climbing lanes installation was found to be between 2 and 11, depending on the location. The majority of fatal crashes on I-80 occurred in car-truck collisions. Impaired driving, use of alcohol or illegal drugs, not using seatbelts, fatigue and dangerous driving were found to increase the injury severity significantly. A large portion of truck-related crashes had tire failure as the main contributing factor.

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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 ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
CARE	Critical Analysis Reporting Environment
CL	Climbing Lane
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
DOT	Department of Transportation
EB	Empirical Bayes
FARS	Fatality Analysis of Reporting System
FENB	Fixed Effect Negative Binomial
FHWA	Federal Highway Administration
F+I	Fatal plus Injury
FMCSA	Federal Motor Carrier Safety Administration
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
I-80	Interstate 80
LOS	Level of Service
MP	Mile Post
MTC	Multiple Truck Crashes
MVMT	Million Vehicle Miles Traveled
NB	Negative Binomial
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
ODP	Overdispersion Parameter
PDO	Property Damage Only
RAD	Horizontal Curve Radius
RDP	Roadway Data Portal
RENB	Random Effect Negative Binomial
RR	Relative Risk
RTM	Regression-to-the-Mean
SAS	Statistical Analysis Software
SD	Standard Deviation
SPF	Safety Performance Function
STC	Single Truck Crashes
TMT	Truck Miles Traveled
TRB	Transportation Research Board
TTC	Total Truck Related Crashes
USDOT	United States Department of Transportation
VG	Vertical Grade

VMS	Variable Message Sign
VMT	Vehicles Miles Travelled
VSL	Variable Speed Limit
WYDOT	Wyoming Department of Transportation
ZINB	Zero-Inflated Negative Binomial
ZIP	Zero-Inflated Poisson

EXECUTIVE SUMMARY

The goal of this study is to quantify impacts of truck traffic on selected freeway segments along Interstate 80 (I-80), in Wyoming, and discuss potential mitigation strategies through analyses of safety and operational implications that result from the interactions between trucks and passenger vehicles. Special attention is given to the roadway geometry (horizontal and vertical alignment, climbing lanes) and traffic characteristics to identify impacts on traffic efficiency and safety. The State of Wyoming road network is characterized by heavy truck traffic. In 2016, truck traffic comprised approximately of 21 percent of the vehicle miles traveled (VMTs) along all routes in Wyoming, according to the Wyoming Department of Transportation (WYDOT) annual traffic report (ATR). The heaviest truck traffic exists along I-80, with about 47 percent truck VMTs. Trucks have significantly different physical and driving characteristics than passenger cars, especially on grades, which have impacts on operational efficiency, safety and pavement deterioration. The presence of heavy vehicles reduces the capacity of freeway segments, with the reduction being more significant along specific grades. Trucks generally decrease speed by more than seven percent on upgrades, as compared to their operation on level terrains, according to the Highway Capacity Manual (HCM). The maximum speed that can be maintained by trucks on upgrades primarily depends on the length and steepness of the grade, as well as the truck's weight-to-power ratio. On the other hand, the operation of passenger vehicles is less impacted by the grade. This leads to variations in speeds between trucks and passenger vehicles, with more complex interactions between the two types.

About nine percent of I-80, in Wyoming, in both directions, is within vertical grades of more than three percent, where certain sections reach grades of close to seven percent. These grades can cause significant truck speed reduction on upgrades, leading to a large speed difference between trucks and passenger cars. There is also a significant speed difference between trucks, depending on their loads and weight-to-power ratio, so it is a common occurrence that trucks pass each other using the left lane. This causes a queue buildup behind the slower moving trucks in both lanes, significantly deteriorating traffic conditions.

The analysis of major crash contributing factors showed that 54 percent of truck crashes occurred during icy road condition, snowy weather condition contributed about 46 percent, and driving too fast and driving in improper lane contributed to approximately 45 percent of total truck related crashes. The maximum percentage of truck crashes occurred within 4000-6000 ft curve radius range, however, this was not found to be significant. The results show that the addition of climbing lanes reduces delays and increases overall traffic speeds on upgrades, and can reduce the total and truck-related crashes 6 to 34 percent, and 1 to 16 percent, respectively, depending on the analyzed location and applied methodology. The majority of fatal crashes on I-80, in Wyoming, occurred in car-truck collisions. Impaired driving, use of alcohol, or illegal drugs, not using seatbelts, fatigue and dangerous driving were found to increase the injury severity significantly. A large portion of truck-related crashes had tire failure as the main contributing factor.

The operational analysis of freeway climbing lanes under heavy truck traffic was performed through microsimulation. Ten segments along I-80, in Wyoming, (each containing a section with an existing climbing lane and a section with a proposed climbing lane as an improvement alternative) were modeled, and performance measures associated with these segments were collected to evaluate the climbing lane efficiency. Microsimulation models were developed for both current (year 2017) and future (year 2027 and 2037) traffic conditions. The performance measures (total delays, average speeds and vehicle spacing) were extracted for the peak hours (3:00 p.m. – 5:00 p.m.) to analyze and compare the existing and future traffic conditions. It was found that the installation of climbing lanes has the potential to improve operational performances for a 10 and 20-year planning horizon. Space headway of vehicles was found higher when traveling through climbing lane segments compared to the segments without climbing lanes, which has the potential to benefit both traffic operations and safety. It was also found that the operational performance of passenger cars was significantly improved with the installation of climbing lanes for the future year scenarios. The 20-year benefit-cost ratio for climbing lanes installation, based on operational and safety improvements, was found to be between 2 and 11, depending on the location. The benefits included travel time savings, emission reductions and crash cost reductions, while costs included construction and maintenance costs for the potential climbing lane locations.

1. INTRODUCTION

Trucking is an indispensable component of any country's prospering and growing economy. It is the foundation of many logistic and supply-chain network. The State of Wyoming is experiencing a high percentage of truck traffic along all highways, especially I-80 through Wyoming, because of an expansion in oil and gas production. Interstate 80 was designed and constructed 60 years ago, and at the time such high truck traffic was not anticipated. The increased interactions between trucks and other vehicles have raised many operational and safety concerns along I-80.

In 2015, truck traffic comprised approximately 22 percent of the VMTs along all routes in Wyoming, according to the WYDOT ATR. The heaviest truck traffic exists along I-80, with about 47 percent truck VMTs. Trucks have significantly different physical and driving characteristics than passenger cars, especially on grades, which have impacts on operational efficiency, safety and pavement deterioration. The presence of heavy vehicles reduces the capacity of freeway segments, with the reduction being more significant along specific grades. Trucks generally decrease speed by more than seven percent on upgrades, as compared to their operation on level terrains, according to the Highway Capacity Manual (HCM) 2010. The maximum speed that can be maintained by trucks on upgrades primarily depends on the length and steepness of the grade, as well as the truck's weight-to-power ratio. On the other hand, the operation of passenger vehicles is much less impacted by the grade. This leads to variations in speeds between trucks and passenger vehicles, with more complex interactions between the two types.

The trucking industry continues to contribute significantly to the economy of the United States. Although leading to economic growth, these developments have led to a sharp increase in the proportion of freight traffic along key routes, many of which pass through rural areas. As one example, I-80 forms a major corridor for transporting goods between the west coast and major cities in the east. This facility carries a heavy truck traffic proportion, ranging from 40 percent in urban areas, to 60 percent in rural areas. These increases in heavy truck traffic on the nation's highways have raised concerns about safety, particularly on the Interstate system.

1.1. Operational and Safety Implications of Truck Traffic

Passenger cars can negotiate upgrades of four to five percent without a noticeable loss in speeds maintained on level roadways. On the other hand, the performance of trucks is greatly affected by vertical grades. Trucks start losing their speeds at freeway grades of about one percent. Trucks generally decrease speed by more than seven percent on upgrades as compared to their operation on level terrains. The reduction in truck speeds depends on the rate and length of grades. This causes a lot of friction between passenger cars and trucks on upgrades, with a noticeable difference in speeds. Also, because of the high truck percentage, it is very common for trucks to use the left lane, which causes a queue buildup behind them and leads to deteriorated traffic conditions.

About eight percent of I-80, in Wyoming, in both directions is within vertical grades of more than three percent, where certain sections reach grades of close to seven percent. These grades can cause significant truck speed reduction on upgrades, leading to a large speed difference between trucks and passenger cars. There is also a significant speed difference between trucks, depending on their loads and weight-to-power ratio, so it is a common occurrence that trucks pass each other using the left lane, as illustrated in figure 1.1. This causes a queue buildup behind the slower moving trucks in both lanes, significantly deteriorating traffic conditions.

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Figure 1.1. Screenshot. Trucks passing and occupying left lane.

Therefore, the presence of heavy truck traffic, along with vertical upgrades degrades, the operational performance of the roadway system. Many researchers and practitioners recommend different control strategies that can be implemented in order to improve operational and safety performance due to the presence of heavy truck traffic. Some of these strategies and improvements may include introducing differential truck adding climbing lanes, speed limits, truck lane restrictions, introducing no-passing zones for trucks, changes in horizontal and/or vertical features of the road, changes in cross section, changes in roadside, and installation or update of safety devices (guardrails, delineators, chevrons, speed advisory signs, pavement markings and similar).

Truck safety has significant implications to motorists, transportation agencies, industry and the general public. Safety is a major consideration for the trucking industry. Of the approximately 415,000 police-reported crashes involving large trucks in 2015 in the United States, there were 3,598 fatal crashes and 83,000 injury crashes. The correlation between the percentage of large trucks and crash rates on the transportation facilities should be of particular concern to state DOT engineers. This especially applies to WYDOT that operates facilities with large percentages of trucks on roads, such as I-80. During the nine year period (2008 – 2016), close to 4,800 truck-related crashes occurred on I-80, in Wyoming (on average, 530 truck-related crashes each year), which speaks about the importance of the truck safety problems on this corridor. Due to the nature of traffic along I-80, the operational performance is closely related to the safety performance. Because of this, the two analyses will complement each other. The most common contributing factors for the truck-related crashes include road condition, weather condition, driver condition, driver action, and crash types.

1.2. Study Objectives and Methodology

This study analyzes the impacts of truck traffic on selected freeway segments along I-80, in Wyoming, as well as mitigation strategies to minimize negative impacts (with a focus on climbing lanes), through analyses of operational and safety implications that result from the interactions between trucks and passenger vehicles. The operational analysis was performed through microsimulation modeling for the current and future traffic conditions along selected freeway segments of I-80, in Wyoming. Based on these results, the study also developed a shock-wave methodology for a quick estimation of freeway conditions. The main objective of the safety analysis is to explore the effectiveness of climbing lanes and calibrate Crash Modification Factors (CMFs) and Relative Risk (RR) for climbing lanes along I-80, in Wyoming, using cross-sectional analysis and propensity scores-potential outcomes framework, respectively. To achieve the aforementioned objective, four main tasks were carried out in this study. The first task concentrates on developing a comprehensive database for I-80, in Wyoming. This was achieved by integrating historical traffic crash information, traffic volumes, weather characteristics, and roadway geometry information. The next task was to calibrate Wyoming-specific Safety Performance Functions (SPFs) for I-80 to perform cross-sectional analysis, since the installation dates for climbing lanes and before data are not available for conducting the before-after analysis with Empirical Bayes (EB). Negative Binomial (NB) and Zero-Inflated Negative Binomial (ZINB) modeling were utilized to develop crash prediction models. The third task was to develop a propensity score model that estimates the probabilities of a crash within a section with and without CLs. The final task was to quantify the safety effectiveness of climbing lanes using both cross-sectional analysis and propensity scores-potential outcomes framework. Based on the analysis, recommendations can be made to enhance truck safety.

Findings from this study are expected to help transportation managers and policy makers to take necessary actions, and decide on management strategies for highway facilities carrying a large percentage of trucks. The benefits for WYDOT, as well as other agencies that face similar problems on their freeway network, are in the detailed assessment of traffic conditions along the corridor, as well as the timeline of improvements that would create most benefits as the traffic increases in the future years.

2. DESCRIPTIVE SAFETY STATISTICS FOR FREEWAY TRUCK TRAFFIC ON I-80

This chapter presents a descriptive safety statistics for I-80, in Wyoming, with a special focus on truck traffic. A truck-related crash is defined as any crash that includes at least one light, medium, or heavy truck. A light truck is considered to weigh less than 10,000 pounds, a medium truck between 10,000 pounds and 26,000 pounds, and a heavy truck is more than 26,000 pounds (Spiegelhalter et al. 2002).

WYDOT performs a statewide traffic data collection using different fixed and portable programmed traffic counter stations. These counters record traffic information, which is presented in the Automatic Traffic Recorder Report (WYDOT 2016), issued monthly and yearly by the WYDOT Planning Office. The information usually incorporates the counter's area, the Average Daily Traffic (ADT) and VMTs. The VMT information is a critical component in registering the percentage of truck and crash rates. For this research, I-80, in Wyoming, was divided into 20 sections, each approximately 20 miles in length. The length of I-80 running through Wyoming is 402.78 miles, and there are 192 recording locations, in both directions.

Crash data and the accompanying information were acquired for the nine-year study period from 2008 to 2016 for every single reported crash on I-80, in Wyoming. The Crash Analysis Reporting Environment (CARE) database was used to obtain all crash-related data. Roadway and traffic data were collected from WYDOT's online database. The information of interest for this study included the crash type, crash severity, horizontal alignment, the milepost where the crash occurred, driver action, road and driver conditions, as well as whether a truck was involved in the crash. These parameters were used to determine the crash frequencies along the I-80 corridor for the study period. The crash analysis was also performed for horizontal curves with different curve radius ranges, starting from only 50 ft to 33,000 ft. Finally, this information, together with the VMT data, is used to calculate the crash rates on all analyzed sections.

2.1. Descriptive Analysis

For this study, I-80, in Wyoming, was divided into 20 sections, each having approximately 20 miles, as shown in table 2.1. Since horizontal curves are a significant safety issue on expressways, horizontal curve parameters were also used in analysis. I-80, in Wyoming, includes many horizontal curve segments: out of 402.78 miles of roadway, around 23 percent is within horizontal curves.

Approximately five thousand truck crashes were recorded along I-80, in Wyoming, during the analyzed nine-year time period. The classification of crashes by crash severity is shown in table 2.2. Three types of crash severity levels included property damage only (PDO), injury, and fatal crashes. On average, about 81 percent of the truck crashes were PDO crashes, while injury crashes included about 17.5 percent. Fatal and other unknown severity accounted for the rest of crashes. The maximum number of recorded truck crashes occurred in 2008, followed by 2016. The highest number of fatal crashes was recorded in 2016.

The analyzed contributing factors for the truck-related crashes included road condition, weather condition, driver condition, driver action, and crash types, as shown in table 2.3. The results showed that, on the nine-year average, 54 percent of crashes occurred during icy road conditions, and 32 percent of crashes occurred during dry road conditions. Snowy and wet road conditions contributed to eight percent and four percent of crashes, respectively. The analysis of the impacts of weather conditions on crashes showed that about 46 percent of crashes occurred during snowy weather conditions. About six percent and four percent of crashes occurred during strong wind and cloudy conditions, respectively.

Table 2.1. I-80 Segmentation with horizontal curve length information.

Section	Milepost	Total Section Length (mi)	Length in Horizontal Curvature (mi)	Section Length in Horizontal Curvature (%)
1	0 - 21.751	21.751	9.353	43
2	21.751 - 41.968	20.236	4.048	20
3	41.987 - 61.591	19.604	6.655	34
4	61.591 - 82.621	21.03	2.721	13
5	82.621 - 102.358	19.737	6.128	31
6	102.358 - 122.272	19.914	4.901	25
7	122.272 - 142.17	19.898	6.697	34
8	142.17 - 165.582	23.412	0.838	4
9	165.582 - 184.288	18.706	2.840	15
10	184.288 - 201.164	16.876	1.058	6
11	201.164 - 219.594	18.43	4.497	24
12	219.594 - 238.15	18.556	2.400	13
13	238.15 - 260.232	22.082	6.093	28
14	260.232 - 280.901	20.669	5.829	28
15	280.901 - 297.663	16.762	3.178	19
16	297.663 - 323.049	25.386	5.005	20
17	323.049 - 342.56	19.511	7.707	40
18	342.56 - 362.037	19.477	7.725	40
19	362.037 - 386.389	24.352	3.482	14
20	386.389 - 402.78	16.391	3.202	20
Total		**402.78**	**94.357**	**23**

Table 2.2. Truck crash severity.

Crash Severity	2008	2009	2010	2011	2012	2013	2014	2015	2016	Percent
PDO	628	374	382	450	406	434	493	350	495	81.13
Injury	156	103	89	93	81	87	89	81	84	17.45
Fatal	5	3	4	7	6	3	3	4	7	0.85
Unknown	5	3	3	2	0	4	1	4	5	0.55
Total Crash	**795**	**483**	**478**	**552**	**493**	**528**	**586**	**439**	**591**	**100**

The analysis of driver condition showed that about 90 percent of the crashes occurred in apparently normal state. Falling asleep contributed to approximately two percent of crashes. Emotional, fatigued, sickness, alcoholic and other driver conditions accounted for the rest of crashes. The next contributing factor was driver action. It indicated that driving too fast and driving in improper lane contributed to approximately 45 percent of crashes. About 25 percent of crashes showed no apparent improper driving. Following too close, running off road, and other improper driving action accounted for about 19 percent of crashes. This analysis can provide some guidelines for the mitigation strategies to be considered in order to reduce the truck-related crashes.

The manner of collision presented in table 2.3 shows different crash types, such as: angle, head on, single vehicle, rear end, sideswipe etc. The analysis showed that about 64 percent of the truck crashes along I-80 were single vehicle crashes. The rear end and sideswipe collision contributed to about 18 percent and 11 percent, respectively. Trucks have large physical dimensions, more restrictive acceleration and braking capabilities, and large blind spots that could be responsible for the rear end and sideswipe collisions. Angle and other type of collisions accounted for the rest of crashes.

Table 2.3. Truck crash contributing factors and crash types.

		2008	2009	2010	2011	2012	2013	2014	2015	2016	Percent
Road Condition	Dry	170	134	133	174	182	155	185	199	234	31.67
	Wet	29	25	23	20	29	20	24	21	28	4.43
	Slush	8	7	4	11	4	3	3	4	9	1.07
	Snow	61	67	46	43	25	64	41	30	39	8.41
	Ice or Frost	520	248	269	303	252	286	331	185	279	54.05
	Other	7	2	3	1	1	0	2	0	2	0.36
Weather Condition	Clear	278	167	198	226	220	203	222	235	267	40.77
	Cloudy	23	24	19	19	20	21	39	16	32	4.31
	Fog	6	7	6	0	11	2	3	3	1	0.79
	Rain/Sleet/Hail	8	13	12	11	9	15	10	13	15	2.14
	Snowing/Blizzard	426	250	224	257	193	264	275	151	218	45.66
	Strong Wind	51	21	18	38	40	23	37	20	57	6.17
	Unknown	2	1	1	1	0	0	0	1	1	0.14
Driver Condition	Apparently Normal	740	444	439	497	442	469	512	398	530	90.41
	Emotional	9	3	5	2	1	4	1	0	1	0.53
	Fatigued	5	1	2	3	2	2	9	5	7	0.73
	Fell Asleep/Faint	5	8	7	14	12	8	14	13	14	1.92
	Ill or Sickness	4	1	1	3	1	4	6	0	2	0.44
	Alcohol or Drug use	1	4	1	1	4	2	2	0	2	0.34
	Other	31	22	23	32	31	39	42	23	35	5.62
Driver Action	Avoiding an object	9	8	7	7	12	11	8	9	10	1.64
	Ignore Traffic Signs	24	5	8	16	16	19	22	7	19	2.75
	Drove too fast	352	192	200	189	142	161	172	93	157	33.53
	Careless/Aggressive	6	1	2	12	9	2	5	6	6	0.99
	Improper lane	44	28	52	55	58	60	88	66	109	11.32
	Following too close	27	19	17	16	16	19	20	18	16	3.40
	No improper driving	201	130	107	133	125	136	137	116	135	24.67
	Other improper acts	48	32	28	34	37	28	36	32	42	6.41
	Ran Off road	54	35	36	61	45	53	61	61	64	9.50
	Swerve	9	14	9	13	19	15	17	8	9	2.29
	Unknown	21	19	12	16	14	24	20	23	24	3.50
Crash Types	Angle	47	31	25	37	23	30	33	26	31	5.72
	Head On	3	2	2	2	0	1	1	2	3	0.32
	Single vehicle	479	299	320	353	326	335	375	260	399	63.62
	Rear End	161	87	73	106	77	97	98	78	95	17.63
	Sideswipe	79	59	53	46	54	56	75	70	61	11.18
	Other	26	5	5	8	13	9	4	3	2	1.52

2.2. Crash Frequency Analysis

A crash frequency analysis was performed separately for all vehicles and trucks for the twenty analyzed sections of I-80. A separate analysis was performed for the portions of the roadway within horizontal curves. Tables 2.4 and 2.5 show crash frequencies for all vehicles and trucks, respectively, for each segment. A significant number of all vehicle crashes occurred in section 5 and 13, which accounts for approximately 25 percent of all crashes.

Table 2.4. Crash frequencies for all vehicles occurring in horizontal curves.

Section	2008	2009	2010	2011	2012	2013	2014	2015	2016	% of Crashes in each Section
1	26	23	28	22	24	24	30	32	38	8.21
2	2	2	8	2	3	8	6	9	4	1.46
3	5	5	0	0	8	6	6	12	13	1.83
4	0	0	0	0	4	2	0	1	6	0.43
5	48	41	32	37	41	41	25	47	51	12.06
6	37	40	27	31	18	29	26	19	22	8.28
7	39	45	24	35	20	37	36	24	20	9.31
8	1	3	4	3	3	0	2	3	3	0.73
9	9	6	7	8	9	5	4	7	6	2.03
10	7	2	3	7	1	0	3	1	4	0.93
11	58	26	19	23	17	24	22	24	32	8.14
12	8	8	11	4	4	11	6	9	12	2.43
13	73	38	36	52	50	42	20	17	26	11.76
14	31	24	23	26	30	21	35	33	29	8.37
15	11	6	12	17	13	8	16	10	10	3.42
16	38	31	38	31	19	29	19	34	25	8.77
17	10	13	18	17	24	34	30	29	45	7.31
18	0	0	0	0	7	5	5	10	10	1.23
19	11	6	12	9	8	14	7	4	7	2.59
20	0	0	0	0	4	4	1	1	11	0.70

A significant number of truck-related crashes occurred in sections 13 and 14, accounting for approximately 28 percent of all truck-related crashes. A comparison of results in tables 2.4 and 2.5 shows that sections 5, 13 and 14 were most dangerous, contributing to the highest percentage of crashes. Those sections must be given priority first for taking necessary actions for better roadside safety improvements.

Table 2.5. Truck crash frequencies occurring in horizontal curves.

Section	2008	2009	2010	2011	2012	2013	2014	2015	2016	% of Crashes in each Section
1	11	4	6	5	4	1	7	7	6	5.44
2	1	1	1	0	0	1	3	4	1	1.28
3	3	0	0	0	0	1	5	2	4	1.60
4	0	0	0	0	3	0	0	0	3	0.64
5	13	11	7	10	6	5	6	8	8	7.90
6	14	6	8	5	3	8	5	3	4	5.98
7	12	9	8	10	10	16	16	5	3	9.50
8	0	1	2	2	1	0	1	3	0	1.07
9	2	2	2	2	4	2	2	2	3	2.24
10	5	1	2	2	1	0	1	1	4	1.81
11	20	6	5	7	1	11	3	8	12	7.79
12	6	3	2	1	0	6	1	4	5	2.99
13	31	16	12	19	18	24	7	6	11	15.37
14	11	9	6	14	20	9	23	16	11	12.70
15	5	2	5	8	7	3	7	3	5	4.80
16	8	9	7	4	5	11	13	11	6	7.90
17	3	4	2	4	7	20	5	10	19	7.90
18	0	0	0	0	3	1	2	1	0	0.75
19	0	2	2	0	2	4	1	0	0	1.17
20	0	0	0	0	0	3	1	1	6	1.17

There are 261 horizontal curves along I-80, in Wyoming. The curve radii range is between 50 ft and 33,000 ft. The crash frequency was analyzed for different curve radius ranges, as shown in tables 2.6 and 2.7. Table 2.6 shows the number of all vehicle crashes within different curve radius ranges. The results indicate that about 40 percent of all vehicle crashes occurred within curves of 4,000 to 6,000 ft radius. Twenty five percent of crashes occurred within curves that have radius of more than 9,000 ft, while about 27 percent of all vehicle crashes occurred within curves of 1,500 to 4,000 ft radius. Table 2.7 shows the number of truck-related crashes within different curve radius ranges. The results indicated that about 45 percent of truck related crashes occurred within curves of 4,000 to 6,000 ft radius. Twenty five percent within curves with radius of more than 9,000 ft, and 24 percent within curves of 1,500 to 4,000 ft curve radius.

A comparison of all crashes and truck crashes from tables 2.4 – 2.7 indicates that out of 4,951 all vehicle crashes that occurred within horizontal curves, approximately 30 percent were truck related crashes. It also revealed that truck crash frequency was similar to all vehicle crashes within different curve radius range. The maximum percentage of crashes occurred within curves of 4,000 to 6,000 ft radius. Therefore, safety improvements on that portion of highway curves need to be established to reduce those crashes.

Table 2.6. All vehicle crash frequencies for different curve radius ranges.

Radius of Curve (ft)	Crash Frequencies within Given Horizontal Curve Radius Range (All Vehicles)									
	2008	2009	2010	2011	2012	2013	2014	2015	2016	% of Crashes in each Range
< 1,500	13	18	19	10	12	19	16	17	12	4.65
1,500 - 3,000	56	38	48	54	43	43	36	42	43	13.30
3,000 - 4,000	51	47	38	51	32	41	44	41	54	13.39
4,000 - 5,000	59	39	39	52	42	37	33	36	40	12.16
5,000 - 6,000	107	80	84	72	92	104	68	112	120	27.74
6,000 - 9,000	13	10	10	11	12	11	17	11	16	4.03
> 9,000	115	87	64	74	74	89	85	67	89	24.72
Total	**625**	**482**	**463**	**482**	**486**	**562**	**455**	**525**	**632**	**100.00**

Table 2.7. Truck crash frequencies for different curve radius ranges.

Radius of Curve (ft)	Crash Frequencies within Given Horizontal Curve Radius Range (Trucks)									
	2008	2009	2010	2011	2012	2013	2014	2015	2016	% of Crashes in each Range
< 1,500	1	4	4	0	4	8	6	6	1	3.63
1,500 - 3,000	21	12	10	10	11	17	15	13	14	13.13
3,000 - 4,000	25	7	12	10	6	9	12	7	11	10.57
4,000 - 5,000	22	12	10	24	15	17	15	13	18	15.58
5,000 - 6,000	31	26	20	22	37	39	32	35	31	29.14
6,000 - 9,000	3	1	2	5	2	3	2	3	7	2.99
> 9,000	42	24	19	22	20	33	27	18	29	24.97
Total	**204**	**122**	**109**	**135**	**145**	**205**	**161**	**150**	**184**	**100.00**

2.3. Crash Rate Analysis

Crash rate analysis was performed in order to account for different levels of traffic exposures. The crash rates in this study are given in crashes per one million VMTs. The crash rate measures the level of safety of a particular roadway section and allows for a comparison between sections.

Table 2.8 shows weighted crash rates for the entire I-80, in Wyoming, obtained on a section-by-section basis. Truck miles traveled (TMTs) were used to calculate truck-related crash rates. The results also show crash rates for roadway segments within horizontal curves.

Table 2.8. Crash rates (crashes per 1,000,000 VMTs) and VMTs along I-80.

Year	Total Crash Rates		Crash Rates inside Horizontal Curves		VMT (10^6)	
	All Vehicles	Trucks	All Vehicles	Trucks	All Vehicles	Trucks
2008	2.650	1.724	0.465	0.319	44.215	22.235
2009	1.891	1.595	0.352	0.190	44.176	20.360
2010	1.870	1.130	0.339	0.186	44.372	20.563
2011	1.958	1.283	0.373	0.223	43.481	20.625
2012	1.613	1.211	0.351	0.240	43.904	19.712
2013	1.734	1.329	0.384	0.332	44.339	19.488
2014	1.760	1.313	0.328	0.256	45.583	21.587
2015	1.528	0.996	0.345	0.217	45.834	21.890
2016	1.823	1.646	0.415	0.303	44.826	19.566

The truck crash rate was at a maximum in 2008, with close to 1.7 crashes per million truck miles traveled for overall section. The lowest crash rate for trucks (close to 1.0) occurred in 2015. The similar trend can be seen for all vehicles crash rate. The analysis of crash rates within horizontal curves shows similar trends for all vehicles and trucks.

2.4. Crash Prediction Models

In this section, the development of truck crash characteristics and prediction models is described. Different models were explored in order to determine the ones that are most suitable for local conditions. The NB or Poisson-Gamma regression model has been the most widely used model for crash prediction (Highway Safety Manual 2010). However, since the dataset contains a lot of zero truck crashes, ZINB models were used. The general form of the NB regression model is given in the equation in figure 2.1.

$$\lambda_i = \exp\left(\beta_0 + \beta_1 X_{1i} \dots \dots \dots \dots \dots \beta_p X_{pi}\right)$$

Figure 2.1. Equation. Negative Binomial regression model.

The variables used in the NB equation are as follows:

λ_i = predicted crash frequency on segment *i*;

β_p = regression coefficient for the variable *k*; and

X_{pi} =linear predictor *k* of segment *i*.

The probability function of the Zero-Inflated distribution is given by the equation in figure 2.2.

$$P(Y = y) = \begin{cases} w + (1 - w)e^{-\lambda} & for\ y < 0 \\ \dfrac{(1 - w)\lambda^{y} e^{-\lambda}}{y!} & for\ y > 0 \end{cases}$$

Figure 2.2. Equation. Probability density function of Zero-Inflated Distribution.

In the Zero-Inflated model, y represents the number of crashes, and w can be represented by a probability model that incorporates the effects of covariates.

2.4.1. Data Preparation and Description

Nine years of crash data, roadway geometrical characteristics and weather data were collected from several sources for the time period from 2008 to 2016. WYDOT performs a statewide traffic data collection using different fixed and portable programmed traffic counter stations. The information includes the counter's area, the ADT and VMT. The length of I-80, running through Wyoming, is 402.78 miles, and there are 192 recording locations, in both directions.

Roadway geometric characteristics, cross-section elements, pavement type, and traffic data were extracted from the WYDOT Roadway Data Portal (RDP). In addition to field visits, other non-traditional data sources, such as Google Earth Pro® and Google Maps®, were used to check, confirm, and obtain missing data related to the locations of interchanges and climbing lanes, and variable speed limits (VSL).

All crash data were obtained from WYDOT’s CARE database, which provides detailed information about crashes occurred in Wyoming, starting from 1994. Finally, weather data were extracted from the NOAA website. For this study, the average number of rainy, snowy, and windy days per year for each freeway segment were used as the main weather factors to predict crashes. These data were retrieved from the nearest weather stations along the I-80 corridor in Wyoming. A windy day was defined as having wind speeds of 40 mph or more occurring during that day.

Homogeneous segmentation was established to scrutinize the homogeneity in horizontal and vertical roadway geometry. First, the selected freeway segments were divided into straight and curved sections. Then they were consecutively divided based on different geometrical, traffic, and weather characteristics that were used to develop crash prediction models. Equivalent vertical grades were calculated and considered in the segmentation process. For determining these equivalent grades, average and composite grade methods were used as provided in the HCM. A minimum length criterion of 0.1 miles was considered to avoid low exposure problem and excess zero crashes. Segments having a length of less than 0.1 miles were combined with the adjacent segments based on the similarity in characteristics. Based on this approach, I-80, in Wyoming, was segmented into 1,278 total homogeneous segments, 658 in the eastbound, and 620 segments in the westbound direction. Table 2.9 shows the descriptive statistics for the variables used in the analysis. The numbers in the table were derived for the nine-year period.

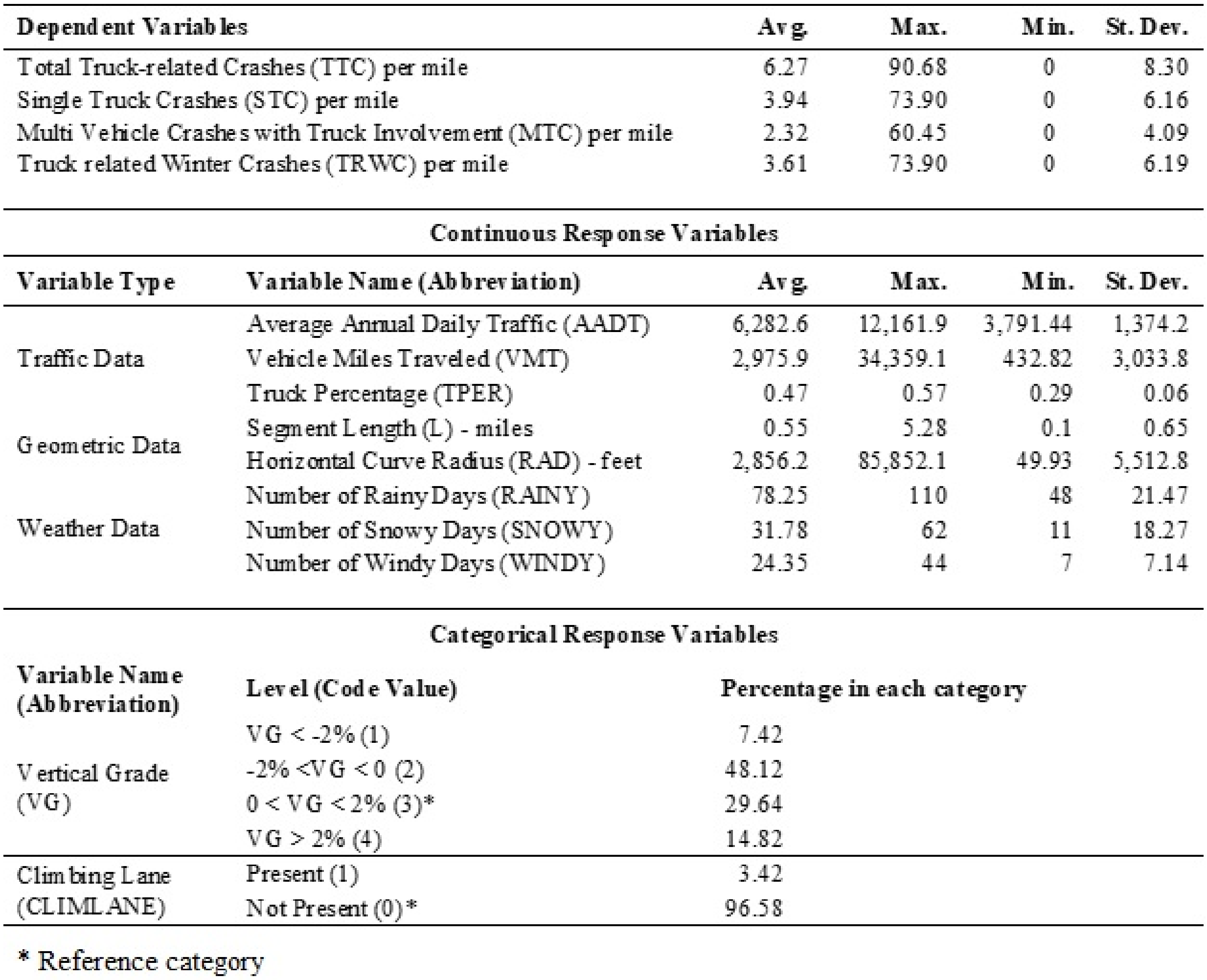
The four crash types were selected based on the target crash of interest along I-80, in Wyoming. Geometric data included segment length, horizontal curve radius, and vertical grade, where vertical grade was divided into four categories: downgrades less than -two percent as VG (1); VG (2), if the downgrades range from zero to -two percent; VG (3) when the upgrades range from zero to two percent; and upgrades greater than two percent as VG (4). In this study, VG (3) was chosen as the reference category to observe the impacts of downgrades and excessive upgrades compared to the reference grade section. The maximum truck percentage observed was 57 percent during the study period. The weather data were shown as the average number of days per year. The maximum number of rainy and snowy days per year observed were 110 and 62, respectively. The windy days were defined as having a wind speed of 40 mph or more any time during the day. There are fourteen miles of climbing lanes along I-80 in Wyoming in both directions at different locations due to the severe upgrade sections. The presence of climbing lanes was also considered as an independent variable in truck-related crashes.

2.4.2. Model Development

The ZINB model was used to develop the SPFs for four types of dependent variables: total truck-related crashes (TTC):, single truck crashes (STC): multiple vehicle crashes with truck involvement (MTC): and truck-related winter crashes (TRWC). The models were developed for the nine-year crash data.

Table 2.10 provides parameter estimates of Wyoming-specific SPFs for different truck crash types using the ZINB model, where most of the estimates shown were significant at the 95 percent confidence level. The model shows that the vertical grade (VG) and horizontal curve radius (RAD) are significant in influencing truck-related crashes. The results indicate that sites having VG (1) increase the mean of TTC, STC, MTC, and TRWC by 51 percent, 49 percent, 54 percent, and 52 percent, respectively, compared with VG (3) sites. Moreover, in comparison to VG (3), VG (2) was found to increase the mean TTC, STC, MTC, and TRWC by 17 percent, 14 percent, 24 percent, and 31 percent, respectively; and VG (4) was found to increase TTC, STC, MTC, and TRWC by 42 percent, 28 percent, 67 percent, and 42 percent, respectively. A one-unit increase in curve radius decreases the mean of TTC, MTC, and TRWC by 0.01 percent. Other geometrical characteristics, such as shoulder type and shoulder width, were not included in the models because they do not change significantly along I-80 in Wyoming.

Table 2.9. Descriptive statistics of the investigated variables.



Dependent Variables	Avg.	Max.	Min.	St. Dev.
Total Truck-related Crashes (TTC) per mile	6.27	90.68	0	8.30
Single Truck Crashes (STC) per mile	3.94	73.90	0	6.16
Multi Vehicle Crashes with Truck Involvement (MTC) per mile	2.32	60.45	0	4.09
Truck related Winter Crashes (TRWC) per mile	3.61	73.90	0	6.19

Continuous Response Variables

Variable Type	Variable Name (Abbreviation)	Avg.	Max.	Min.	St. Dev.
Traffic Data	Average Annual Daily Traffic (AADT)	6,282.6	12,161.9	3,791.44	1,374.2
	Vehicle Miles Traveled (VMT)	2,975.9	34,359.1	432.82	3,033.8
	Truck Percentage (TPER)	0.47	0.57	0.29	0.06
Geometric Data	Segment Length (L) - miles	0.55	5.28	0.1	0.65
	Horizontal Curve Radius (RAD) - feet	2,856.2	85,852.1	49.93	5,512.8
Weather Data	Number of Rainy Days (RAINY)	78.25	110	48	21.47
	Number of Snowy Days (SNOWY)	31.78	62	11	18.27
	Number of Windy Days (WINDY)	24.35	44	7	7.14

Categorical Response Variables

Variable Name (Abbreviation)	Level (Code Value)	Percentage in each category
Vertical Grade (VG)	VG < -2% (1)	7.42
	-2% <VG < 0 (2)	48.12
	0 < VG < 2% (3)*	29.64
	VG > 2% (4)	14.82
Climbing Lane (CLIMLANE)	Present (1)	3.42
	Not Present (0)*	96.58

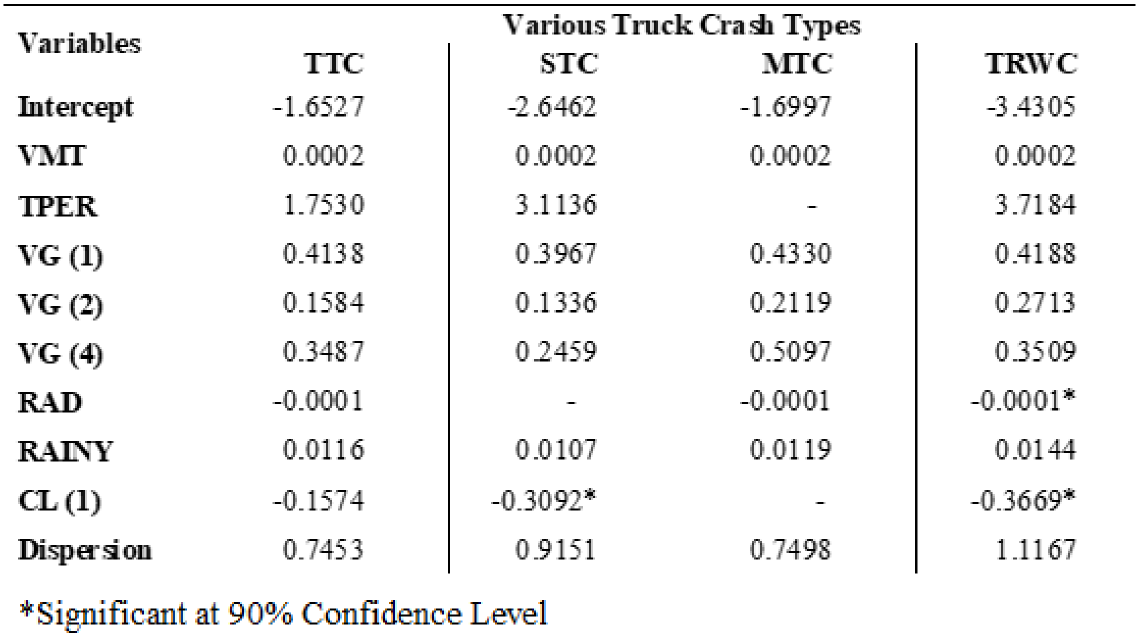
* Reference category

In this study, different measures of traffic volumes and traffic composition were used as independent variables. VMT and truck percentage (TPER) fit the model data best. The results show that a one-unit increase in VMT increased the percentage of TTC, STC, MTC, and TRWC by 0.02 percent. Furthermore, for a unit increase in truck percentage, the estimated mean of TTC, STC, and TRWC was found to increase significantly.

Weather conditions presented in the analysis were the number of days per year that rain, snow, or strong wind impacts each freeway segment on I-80. Among these three weather variables, rainy days were found significant in each of the models. The estimates of snowy and windy days were not significant, and hence they were removed from the models. One day increase in rainy days per year was found to increase the estimated mean of TTC, STC, MTC, and TRWC by 1.20 percent, 1.10 percent, 1.20 percent, and 1.45 percent, respectively.

The results also indicate that the presence of climbing lanes on I-80, denoted by CL (1), reduces the estimated mean of TTC, STC, and TRWC by 85 percent, 69 percent, and 73 percent respectively. Therefore, climbing lanes are an effective countermeasure that has a significant potential to reduce truck-related crashes along sections with steep vertical grades.

Table 2.10. Parameter estimates of Wyoming-specific SPFs for various truck crash types using ZINB models on I-80 in Wyoming.



Variables	Various Truck Crash Types			
	TTC	STC	MTC	TRWC
Intercept	-1.6527	-2.6462	-1.6997	-3.4305
VMT	0.0002	0.0002	0.0002	0.0002
TPER	1.7530	3.1136	-	3.7184
VG (1)	0.4138	0.3967	0.4330	0.4188
VG (2)	0.1584	0.1336	0.2119	0.2713
VG (4)	0.3487	0.2459	0.5097	0.3509
RAD	-0.0001	-	-0.0001	-0.0001*
RAINY	0.0116	0.0107	0.0119	0.0144
CL (1)	-0.1574	-0.3092*	-	-0.3669*
Dispersion	0.7453	0.9151	0.7498	1.1167

*Significant at 90% Confidence Level

While conducting this study, several data limitations and gaps were encountered. The crash data of ten years (2007-2016) were first extracted from CARE database to develop the SPFs. The data quality for 2007 was not consistent, and therefore, it was excluded from the dataset. Future studies should include more years of crash data. There was also some potential inaccuracy in the WYDOT roadway geometry database (i.e horizontal and vertical alignment, existence of climbing lanes etc.). Lots of weather data were missing from the NOAA website. The common issue associated with this database was the unavailability of twelve months of weather data in one year period. Moreover, wind speed data was rare for most of the weather stations.

2.5. Safety Effectiveness of Truck Climbing Lanes

This section describes the analysis of effectiveness of climbing lanes, and the calibration of CMFs and RR for climbing lanes along I-80, in Wyoming, using cross-sectional analysis and propensity scores-potential outcomes framework, respectively. Four main tasks were carried out throughout this study. The first task concentrated on developing a comprehensive database for I-80, in Wyoming. This was achieved by integrating historical traffic crash information, traffic volumes, weather characteristics, and roadway geometry information. The next task was to calibrate Wyoming-specific SPFs for I-80 to perform cross-sectional analysis, since the installation dates for climbing lanes and before data are not available for conducting the before-after analysis with EB. NB and ZINB modeling were utilized to develop crash prediction models. The third task was to develop a propensity score model which estimates the probabilities of a crash within a section with and without climbing lanes. The final task was to quantify the safety effectiveness of climbing lanes using both cross-sectional analysis and propensity scores-potential outcomes framework. Based on the analysis, recommendations can be made to enhance truck safety.

2.5.3. Research Methodology

Cross-sectional analysis and propensity scores-potential outcomes framework were used to evaluate the effectiveness of truck climbing lanes in reducing total crashes and truck-related crashes along I-80, in Wyoming. For the cross-sectional analysis, the NB and ZINB models were used to develop SPFs for total and truck crashes respectively. If the dataset contains lots of zero truck crashes, ZINB models would be more appropriate. The general form of the NB regression model is given in the equation in figure 2.1. The probability density function of the NB distribution is given by the equation in figure 2.3.

$$P(Y = y|x) = \frac{\Gamma(y + \alpha^{-1})}{\left(y!\,\Gamma(\alpha^{-1})\right)}\left(\frac{\alpha\mu(x)}{1 + \alpha\mu(x)}\right)^{y}\left(\frac{1}{1 + \alpha\mu(x)}\right)^{\alpha^{-1}}$$

Figure 2.3. Equation. Probability density function of Negative Binomial Distribution.

In this equation, P is the probability distribution, y is the expected number of crashes, and α is the over dispersion parameter of the NB model. When α approaches zero, the distribution of Y becomes a Poisson distribution with equal mean and variance.

If the presence of a climbing lane at any segment is denoted as CL=1, and 0 implied a segment without a climbing lane, then the SPFs for freeway segments including a climbing lane as a variable can be expressed by the equation given in figure 2.4.

$$Y_i = e^{(\widehat{\beta}_0 + \widehat{\beta}_1 \times CL)}$$

Figure 2.4. Equation. Safety Performance Function for freeway segments.

For the segments with and without climbing lanes, the resulting equation can be defined by assigning CL=1 and CL=0 in the previous equation, respectively. The CMF for having climbing lanes can be determined using the equation in figure 2.5.

$$CMF = e^{(\hat{\beta}_1)}$$

Figure 2.5. Equation. Crash Modification Factor for climbing lanes.

Propensity scores-potential outcomes approach estimates the probability of a truck crash occurrences with and without the presence of truck climbing lanes. Various sizes of caliper matching based on the propensity score were used to determine the range of the RR in the sensitivity assessment. The RR measures the probability of a truck crash on a road without the treatment versus a road with treatment, thereby reflecting the effectiveness of climbing lanes. The first step is to estimate the propensity scores. Binary logit or probit regression model is usually used for this purpose. The probability for an outcome based on a binary logit (i.e., the propensity score) is specified using the equation in figure 2.6.

$$P_n(i) = \frac{\exp(\alpha_i x_n)}{1 + \exp(\alpha_i x_n)}$$

Figure 2.6. Equation. Outcome probability based on Propensity Scores.

In the previous equation, x_n is the set of covariates, α_i is a vector of parameters to be estimated, and $Pn(i)$ is the probability that a location receives the treatment. The goal of this model is to balance the covariates, and not to find statistically significant relationships between the covariates and the treatment. Therefore, the variables included in the binary logit model for propensity scores were selected based on the relevance to the treatment instead of focusing on statistical significance.

After the matching process based on propensity scores had been completed, the matched treated and untreated groups were divided, and the estimated probabilities of a crash occurrence were determined using the binary logit model from the equation in figure 2.6. The crashes were coded as a binary variable this time, where a value of 1 is assigned for an entity with at least one crash, and zero indicating otherwise. Once the expected probabilities of crash occurrences were estimated for both treated and untreated groups, the RR was estimated using the equation shown in figure 2.7.

$$RR = \frac{E[P_{nUT}]}{E[P_{nT}]}$$

Figure 2.7. Equation. Risk Ratio estimation.

In the previous equation, RR is the risk ratio, $E[P_{nUT}]$ is the expected probability of a crash occurrence for the untreated group, and $E[P_{nT}]$ is an expected probability of a crash occurrence for the treated group. A sensitivity analysis was conducted to examine the effect of different caliper values ranging from 0.05 to 0.5, with an interval of 0.05 on the RR, which can also remove the initial bias associated with covariates.

2.5.4. Data Preparation and Description

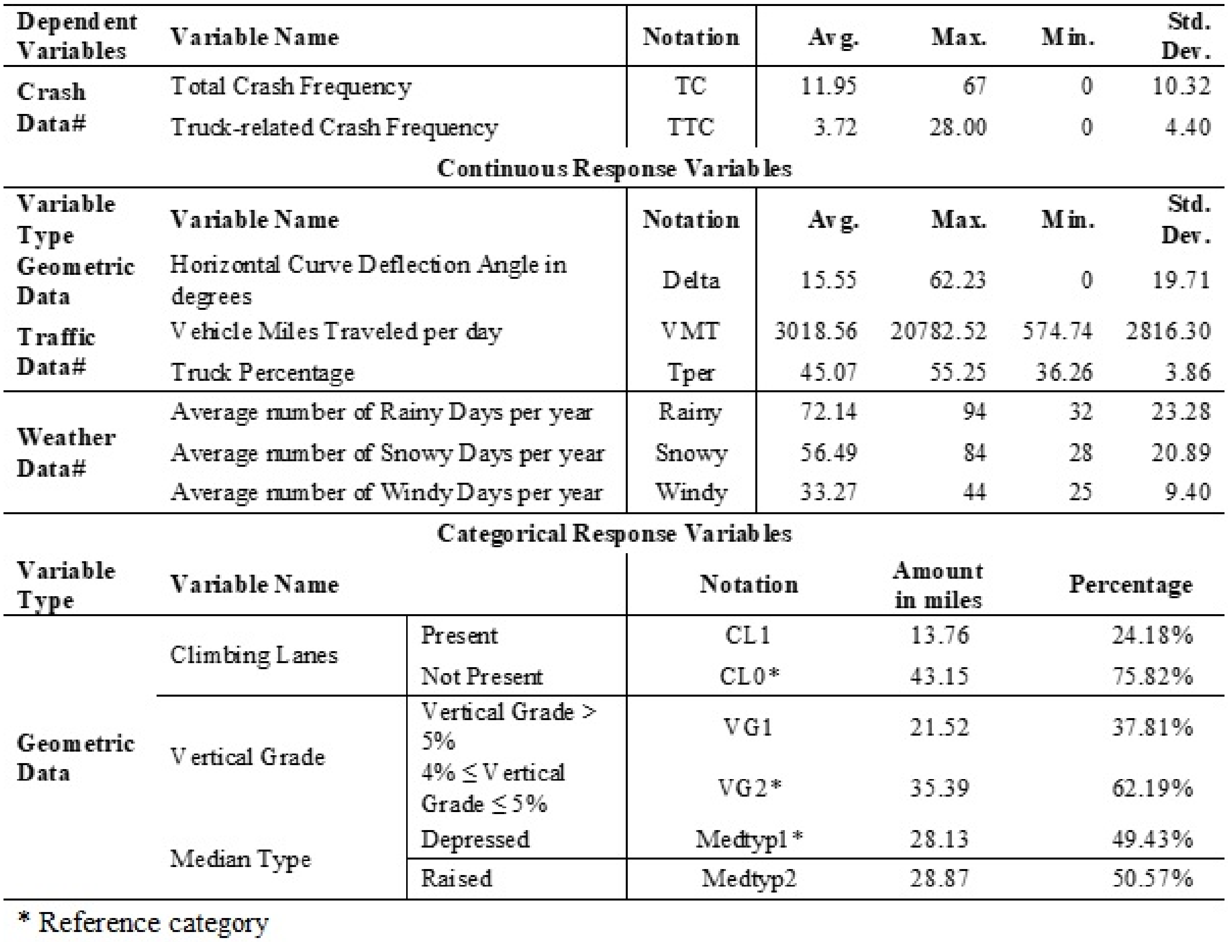
In this study, nine years of crash data, and other roadway geometrical and weather data were collected from several sources for the time period from 2008 to 2016. Roadway geometric characteristics, cross-section elements, pavement type, and traffic data were extracted from the WYDOT RDP. Other non-traditional data sources, such as Google Earth Pro® and Google Maps®, were used to check, confirm, and obtain missing data.

CARE database was used to obtain total crash and truck-related crashes. Weather data were extracted from the NOAA website. For this study, the average numbers of rainy, snowy, and windy days per year for each freeway segment were used as the main weather factors to predict crashes. These data were retrieved from the nearest weather stations along I-80 in Wyoming, where a windy day was defined as having a wind speed of 40 mph or more any time during the day.

According to the AASHTO Green Book 2011, one of the criteria for the warrants of climbing lanes is a truck speed reduction in excess of 10 mph. It also indicates that having a continuous one-mile upgrade of four percent reduces heavy truck speed significantly. Therefore, the sites having upgrades of four percent and more were considered as the comparison sites without climbing lanes. The dataset consisted of 57 miles in which the treatment sites having climbing lanes were about 14 miles, and the comparison sites having similar geometrical characteristics without climbing lanes were about 43 miles long.

Homogeneous segmentation was established to scrutinize the homogeneity in horizontal and vertical roadway geometry. Segments having a length less than 0.1 miles were combined with the adjacent segments based on the similarity in characteristics to avoid low exposure problem and excess zero crashes. For cross-sectional analysis, the examined freeway was divided into 118 segments, where 33 and 85 segments were the treatment and comparison sites respectively, using the aggregated crash count data for the study period. A panel count database was developed to perform propensity scores modeling to avoid low segmentation count. The panel count database resulted in 297 treatment and 765 comparison sites, which summed up a total of 1,062 segments. Tables 2.11 and 2.12 show the descriptive statistics for the variables used in the cross-sectional and propensity scores analysis respectively.

Table 2.11. Variables for cross-sectional analysis using aggregated count data.



Dependent Variables	Variable Name	Notation	Avg.	Max.	Min.	Std. Dev.
Crash Data#	Total Crash Frequency	TC	11.95	67	0	10.32
	Truck-related Crash Frequency	TTC	3.72	28.00	0	4.40

Continuous Response Variables

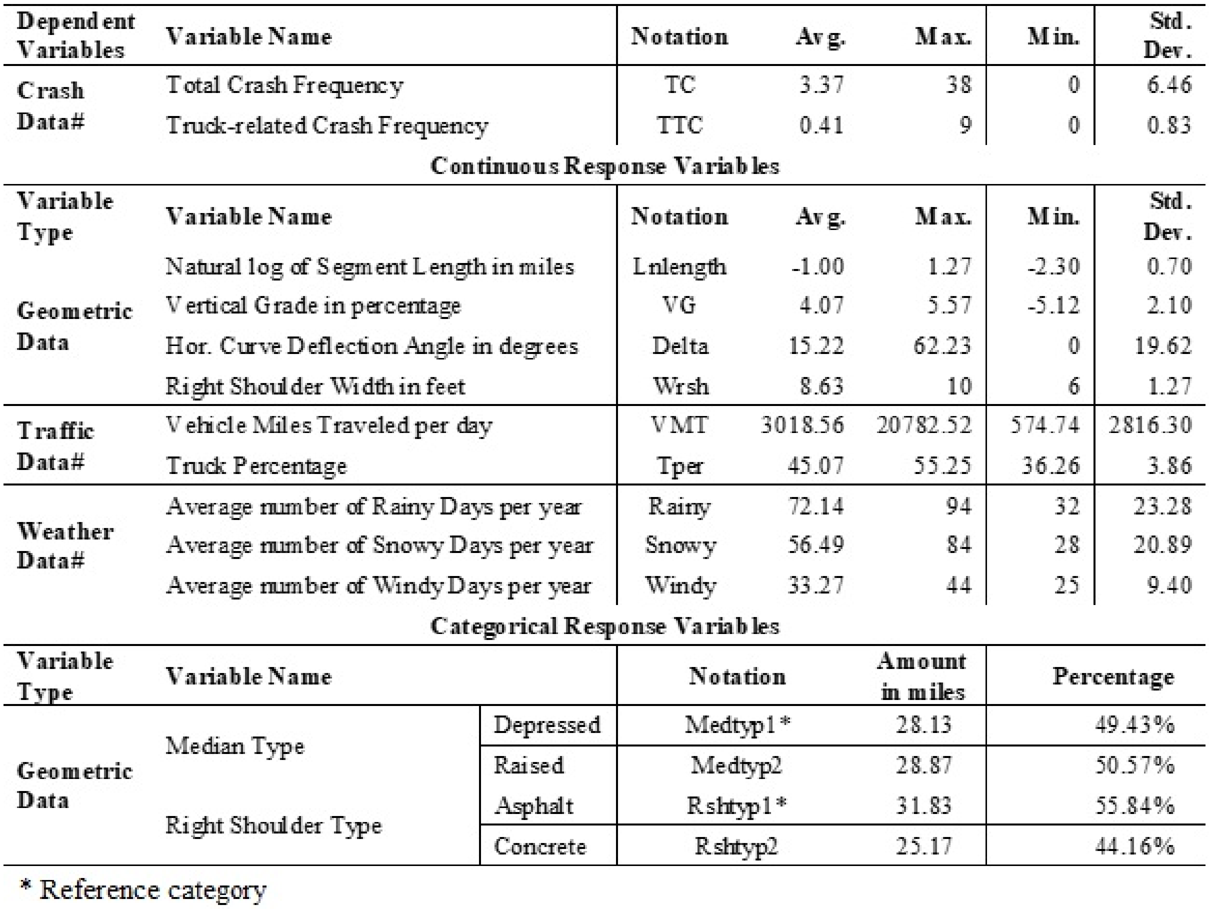
Variable Type	Variable Name	Notation	Avg.	Max.	Min.	Std. Dev.
Geometric Data	Horizontal Curve Deflection Angle in degrees	Delta	15.55	62.23	0	19.71
Traffic Data#	Vehicle Miles Traveled per day	VMT	3018.56	20782.52	574.74	2816.30
	Truck Percentage	Tper	45.07	55.25	36.26	3.86
Weather Data#	Average number of Rainy Days per year	Rainy	72.14	94	32	23.28
	Average number of Snowy Days per year	Snowy	56.49	84	28	20.89
	Average number of Windy Days per year	Windy	33.27	44	25	9.40

Categorical Response Variables

Variable Type	Variable Name		Notation	Amount in miles	Percentage
Geometric Data	Climbing Lanes	Present	CL1	13.76	24.18%
		Not Present	CL0*	43.15	75.82%
	Vertical Grade	Vertical Grade > 5%	VG1	21.52	37.81%
		4% ≤ Vertical Grade ≤ 5%	VG2*	35.39	62.19%
	Median Type	Depressed	Medtyp1*	28.13	49.43%
		Raised	Medtyp2	28.87	50.57%

* Reference category

Table 2.12. Variables for Propensity Scores analysis using panel count data.



Dependent Variables	Variable Name	Notation	Avg.	Max.	Min.	Std. Dev.
Crash Data#	Total Crash Frequency	TC	3.37	38	0	6.46
	Truck-related Crash Frequency	TTC	0.41	9	0	0.83

Continuous Response Variables

Variable Type	Variable Name	Notation	Avg.	Max.	Min.	Std. Dev.
Geometric Data	Natural log of Segment Length in miles	Lnlength	-1.00	1.27	-2.30	0.70
	Vertical Grade in percentage	VG	4.07	5.57	-5.12	2.10
	Hor. Curve Deflection Angle in degrees	Delta	15.22	62.23	0	19.62
	Right Shoulder Width in feet	Wrsh	8.63	10	6	1.27
Traffic Data#	Vehicle Miles Traveled per day	VMT	3018.56	20782.52	574.74	2816.30
	Truck Percentage	Tper	45.07	55.25	36.26	3.86
Weather Data#	Average number of Rainy Days per year	Rainy	72.14	94	32	23.28
	Average number of Snowy Days per year	Snowy	56.49	84	28	20.89
	Average number of Windy Days per year	Windy	33.27	44	25	9.40

Categorical Response Variables

Variable Type	Variable Name		Notation	Amount in miles	Percentage
Geometric Data	Median Type	Depressed	Medtyp1*	28.13	49.43%
		Raised	Medtyp2	28.87	50.57%
	Right Shoulder Type	Asphalt	Rshtyp1*	31.83	55.84%
		Concrete	Rshtyp2	25.17	44.16%

* Reference category

2.5.5. *Cross-Sectional Analysis*

The cross-sectional analysis was performed using climbing lanes as a categorical variable with ‘no climbing lanes’ as the reference category. The first step of this analysis was to develop the crash prediction models (also referred as SPFs) for total and truck-related crashes, which was accomplished using NB and ZINB models respectively. These models were developed using nine years of crash data (2008 – 2016). The parameter estimates, along with the standard errors (SE) and p values of final models, are provided in table 2.13. The leave-one-out approach was used for cross-validation to determine the model accuracy. It shows that the predictive accuracy of the crash prediction model for total crashes and truck-related crashes were 95 percent and 88 percent, respectively.

Table 2.13. Wyoming-specific crash prediction models for total crashes and truck-related crashes in Cross-Sectional analysis.

Variable	Total crashes (NB)			Truck-related crashes (ZINB)		
	Coefficient	**SE**	**p-value**	**Coefficient**	**SE**	**p-value**
Intercept	-1.7854	1.2044	0.1382	-4.327	1.4678	0.0032
VMT	0.0002	0	<.0001	0.0002	0	<.0001
Tper	6.2547	2.2318	0.0051	10.6121	2.735	0.0001
CL (Present)	-0.5567	0.2303	0.0156	-0.6192	0.2939	0.0351
VG (Greater than 5%)	0.3168	0.1419	0.0255	-	-	-
Delta	0.0046	0.0032	0.1412	-	-	-
Medtyp (Raised)	0.3886	0.1551	0.0122	0.4935	0.209	0.0182
VMT*CL (Present)	0.0002	0.0001	0.0075	0.0001	0.0001	0.1467
Rainy	-0.0127	0.0051	0.0125	-0.0134	0.0064	0.0366
Windy	0.0404	0.0132	0.0022	0.0301	0.0176	0.087
Dispersion	0.3218	0.0586		0.397	0.0947	
CMF	**0.57**			**0.54**		
Probability of Zero Crash	0.04			0.12		
Cross Validation (leave-one-out approach) Model Accuracy	95%			88%		

The table shows that the geometric elements that were significant in influencing total crash frequency included vertical grade (VG), horizontal curves deflection angle (Delta), and median type (Medtyp). Among these three variables, vertical grade and median type were selected as a categorical variable. Different forms of traffic volume measures were used to investigate the effect of the AADT. Among these, VMT and truck percentage (Tper) were found to fit the data better based on p-value < 0.05. Weather conditions presented in the analysis were the number of days per year that rain, snow, or strong wind impacts each freeway segment on I-80. Among these three weather variables, rainy and windy days were found significant in the models. In general, it is found that the presence of climbing lanes reduces both total and truck-related crashes, with CMF of 0.57 and 0.54 respectively. These results are significant at a 95 percent confidence level.

2.5.6. Propensity Scores-Potential Outcomes Framework

The propensity score model developed for the treatment (presence of climbing lanes) is shown in table 2.14. Propensity scores were estimated using binary logistic regression where only two treatment levels (presence verses absence of a climbing lane) were considered. Covariates that can influence the treatment selection were included in the propensity score model, regardless of their statistical significance. As shown in table 2.14, the variables associated with a lower probability of a presence of a climbing lane on a selected freeway segment include the natural log of segment length, vertical grade, median type, the width of right shoulder, and an average number of snowy days per year. On the other hand, variables associated with a higher probability of presence of climbing lane are VMT, truck percentage, delta, right shoulder type, average number of rainy, and windy days per year.

Table 2.14. Propensity Score model.

Variable	Coefficient	SE	p-value
Intercept	-3.5925	1.8665	0.0543
Lnlength	-1.1369	0.2981	0.0001
VMT	0.0001	0.0001	0.0710
Tper	8.9579	2.3781	0.0002
Delta	0.0168	0.0050	0.0008
VG	-0.4750	0.0691	<.0001
Medtyp (Raised)	-0.1883	0.2579	0.4653
Rshtyp (Asphalt)	3.2678	0.4123	<.0001
Wrsh	-0.8353	0.0864	<.0001
Rainy	0.0317	0.0090	0.0004
Snowy	-0.0212	0.0071	0.0029
Windy	0.0978	0.0237	<.0001
Number of Obsevations = 1,062			
Likelihood Ratio, LR $\chi^2(11) = 469.4543$			

The comparable treated and comparison groups were selected based on propensity scores, where caliper-based 1:1 NN matching was adopted. Matching was done with calipers 0.05 – 0.50σ. After the matching process, the NB models were first applied to the matched data in order to obtain more reliable CMFs. Unfortunately, the results were not satisfactory to compare those with the CMFs provided in table 2.13. Therefore, binary logistic regression models were introduced to determine the RR, which is also referred to as the safety effective measure. A series of binary logistic models were produced for calipers ranging from 0.05 – 0.50σ to evaluate the sensitivity of the analysis. Those models evaluated the probability of an occurrence of a total and truck-related crash for the selected freeway segments with climbing lanes. The estimates of the model for treated and comparison groups with caliper value of 0.05σ are shown as an example below in table 2.15. The expected probability of occurrence of total crashes for matched comparison and treated group was 0.554 and 0.414 respectively. The RR is 0.554/0.414 = 1.34. This indicates that the probability of a total crash occurring at comparison sites is 1.34 times higher than at a treated site, given the propensity scores are comparable. On the other hand, the expected probability of occurrence of a truck-related crash for comparison and treated segments was estimated at 0.926 and 0.802, respectively. The RR is 0.926/0.802 = 1.16, which indicates that the absence of climbing lane in comparison segments increases the probability of occurrence of a truck-related crash by approximately 16 percent compared to the treated segments with climbing lanes. There is no mathematical relation found between CMF and RR in the literature. However, it can be said that the way they represent the results for safety effectiveness is inversely proportional (i.e. CMF represents the percentage of crash reduction for having treatment, while RR represents the percentage of increase in crashes if the treatment does not exist).

Table 2.15. Binary logistic regression for matched comparison and treated group (Caliper = 0.05σ)

Total Crashes	**Comparison Group**			**Treated Group**		
	Coefficient	**SE**	**p-value**	**Coefficient**	**SE**	**p-value**
Intercept	2.5876	3.6263	0.4755	2.0624	1.7233	0.2314
Lnlength	-1.0014	0.9680	0.3009	1.9420	1.1032	0.0783
VMT	-0.0002	0.0004	0.6186	-0.0007	0.0004	0.0984
Delta	-0.0191	0.0099	0.0542	-0.0265	0.0118	0.0251
VG	-0.5566	0.5519	0.3132	0.4976	0.2042	0.0148
Medtyp (Raised)	-0.5446	0.5593	0.3301	0.2169	1.2716	0.8646
Rshtyp (Asphalt)	0.0712	0.5802	0.9024	-0.1791	0.8085	0.8246
Snowy	0.0043	0.0103	0.6795	-0.0056	0.0230	0.8091
	No. of Observations = 150			No. of Observations = 150		
	LR $\chi^2(7) = 37.9608$			LR $\chi^2(7) = 14.8043$		
Truck-related Crashes	**Comparison Group**			**Treated Group**		
	Coefficient	**SE**	**p-value**	**Coefficient**	**SE**	**p-value**
Intercept	-0.5616	1.8834	0.7656	-1.0669	4.0588	0.7927
Lnlength	-0.0704	1.3236	0.9576	-1.9205	1.0656	0.0715
VMT	-0.0004	0.0005	0.4364	0.0002	0.0003	0.5059
Delta	0.0110	0.0138	0.4255	-0.0163	0.0101	0.1072
VG	-0.2152	0.2251	0.3392	-0.1579	0.6571	0.8101
Medtyp (Raised)	1.6737	1.5418	0.2777	-0.4195	0.6298	0.5053
Rshtyp (Asphalt)	1.2209	0.9856	0.2154	0.4777	0.7232	0.5089
Snowy	0.0322	0.0310	0.2993	0.0099	0.0113	0.3801
	No. of Observations = 150			No. of Observations = 150		
	LR $\chi^2(7) = 16.9948$			LR $\chi^2(7) = 25.4942$		

The cross-sectional analysis has a tendency to over or underestimate the effectiveness of a treatment, since it does not account for the regression-to-the-mean bias. Therefore, a relatively new method, propensity scores with potential outcomes, was adopted to overcome the limitations and determine the effect of treatments based on observational, non-randomized data. The panel count database was developed to perform this analysis to avoid low segmentation count. The sensitivity analysis shows that the RR for total and truck-related crashes was always greater than one for calipers ranging from 0.05 to 0.50σ, which indicates that the probability of a crash occurring at comparison sites without climbing lanes is higher than at treated sites with climbing lanes. In other words, the treatment was found to be 6 to 34 percent, and 1 to 16 percent effective in reducing total and truck-related crashes, respectively, for different caliper values. This method is using the dual modeling approach that makes it more accurate than cross-sectional analysis. Both the CMF and RR provides the results that represent directly or indirectly the safety effectiveness of climbing lane, and it was found effective in reducing total and truck-related crashes that make the results related and consistent.

Recommendations can be made for cross-sectional analysis to integrate propensity scores into the process for identification and selection of a suitable comparison group. The present study used 1:1 NN technique for matching. Future study will include more corridors containing climbing lanes and will apply 1:2 NN technique for comparison. The cross-sectional analysis should develop NB models using the matched data in order to obtain more reliable CMFs. Future work should analyze the climbing lane effectiveness for different severity of total and truck-related crashes. The results of this study would be beneficial to conduct cost-benefit analysis to justify the warrants for climbing lanes based on crash reduction.

3. OCCUPANT INJURY SEVERITY IN PASSENGER CAR-TRUCK COLLISIONS ALONG I-80, IN WYOMING

Traffic crashes have significant impacts on society. Injured or killed individuals must deal with pain and suffering, medical costs, wage loss, higher insurance premium rates, and vehicle repair costs (Chang and Mannering 1999). Crashes involving trucks are a growing concern because of the higher level of injury severity and significant economic impact. Recent statistical data also indicates a higher fatal crash involvement by heavy trucks over passenger cars in the United States, controlling for the number of registered vehicles and VMTs (FMCSA 2017). In 2017, over 4,700 people died in large truck-related crashes in the United States, where 72 percent of people killed in those crashes were occupants of other vehicles (NHTSA 2017). Although the number of motor vehicle occupant and non-occupant fatalities decreased by 1.8 percent in 2017 compared to 2016, fatalities in crashes involving large trucks increased by 9 percent during this time period. Among the motor vehicle occupants killed in traffic crashes, approximately 37 percent were due to truck-related crashes (NHTSA 2017b). The approximate average cost of a large-truck related crash in 2005 was more than $91,000 (Zaloshnja and Miller 2007), corresponding to more than $120,000 in 2019 based on the two percent average yearly inflation rate (Bureau of Labor Statistics 2019). Reducing truck-related crashes has become the prime target of the U.S. Department of Transportation (DOT).

Wyoming has the highest truck-related crash rate in the United States, twice as high as the national average (Weber and Murray 2014). I-80, in Wyoming, is used more by heavy truck traffic than any other roadway system (WYDOT 2017). A large portion of I-80, in Wyoming, passes through mountainous and rolling terrain, which results in the presence of significant vertical grades. Furthermore, different adverse weather conditions such as fog, snow, blizzards, slush, rain, and strong winds are frequent phenomena in Wyoming. From 2007 to 2016, nearly 50 percent of motor vehicle crashes along I-80, in Wyoming, were truck-related, and a major portion of fatalities occurred in car-truck crashes, based on the WYDOT annual crash reports. The occupants of passenger vehicles are more likely to be killed or severely injured when a passenger vehicle collides with a truck.

This section identifies the significant contributing factors affecting the injury severity of car drivers, car passengers, and truck occupants from the aspects of car-truck collisions. The factors used in the analysis include car driver, car passenger, truck occupant, crash, and geometric characteristics, as well as adverse weather conditions. The effects of these variables were quantified using a statistical analyzing tool.

3.1. Literature Review

Duncan et al. developed an ordered-probit model to examine the injury severity of passenger car occupants in the case of rear-end collisions between heavy trucks and passenger cars (Duncan et al. 1998). The study used the Highway Safety Information System (HSIS) data from North

Carolina for the years 1993 to 1995. The results indicated that the factors related to darkness, high-speed differentials, high-speed limits, grades (especially when wet), being in a car struck from the rear, driving while drunk, and being female increase the likelihood of high injury severity for car occupants. The study also found a reduction in injury severity at snowy/icy road and congested traffic conditions as compared to dry and free-flow traffic conditions respectively.

Blower, in his study, focused on crashes involving one truck and one passenger vehicle (Blower 1998). The findings of the study revealed that passenger car drivers tended to make more mistakes in collisions, compared to truck drivers. The finding was supported by Kostyniuk et al., whose study found that the behavior of car drivers was more likely unsafe compared to truck drivers in the car-truck collisions (Kostyniuk et al. 2002). Chang and Mannering introduced Nested Logit models to analyze injury severity based on vehicle occupancy in truck- and non-truck-involved crashes using data from the state of Washington (Chang and Mannering 1999). The analysis considered three severity levels: property damage only, possible injury, and injury/fatality. The results indicated significantly higher severe injuries for multi-occupant over single-occupant vehicles when trucks were involved. The authors also found that rear-end collision, and right or left turn crash types increased the probability of injury severity.

Khorashadi et al. (2005) modeled the severity of rural and urban driver injuries for both passenger cars and large trucks in the case of large truck-involved crashes using four years of California crash data. Multinomial logit models were developed considering four driver injury severity categories (no injury, complaint of pain, visible injury, and severe/fatal injury). The results indicated that different driver and vehicle characteristics, and environmental, road, and traffic conditions significantly contributed to the severity of injuries in both rural and urban driver models.

Another occupant injury severity analysis conducted by Christoforou et al. (2010) developed a random-parameter ordered-probit model to examine the effect of speed and traffic volume on the A4-A86 junction in the Paris region. The results indicated higher injury severity for increased traffic volumes, and differential speed effects on severity depending on flow conditions. Islam and Hernandez (2013) applied the random-parameter ordered-probit model to explore crash, vehicle, and driver characteristics that influence injury severity of truck-involved crashes using the 2005-2008 National Automotive Sampling System General Estimates System (NASS GES) data. The findings indicated a high correlation with the level of injury severity while taking a number of complex interactions between investigated variables. A study by Zhu and Srinivasan (2011) applied an ordered probit model, that showed that driver distraction (truck drivers), alcohol use (car drivers), and emotional factors (car drivers) increased the injury severity of the corresponding occupants. A study by Xu et al. (2017) investigated injury severity analysis and pre-crash driving actions in passenger car-truck collisions using one-year (2013) crash data from the Virginia Department of Transportation. The results indicated that speeding, failing to maintain proper control, or ignoring officers, signals, or signs, increased the injury severity of passenger car drivers. Conversely, wrong place and no-right-of-way increased injury chance of truck drivers.

Two related studies analyzed the injury severity of truck-involved crashes at highway-rail grade crossings and different lighting conditions on rural and urban roadways (Hao et al. 2016, Uddin and Huynh 2017). The findings from these papers included a reduction of driver injury severity for better speed control of trucks at highway-rail grade crossings, and various contributing effects on injury severity for different lighting conditions and area type. A follow-up study by Uddin and Huynh (2018) explored factors affecting injury severity of crashes involving hazardous material (HAZMAT) large trucks by developing both fixed and random parameters ordered probit models of injury severity. The results indicated higher probabilities of injuries for male occupants, truck drivers, crashes occurring in rural locations, under dark-unlit and dark-lit conditions, and on weekdays. On the other hand, the older occupants (age 60 and over), truck making a turn, rear-end collisions, collisions with an object, crashes occurring on non-interstate highways, higher speed limit highways (≥65 mph), and flat terrain were found to reduce the probability of injuries.

Recent studies in Wyoming investigated truck-related crashes along Interstate highways using violation and crash data (Mashadi et al. 2018, Rezapour et al. 2018, Rezapour and Ksaibati 2018). These studies employed two approaches to identify contributing factors to truck-related crashes and truck-related violations using the logistic regression method. The results of the first approach indicated that driving on dry-roadway surfaces, driver distraction, and rollover types of truck crashes, speed compliance failure, and higher posted speed limits increased the odds of injury/fatal single and multiple vehicle crashes. With the second approach, the results of violations indicated that being nonresident, driving off-peak hours, and driving on weekends could increase the risk of truck-involved crashes. Ahmed et al. investigated the influence of heavy trucks to crash injury severity and addressed the impact of large truck movement on the safety of roadways for various road classifications in Wyoming (Ahmed et al. 2018). The results showed 2.3 and 4.5 times higher severe crashes with the involvement of a heavy truck on the state and interstate highways, respectively.

The literature review shows that statistical models are the primary method used in the analysis of traffic crashes and their severity. Savolainen et al. (2011) outlined the evolution of research and statistical analyses of traffic injury severities. Based on this study, binary logit model (BLM), nested logit model (NLM), ordered logit model (OLM), ordered probit model (OPM), and random parameters (Mixed) logit model (MLM) are the most widely used methods to analyze crash injury severities. Bayesian statistics are also used in traffic safety analysis (Xie et al. 2009, Meng et al. 2017). This approach is considered to perform better than the traditional maximum likelihood estimation (MLE) (Ahmed et al. 2018). In this study, the BLM models with Bayesian inference techniques were used to investigate the occupant injury severity level in car-truck collisions along I-80, in Wyoming.

3.2. Research Methodology

The occupant injury severity was analyzed for crashes between passenger cars and trucks, which included light, medium or heavy truck. The first step of the analysis was to acquire crash records and roadway geometrical characteristics from WYDOT. After collecting and organizing a crash database, a descriptive analysis was conducted for a 10-year period (2007-2016).

The next and final step of the analysis was to develop statistical models for the car driver, car passenger, and truck occupants. Binary logit models, with a Bayesian inference approach, were applied in this study to examine the effect of the driver, roadway, and environmental factors to severe and non-severe injuries of the occupants in car-truck collisions. Occupant injury severity was defined as the response variable (y) in all three models, where y = 1 for severe injury and y = 0 for non-severe injury. Based on the WYDOT crash reports, fatal and incapacitating injuries were defined as severe, and non-severe crashes comprised non-incapacitating injury, possible injury, and no injury.

One of the limitations of the classical logistic regression models includes considering the model variables as fixed, unknown constants, and the data is used only to best estimate the unknown values of the variables. Bayesian approach framework accounts for the limitation by treating the model variables as random, and the data is used to simulate the behavior of the variables in assessing their distributional properties. The Bayesian inference has a natural interpretation that formed a credibility interval by deriving the simulated posterior probability of the variables. The applicability of selecting the parametric family for prior probability distributions is another advantage of using the Bayesian approach over the classical method. Among the three different priors, uniform prior following normal distributions were used in this study based on the literature. Bayesian inference has the ability to avoid overfitting issue for both limited and large number of observations (Ahmed et al. 2018).

For this study, both response (severe/non-severe) and explanatory (driver and occupant characteristics, crash characteristics, roadway geometry, and weather characteristics) variables were converted into a binary format of either one or zero (1 or 0). If severe injuries (y = 1) and non-severe injuries (y = 0) have respective probabilities of p and 1 – p, then the general form of logistic regression can be expressed in the equation shown in figure 3.1 (Ahmed et al. 2018).

$$log\left(\frac{p}{1-p}\right) = \beta_0 + \beta X$$

Figure 3.1. Equation. Logistic Regression Model.

In this equation, β_0 is the intercept, β is the regression coefficients for the explanatory variables to be estimated, and X is the vector of the explanatory variables. The logit equation correlates with the explanatory variables to the probability of a severe injury (y = 1). The expected probability of severe injuries for a given value of predictor variables (X) can be theoretically calculated and expressed from the equation shown in figure 3.2.

$$p(y = 1) = \frac{e^{\beta_0 + \beta X}}{1 + e^{\beta_0 + \beta X}}$$

Figure 3.2. Equation. Probability of a severe injury.

The R statistical software with BRMS (Bayesian Regression Models using Stan) package was applied to develop the models using three Monte Carlo Markov Chains (MCMC) that produce the estimated posterior distribution of observations through Gibbs sampling. The BRMS package permits R users to easily specify a wide range of Bayesian single-level and multilevel models using the probabilistic language Stan. The adaptive rejection was set up as 3,000 iterations, where first 1,000 observations were tossed out. The convergence of the model was ensured by using the Gelman-Rubin statistic ($\hat{R}$) (Gelman and Rubin 1992). The value equal to 1 indicates perfect convergence. Another measure used in the models was the effective number of variables (pD), which implies the complexity of the models. The 95 percent Bayesian credible interval (95 percent BCI) was applied to identify the significant predictors which follow the normality assumption on unknowns and confidence interval estimations (Gelman et al. 2013).

Odds ratios were estimated to interpret the effect of the significant variables on injury severity. In the models, these ratios demonstrated the probability of a severe injury in car-truck crashes with the presence or absence of certain conditions.

3.3. Data Preparation and Description

This study used ten years of crash records from the CARE database, from 2007 to 2016, to investigate the occupant injury severity in car-truck collisions. The CARE database separates vehicle crashes and person crash files. The first step was to select the person crashes that occurred on I-80 in Wyoming to get the information about the drivers, passengers, and other occupants. It was then merged with the vehicle crash file based on the unique crash case number to obtain more details about vehicles and other crash characteristics, including environmental conditions. At this stage, car-truck crashes were filtered out and used for further analysis. Roadway geometric characteristics and cross-section elements were extracted from WYDOT's Roadway Database. The CARE database provides the exact location of each crash in terms of milepost. The final step was to combine the person-vehicle crash file to the roadway data file based on the milepost.

Once the person-vehicle-roadway data were compiled, a descriptive analysis was performed. The comprehensive crash data provided detailed information associated with each crash. This information included the date and time, location (longitude-latitude and name), manner of the collision, driver characteristics, environmental conditions, vehicle information, functional classification of the highway, crash severity, and many other roadway geometries. During the analyzed time period, a total of 1,009 car-truck crashes were recorded, which resulted in the involvement of 2,018 vehicles and 2,830 injuries. Table 3.1 shows the number of car-truck crashes broken down by truck types, and the associated number of injuries. The table also provides crash severity for the occupants. Among the total occupants involved in car-truck crashes, 1,009 were car drivers, 684 were car passengers, and 1,137 were truck occupants. Truck occupants included both drivers and any other occupants (for example a second driver in the sleeper cab) . As expected, car occupants were found to have more than twice severe injuries compared to truck occupants.

Table 3.1. Crashes and injury information.

Crash Records (2007-2016)			
Crash Type	**Number of Crashes**	**Number of Injured Person**	
Total Crashes	17894	35909	
Truck-related	8354	19951	
Car-Truck	1009	2949	
Car-Heavy Truck	978	2852	
Car-Medium Truck	21	66	
Car-Light Truck	10	31	
Occupant Injury Severity Records (2007-2016)			
Occupant Type	**Non-Severe**	**Severe**	**Total**
Car Driver	947	62	1009
Car Passenger	626	58	684
Truck Occupant	1082	55	1137
Truck Driver	964	45	1009
Truck Passenger	118	10	128

Table 3.2 shows the descriptive statistics for the variables used in the analysis. The factors affecting the injury severity of car-truck crashes were broadly classified into occupant characteristics, crash characteristics, and roadway geometrics. All the variables were converted into categorical predictors and set up as binary, depending on whether the corresponding factor described a severe crash or not. The occupant characteristics included age, gender, driver impairment, seating position, driver occupation, driver residency, safety equipment use, airbag deployment, alcohol or drug use, driving dangerously, and driver fatigue. In this study, age greater than or equal to 55 was considered as old drivers/occupants (Zhu et al. 2011). Impaired driving was identified based on the driver condition (emotional, fatigued, sleepy, sick, and under the influence of alcohol or drug). Apparently normal driving condition was considered as non-impaired driving. Driver residency referred to the driver being from Wyoming or not. Seat belt usage or other restraint types was classified as safety equipment usage.

The investigated crash characteristics included the day of the week, lighting condition, time of day, angle crashes, sideswipe crashes, junction relation, road surface conditions, weather conditions, speeding, and negotiating a curve. Day of the week was labelled as weekday and weekend. Among various collision types, angle, and sideswipe accounted for more than 50 percent of total car-truck crashes. The presence of intersections, interchanges, an exit ramp, entrance ramp, etc. were grouped as a junction variable. Other than the dry surface, roadway having ice, snow, slush, rain etc. was grouped into not-dry condition. Similarly, different inclement weather conditions were labelled as not-clear. Vertical grades and horizontal alignment were categorized into upgrades or downgrades, and curve or straight segments, respectively. In the binary coded response, zero was taken as the reference category for each variable, which means the modeling results were observed for the opposite (1) coded factors.

Table 3.2. Descriptive statistics: variables and occupant injury severity.

	Variables	Coded Response	Car Driver		Car Passenger		Truck Occupant	
			Count	Percent	Count	Percent	Count	Percent
Occupant Characteristics	Old (Age ≥ 55)	0 = Not Old	746	73.94	557	81.43	769	67.59
		1 = Old	263	26.07	127	18.57	368	32.41
	Gender	0 = Male	631	62.54	315	46.05	1049	92.26
		1 = Female	378	37.46	369	53.95	88	7.74
	Impaired Driving	0 = No	783	77.60	542	79.24	866	76.18
		1 = Yes	226	22.39	142	20.76	271	23.82
	Seating Position	0 = Front Row	-	-	400	58.48	1019	89.65
		1 = Other	-	-	284	41.52	118	10.35
	Driver Occupation	0 = Other	-	-	-	-	435	38.30
		1 = Transport Related	-	-	-	-	702	61.70
	Driver Residence	0 = WY	269	26.66	186	27.19	86	7.58
		1 = Not WY	740	73.34	498	72.81	1051	92.42
	Seat Belt Usage	0 = Used	970	96.14	618	90.35	874	76.85
		1 = Not Used	39	3.87	66	9.65	263	23.15
	Airbag Deployment	0 = Deployed	166	16.45	150	21.93	5	0.42
		1 = Not Deployed	843	83.55	534	78.07	1132	99.58
	Alcohol	0 = Not Involved	983	97.42	680	99.42	1128	99.24
		1 = Involved	26	2.58	4	0.59	9	0.76
	Drug	0 = Not Involved	987	97.82	683	99.85	1132	99.58
		1 = Involved	22	2.18	1	0.15	5	0.42
	Driving Dangerous	0 = No	945	93.66	667	97.52	1093	96.13
		1 = Yes	64	6.34	17	2.49	44	3.87
	Driver Fatigued	0 = No	1001	99.21	675	98.68	1125	98.91
		1 = Yes	8	0.79	9	1.32	12	1.09
Crash Characteristics	Day of Week	0 = Weekday	703	69.67	422	61.69	771	67.85
		1 = Weekend	306	30.33	262	38.30	366	32.16
	Lighting Condition	0 = Light	755	74.83	519	75.88	854	75.08
		1 = No Light	254	25.17	165	24.12	283	24.92
	Time of Day	0 = Daytime	744	73.74	511	74.71	819	72.05
		1 = Nighttime	265	26.26	173	25.29	318	27.95
	Angle Crash	0 = No	806	79.88	577	84.36	934	82.16
		1 = Yes	203	20.12	107	15.64	203	17.85
	Sideswipe Crash	0 = No	673	66.70	453	66.23	743	65.32
		1 = Yes	336	33.30	231	33.77	394	34.68
	Junction Related	0 = No	267	26.46	234	34.21	301	26.52
		1 = Yes	742	73.54	450	65.79	836	73.49
	Road Condition	0 = Dry	466	46.18	284	41.52	539	47.39
		1 = Not Dry	543	53.82	400	58.48	598	52.61
	Weather Condition	0 = Clear	544	53.92	323	47.22	621	54.63
		1 = Not Clear	465	46.09	361	52.78	516	45.37
	Speeding	0 = No	580	57.48	356	52.05	658	57.83
		1 = Yes	429	42.52	328	47.95	479	42.17
	Negotiating Curve	0 = No	975	96.63	648	94.74	1094	96.21
		1 = Yes	34	3.37	36	5.26	43	3.79
Geometry	Vertical Alignment	0 = Upgrade	473	46.88	325	47.52	548	48.23
		1 = Downgrade	536	53.12	359	52.49	589	51.79
	Horizontal Alignment	0 = Straight	685	67.89	455	66.52	804	70.71
		1 = Curve	324	32.11	229	33.48	333	29.29

3.4. Modeling Results and Discussions

Three separate models were developed using logistic regression with the Bayesian inference approach, where the effects on injury severity were found to be different for the car drivers, car passengers, and truck occupants. The parameter estimates along with the estimated error, credible intervals, and convergence statistic ($\hat{R}$) of the significant variables are presented in the modeling results. The factors affecting the injury severity of the car drivers, car passengers, and truck occupants are shown in tables 3.3, 3.4, and 3.5, respectively. For each predictor in the models, $\hat{R}$ was found to be 1, indicating perfect convergence. Also, the number of effective variables (pD) was found closer to the actual number of significant variables, which implies the non-complexity of the models.

3.4.1. Car Driver Model

The factors affecting the injury severity of car drivers were broadly categorized into the characteristics of the car driver, truck driver, crash, and roadway geometrics. The results indicated that the estimated odds of a severe injury were increased by 3.9, 2.5, 4.3, and 15.6 times with the car drivers being old, female, impaired, and non-Wyoming residents, respectively. Non-Wyoming drivers are not familiar with the challenging roadway along I-80 in Wyoming and high presence of trucks, resulting in more severe crashes. The protection provided by seatbelts and airbags was found to be effective in reducing severe injuries of car drivers. The estimated odds of a severe injury were found to be increased by 9.1 and 3.6 times when the seat belts and airbags were not used and not deployed, respectively. The involvement of an impaired truck driver increased the estimated odds of the car driver severe injury by 2.5 times compared to a non-impaired truck driver. Among the crash characteristics, the severe injury was decreased by estimated odds of 0.4 times during weekends. The reason behind this is a lower percentage of trucks on weekends. The nighttime and sideswipe crashes were also found to reduce the severe injury by estimated odds of 0.3 and 0.2 times respectively, compared to daytime and crash types other than a sideswipe. People are more cautious while driving at night. Sideswipes typically cause property damage only, with no or minor injuries. These are the most probable reasons for reduced severe injuries. Unlit conditions, angle crashes, presence of junctions, icy, wet or snowy roads, and speeding were found to increase the estimated odds of a severe injury by 4.3, 2.6, 3.4, 2.6, and 2.4 times respectively. Among the roadway geometrics, the estimated odds of a severe injury were found 1.9 and 2 times higher for the presence of vertical downgrades and curve segments respectively.

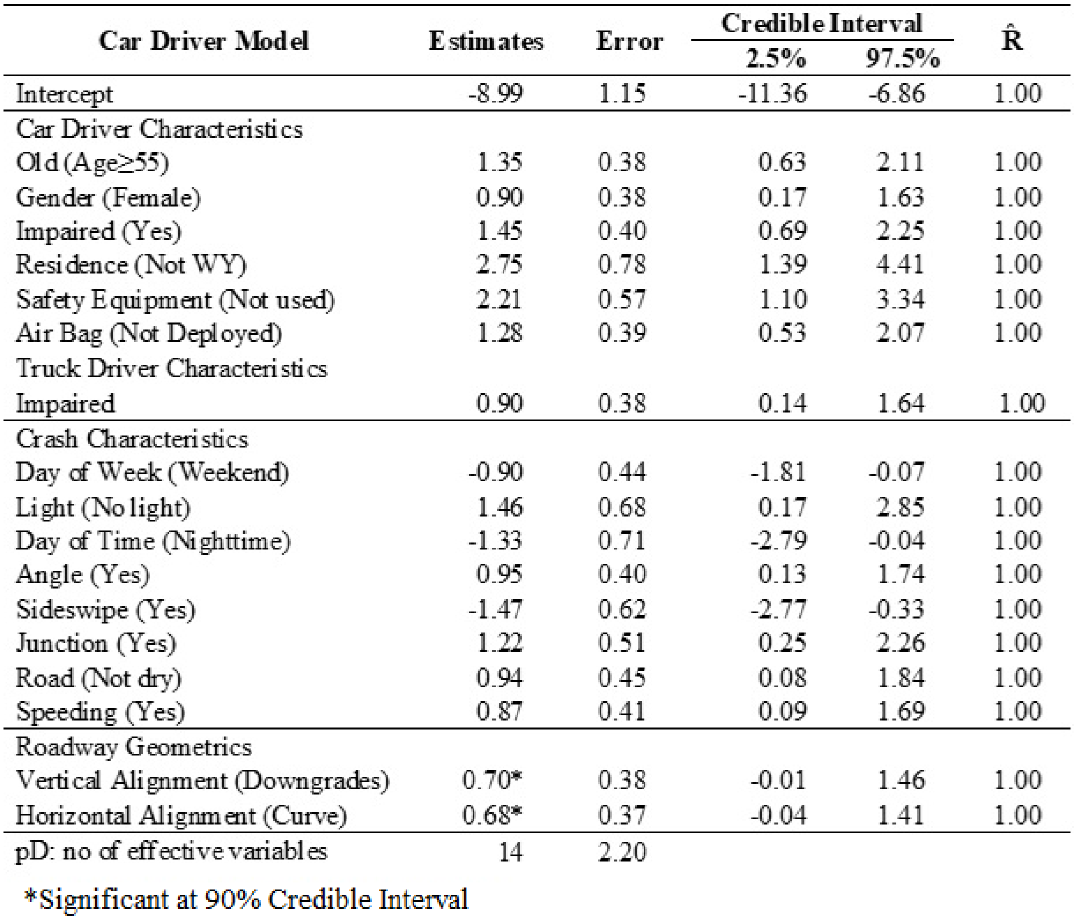
3.4.2. Car Passenger Model

The factors affecting the injury severity of car passengers were broadly classified into the characteristics of car passenger, car driver, truck driver, crash, and roadway geometrics. The results indicated that the estimated odds of a severe injury were increased by 2.8 and 1.9 times when the car passengers were old and female, respectively. Sitting in the second row was found to increase the severe injury of passengers by estimated odds of two times compared to sitting in the front row. Wyoming has a mandatory seat belt use law for all occupants, regardless of the sitting position. However, it was observed that the passengers sitting in the second row were less likely to wear a seatbelt. The severe injury was increased by the estimated odds of 3.6 times when the passengers did not use seat belts. The presence of an impaired car driver, truck driver, and airbags not being deployed increased the severe injury by estimated odds of 3.3, 2.8, and 4.1 times, respectively. Crashes occurring on weekends and during nighttime were found to have reduced severe injuries by estimated odds of 0.4 and 0.2 times when compared to weekdays and daytime. Unlit conditions, sideswipe crashes, icy, wet and snowy roads, adverse weather, and speeding were found to increase the estimated odds of a severe injury by 4.2, 3.1, 3.7, 2.8, and 2.3 times, respectively. Among the roadway geometrics, the estimated odds of a severe injury were found 1.9 and 2 times higher for the presence of vertical downgrades and curve segments respectively.

3.4.3. Truck Occupant Model

The factors affecting the injury severity of truck occupants were broadly grouped into the characteristics of the truck occupant, crash, and roadway geometrics. Car driver characteristics were found insignificant in this case. Occupants in trucks where the drivers used alcohol and illegal drugs were likely to experience more severe injuries by estimated odds of 5.5 and 7.1 times, respectively. If the truck driver was employed in the transportation sector, the truck occupants were likely to experience a severe injury by estimated odds of 1.7 times as compared to other truck driver occupations. Truck occupants were found to have 0.4 times less severe injuries when the truck drivers were non–Wyoming residents. Dangerous and fatigued driving was also found to increase the estimated odds of severe injuries by 2.6 and 24.5 times. The estimated odds of severe injuries were increased by 1.7, 1.8, 2.5, and 3.1 times for unlit conditions, the presence of junctions, speeding, and negotiating a curve, respectively. Downgrades were found to increase the severe injuries by an estimated odd of 1.7 times compared to upgrades.

Table 3.3. Factors affecting injury severity of car drivers.



Car Driver Model	Estimates	Error	Credible Interval		$\hat{R}$
			2.5%	97.5%	
Intercept	-8.99	1.15	-11.36	-6.86	1.00
Car Driver Characteristics					
Old (Age≥55)	1.35	0.38	0.63	2.11	1.00
Gender (Female)	0.90	0.38	0.17	1.63	1.00
Impaired (Yes)	1.45	0.40	0.69	2.25	1.00
Residence (Not WY)	2.75	0.78	1.39	4.41	1.00
Safety Equipment (Not used)	2.21	0.57	1.10	3.34	1.00
Air Bag (Not Deployed)	1.28	0.39	0.53	2.07	1.00
Truck Driver Characteristics					
Impaired	0.90	0.38	0.14	1.64	1.00
Crash Characteristics					
Day of Week (Weekend)	-0.90	0.44	-1.81	-0.07	1.00
Light (No light)	1.46	0.68	0.17	2.85	1.00
Day of Time (Nighttime)	-1.33	0.71	-2.79	-0.04	1.00
Angle (Yes)	0.95	0.40	0.13	1.74	1.00
Sideswipe (Yes)	-1.47	0.62	-2.77	-0.33	1.00
Junction (Yes)	1.22	0.51	0.25	2.26	1.00
Road (Not dry)	0.94	0.45	0.08	1.84	1.00
Speeding (Yes)	0.87	0.41	0.09	1.69	1.00
Roadway Geometrics					
Vertical Alignment (Downgrades)	0.70*	0.38	-0.01	1.46	1.00
Horizontal Alignment (Curve)	0.68*	0.37	-0.04	1.41	1.00
pD: no of effective variables	14	2.20			

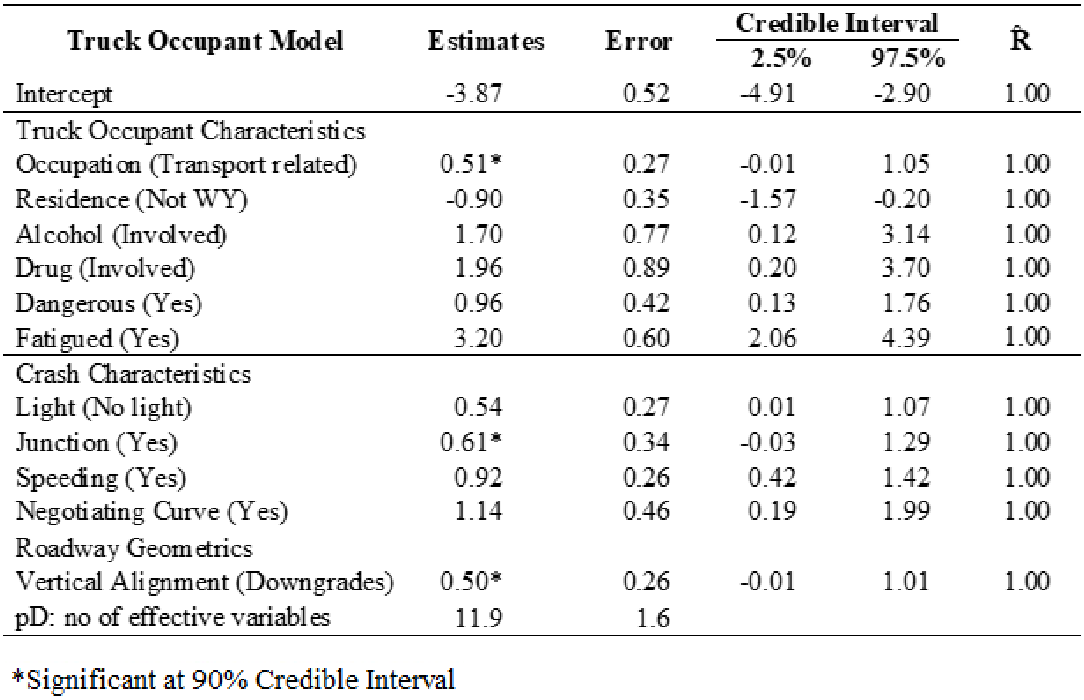
*Significant at 90% Credible Interval

Table 3.4. Factors affecting injury severity of car passengers.

Car Passenger Model	Estimates	Error	Credible Interval 2.5%	Credible Interval 97.5%	$\hat{R}$
Intercept	-9.74	1.12	-12.00	-7.67	1.00
Car Passenger Characteristics					
Old (Age≥55)	1.01*	0.58	-0.03	2.18	1.00
Gender (Female)	0.68	0.35	0.02	1.37	1.00
Seating Position (Other row)	0.69	0.35	0.02	1.37	1.00
Safety Equipment (Not used)	1.27	0.43	0.42	2.09	1.00
Air Bag (Not Deployed)	1.41	0.53	0.39	2.48	1.00
Car Driver Characteristics					
Impaired (Yes)	1.19	0.41	0.37	2.01	1.00
Truck Driver Characteristics					
Impaired (Yes)	1.02	0.37	0.27	1.75	1.00
Crash Characteristics					
Day of Week (Weekend)	-0.85	0.36	-1.58	-0.16	1.00
Light (No light)	1.43	0.67	0.17	2.75	1.00
Day of Time (Nighttime)	-1.45	0.66	-2.80	-0.21	1.00
Sideswipe (Yes)	1.12	0.43	0.32	2.02	1.00
Road (Not dry)	1.32	0.66	0.08	2.66	1.00
Weather (Not clear)	1.04	0.49	0.12	2.05	1.00
Speeding (Yes)	0.85	0.42	0.04	1.69	1.00
Roadway Geometrics					
Vertical Alignment (Downgrades)	0.66*	0.35	-0.01	1.34	1.00
Horizontal Alignment (Curve)	0.70	0.35	0.02	1.38	1.00
pD: no of effective variables	15.4	2.2			

*Significant at 90% Credible Interval

Table 3.5. Factors affecting injury severity of truck occupants.



Truck Occupant Model	Estimates	Error	Credible Interval 2.5%	Credible Interval 97.5%	$\hat{R}$
Intercept	-3.87	0.52	-4.91	-2.90	1.00
Truck Occupant Characteristics					
Occupation (Transport related)	0.51*	0.27	-0.01	1.05	1.00
Residence (Not WY)	-0.90	0.35	-1.57	-0.20	1.00
Alcohol (Involved)	1.70	0.77	0.12	3.14	1.00
Drug (Involved)	1.96	0.89	0.20	3.70	1.00
Dangerous (Yes)	0.96	0.42	0.13	1.76	1.00
Fatigued (Yes)	3.20	0.60	2.06	4.39	1.00
Crash Characteristics					
Light (No light)	0.54	0.27	0.01	1.07	1.00
Junction (Yes)	0.61*	0.34	-0.03	1.29	1.00
Speeding (Yes)	0.92	0.26	0.42	1.42	1.00
Negotiating Curve (Yes)	1.14	0.46	0.19	1.99	1.00
Roadway Geometrics					
Vertical Alignment (Downgrades)	0.50*	0.26	-0.01	1.01	1.00
pD: no of effective variables	11.9	1.6			

*Significant at 90% Credible Interval

3.5. Conclusions

The goal of this section of the study was to examine the contributing factors on occupant injury severity in car-truck crashes. Ten years (2007 - 2016) of historical crash data in the State of Wyoming were used to perform the analysis. More than 50 percent of crashes were truck-related and a major portion of fatalities was observed in car-truck collisions along I-80 in Wyoming.

Binary logistic regression with Bayesian inference approach was applied to develop the injury-severity models based on the car driver, car passenger, and truck occupant categories. The modeling results indicated significant effects of the various driver, passenger, crash, and geometrical characteristics. Old and female car drivers and passengers were found to experience more severe injuries in truck-involved crashes. Occupant behavior characteristics, such as impaired driving, use of alcohol or illegal drugs, seatbelts not being used, fatigue and dangerous driving, were found to increase the injury severity significantly. Therefore, more enforcement and education programs should be introduced to facilitate the safety improvements for both car and truck occupants. The availability of airbags should be ensured in all vehicles. Drivers from other states should prepare themselves appropriately to drive in heavy truck traffic and challenging roadway conditions. The presence of junction and the various adverse weather condition was also found to contribute to severe injuries. Potential countermeasures resulting from this research could include installation of upgraded warning systems at truck stops, restaurants, and gas stations that will give real-time visual information on the existing road and weather conditions, implementation of advance warning signs at severe upgrade and downgrade mountain passes throughout the state, and introducing training for car drivers, as well as for truck drivers, on how to drive around large trucks that also include different strategies to avoid risky driving in ramps, inclement weather, and adverse road condition. Several data limitations and gaps were encountered in this study. The CARE crash database has many missing or unknown values in the investigated variables, which were discarded in this study because they could bias the modeling results.

The SPFs and CMFs developed in this research were implemented in an Excel model (Safety_models.xlsx) that complements the analysis. The model can predict crash frequencies and safety benefits from different countermeasures, with a focus on climbing lanes. This Excel model is calibrated to be used for I-80, in Wyoming, but with sufficient data can be recalibrated for other facilities.

4. CRASH TYPES, INTERCHANGE AND VEHICLE DEFECTS AS CRASH CONTRIBUTING FACTORS

An additional analysis of crash characteristics was conducted to examine important factors potentially contributing to crash occurrences. The investigated characteristics include crash types, interchange types, and vehicle defect types. These parameters were used to determine the crash frequencies along the I-80 corridor in Wyoming for the study period (2007-2016).

4.1. Descriptive Statistics of Crash Types

Table 4.1 shows a descriptive statistic of various crash types categorized into crash severity, manner of collision, junction relation, runoff, lane departure, wild animals, speeding, and negotiating curves. The results show that on average, more than 75 percent of the crashes were PDO crashes, while injury crashes included about 20 percent. Fatal and other unknown severity accounted for the remaining 5 percent of the crashes. Similar results of crash severity were found for truck-related crashes.

The manner of collision presented in table 4.2 shows different collision types, such as angle, head-on, rear-end, sideswipe, etc. The analysis showed that about 20 percent of all crashes along I-80 in Wyoming were either rear-end or sideswipe type. For trucks, these collisions contributed about 44 percent of truck-related crashes. Trucks have large physical dimensions, more restrictive acceleration and braking capabilities, and large blind spots that could be responsible for the rear end and sideswipe collisions. Angle, head-on, and other types of collisions accounted for the rest of the crashes.

While analyzing the junction relation to crashes, it was found that 70 percent of all vehicles and 75 percent of truck-related crashes occurred at the presence of a junction. Junction included any types of interchanges and ramps. The results also indicated significant amounts of runoff and lane departure related crashes accounting for 61 percent and 80 percent, respectively, for all crashes, and 42 percent and 74 percent, respectively, for truck-related crashes.

Speeding has been found as one of the major contributing factors accounting for 44 percent of total and truck-related crashes. The study also analyzed wild animal collisions and crashes while negotiating curves along I-80 in Wyoming. However, the results did not show any significant correlation in these cases.

Table 4.1. Descriptive statistics of crash types for aggregated crash data.

Crash Type	Categories	All Vehicles		Trucks	
		No. of Crash	Percent	No. of Crash	Percent
Crash Severity	Fatal Crashes	168	1%	90	1%
	Injury Crashes	3635	20%	1735	20%
	PDO Crashes	13965	78%	6907	79%
	Unknown	126	1%	39	0%
Manner of Collision	Angle	804	4%	776	9%
	Head On	94	1%	90	1%
	Not a Collision	10411	58%	3331	38%
	Null Value	1280	7%	0	0%
	Other/Unknown	1715	10%	721	8%
	Rear End	2071	12%	2191	25%
	Sideswipe	1519	8%	1662	19%
Junction Relation	Junction	12515	70%	6589	75%
	Non-Junction	3640	20%	2000	23%
	Null Value	1416	8%	13	0%
	Unknown	323	2%	169	2%
Runoff	No	7051	39%	5102	58%
	Yes	10843	61%	3669	42%
Lane Departure	No	3535	20%	2284	26%
	Yes	14359	80%	6487	74%
Speeding	No	10096	56%	4876	56%
	Yes	7798	44%	3895	44%
Wild Animals	No	16455	92%	8704	99%
	Yes	1439	8%	67	1%
Negotiating Curve	No	16690	93%	8305	95%
	Yes	1204	7%	466	5%

4.2. Effects of Interchange Types on Crashes

I-80, in Wyoming, currently has 87 interchanges, most of them with a diamond geometry. Other interchanges include full cloverleaf, partial cloverleaf, three-directional, trumpet, and double quadrant. Table 4.2 and table 4.3 present crash descriptive statistics for interchange types for the aggregated 10 years of all vehicles and truck-related crash data. The variables investigated within these interchanges include crash severity, manner of collision, runoff, lane departure, speeding, work zone, negotiating a curve, and the presence of a drop lane. The results indicated that the majority of crashes occurred in diamond interchanges, followed by trumpet interchanges. While analyzing the manner of collisions, rear-end type contributed to the highest amount of crashes. The reason could be speeding by the vehicles, which is also investigated in the following category.

A significant number of runoff and lane departure crashes were found in the vicinity of interchanges. The presence of a drop lane facilitates the safe exit from the freeway, or entry onto the freeway. A manual data extraction process was performed in this study using non-traditional data sources. Google Earth Pro® and Google Maps® were used to confirm the existence of drop lanes along the whole 402-mile I-80 corridor, in Wyoming, for both directions. The analysis showed no significant differences in crashes with the presence or absence of a drop lane.

Table 4.2. Descriptive statistics of interchange types for aggregated vehicle crash data.

Variables		**Interchange Type**					
		Diamond	**Double Quadrant**	**Full Cloverleaf**	**Partial Cloverleaf**	**Three Directional**	**Trumpet**
Number of Crashes		9894	137	184	561	104	1288
Crash Severity	Fatal	117	2	1	6	1	17
	Injury	2099	29	30	110	18	272
	PDO	7608	106	151	445	83	983
	Unknown	70	0	2	0	2	16
Manner of Collision	Angle	520	4	8	28	4	78
	Head On	51	0	2	4	0	6
	Non Collision	7195	105	140	403	75	932
	Other	104	2	1	3	2	16
	Rear End	1170	15	23	74	13	144
	Sideswipe	854	11	10	49	10	112
Speeding	No	5407	84	104	287	53	745
	Yes	4487	53	80	274	51	543
Runoff	No	3197	32	51	209	23	360
	Yes	6697	105	133	352	81	928
Lane Departure	No	1256	14	22	77	11	142
	Yes	8638	123	162	484	93	1146
Work Zone	No	9521	134	167	554	100	1250
	Yes	373	3	17	7	4	38
Negotiating Curve	No	9152	124	167	505	85	1044
	Yes	742	13	17	56	19	244

Table 4.3. Descriptive statistics of interchange types for aggregated truck crash data.

Variables		**Interchange Type**					
		Diamond	**Double Quadrant**	**Full Cloverleaf**	**Partial Cloverleaf**	**Three Directional**	**Trumpet**
Number of Crashes		5442	74	50	316	40	491
Crash Severity	Fatal	70	1	0	3	1	6
	Injury	1050	11	10	60	8	92
	PDO	4297	62	40	253	31	388
	Unknown	25	0	0	0	0	5
Manner of Collision	Angle	515	2	9	26	2	62
	Head On	45	0	1	3	0	3
	Non Collision	2454	40	18	143	13	189
	Other	114	1	0	2	3	13
	Rear End	1333	21	16	81	11	112
	Sideswipe	981	10	6	61	11	112
Speeding	No	3085	52	36	161	26	300
	Yes	2357	22	14	155	14	191
Runoff	No	2968	36	33	197	23	276
	Yes	2474	38	17	119	17	215
Lane Departure	No	1377	19	15	83	10	109
	Yes	4065	55	35	233	30	382
Work Zone	No	5192	70	41	306	37	463
	Yes	250	4	9	10	3	28
Negotiating Curve	No	5133	69	46	289	39	391
	Yes	309	5	4	27	1	100
Drop Lane	Westbound Direction						

4.3. Vehicle Defects as Crash Contributing Factors

The vehicle should be in good condition so that it handles well while being driven along the roadway. Table 4.4 shows vehicle defect related crashes along I-80, in Wyoming, for aggregated 10 years of all vehicles and truck-related crash data (2007-2016). The analyzed types of vehicle defects include tire, brake system, cruise control, defroster, exhaust system, oversized load, engine, windshield, stalled vehicle, steering, suspension, trailer hitch, lights, wheels, wipers, and others. The result indicated that tire failure crashes contributed to the highest proportion among all other types accounting for 34 percent and 31 percent for all vehicles and trucks, respectively.

Table 4.4. Vehicle defects related crashes.

Vehicle Defects Type	All Vehicles		Trucks	
	Number of Crashes	Percent	Number of Crashes	Percent
Tires	383	34%	161	31%
Brake System	85	7%	61	12%
Cruise Control	41	4%	7	1%
Defroster	2	0%	2	0%
Exhaust System	6	1%	5	1%
Oversized Load	19	2%	6	1%
Power Train/Engine	26	2%	14	3%
Windshield	18	2%	10	2%
Stalled Vehicle	8	1%	8	2%
Steering	21	2%	5	1%
Suspension	6	1%	3	1%
Trailer Hitch	46	4%	15	3%
Vehicle Lights	4	0%	2	0%
Wheels	52	5%	22	4%
Wipers	1	0%	1	0%
Other	133	12%	68	13%
Unknown	290	25%	137	26%
Total	1141	100%	527	100%

The preliminary analysis of tire failure crashes conducted in this study are shown in figures 4.1 – 4.4. The results indicate that the major portion of tire failure crashes occurred during the summer season with the vehicle speed greater than 65 mph. Heated roadway surface and the tire friction at high speeds could be the most significant contributing factors to tire failures. Most of the major tire manufacturing companies recommend the truck speed limit from 65 mph to 75 mph, based on their loads. The posted speed limit for I-80, in Wyoming, is 75 mph and 80 mph. The excessive speed could lead to tire failures resulting in a crash.

The results show that trucks experience more tire failures compared to other vehicle types, accounting for 42 percent. Wyoming has three different truck configurations where a light truck is considered to weigh less than 10,000 pounds, a medium truck between 10,000 pounds and 26,000 pounds, and a heavy truck is more than 26,000 pounds. Pick-up trucks and SUVs are not considered as light trucks in the WYDOT database. The analysis showed that 76 percent of truck tire failures occurred in heavy trucks. The future study will develop statistical models to explore the contributing factors related to tire failure crashes.

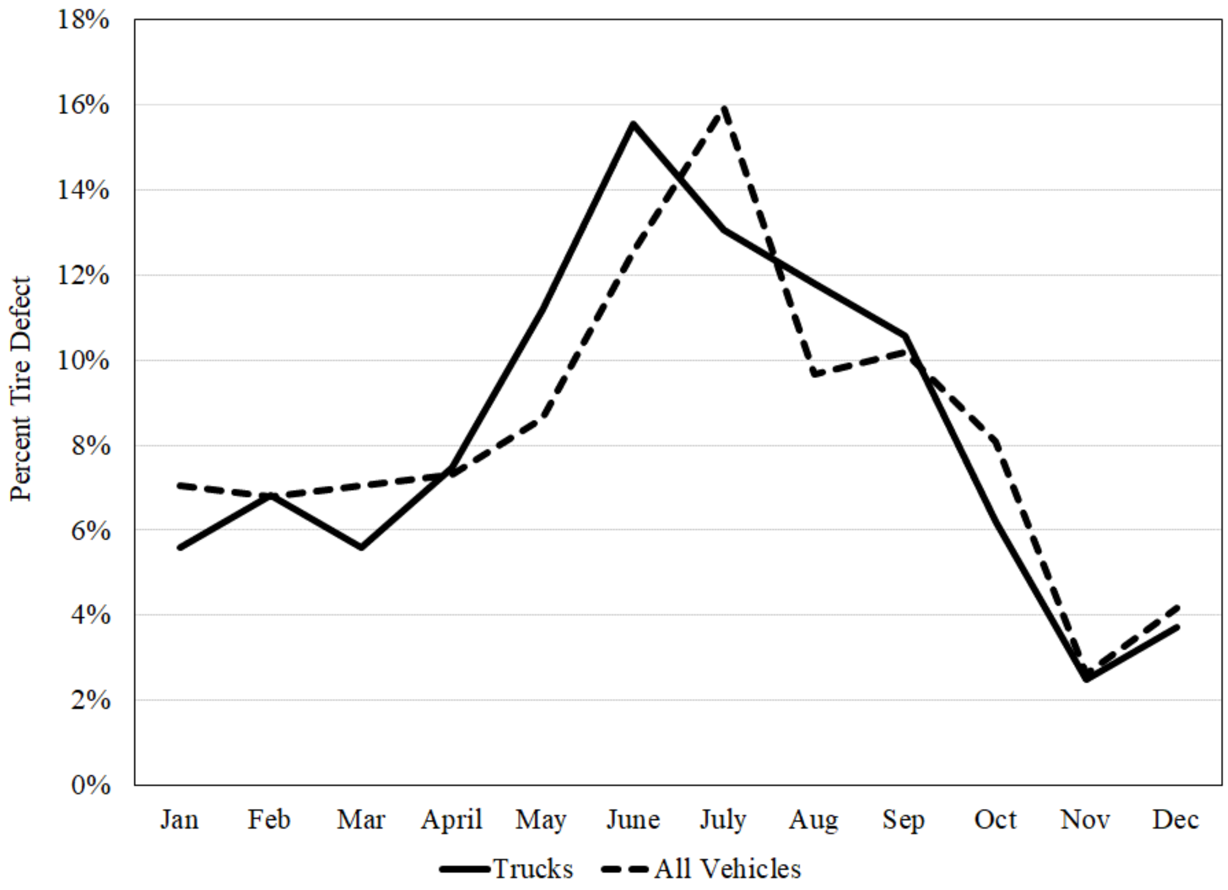


Figure 4.1. Graph. Distribution of tire failure related crashes by time of year.

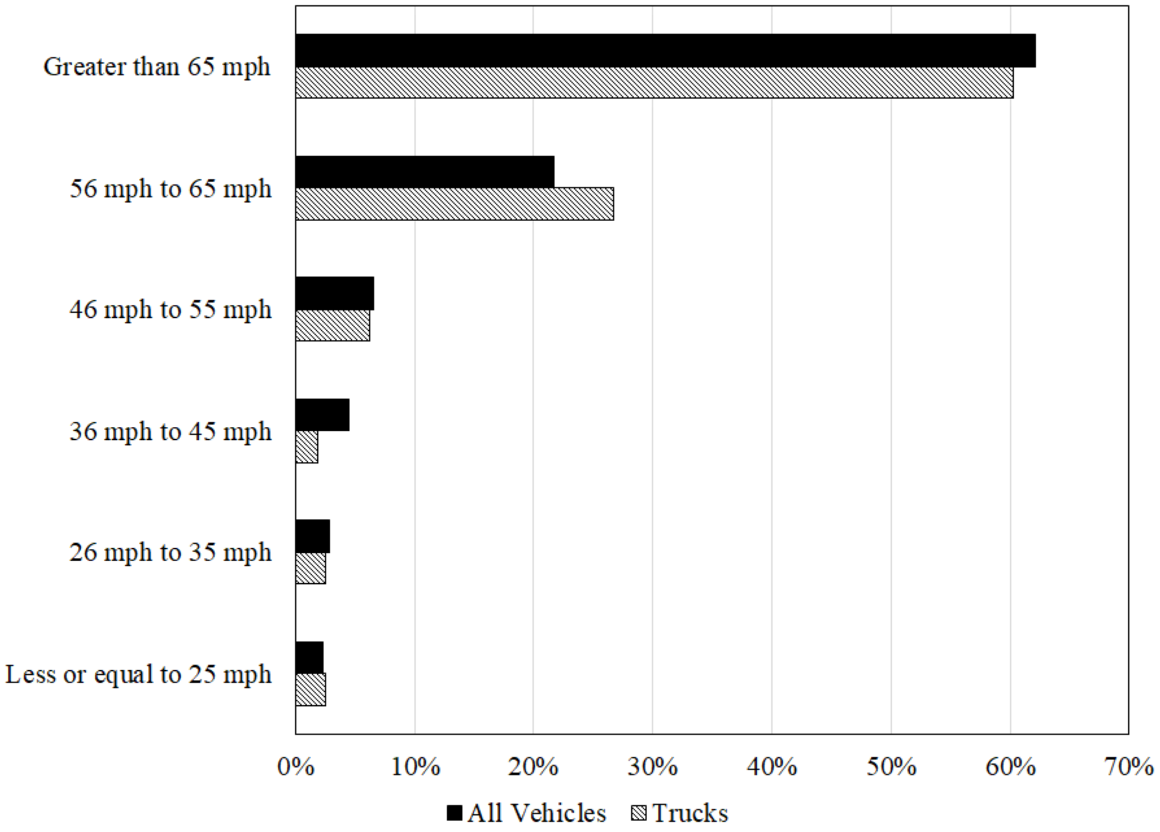


Figure 4.2. Graph. Distribution of tire failure related crashes by estimated speed.

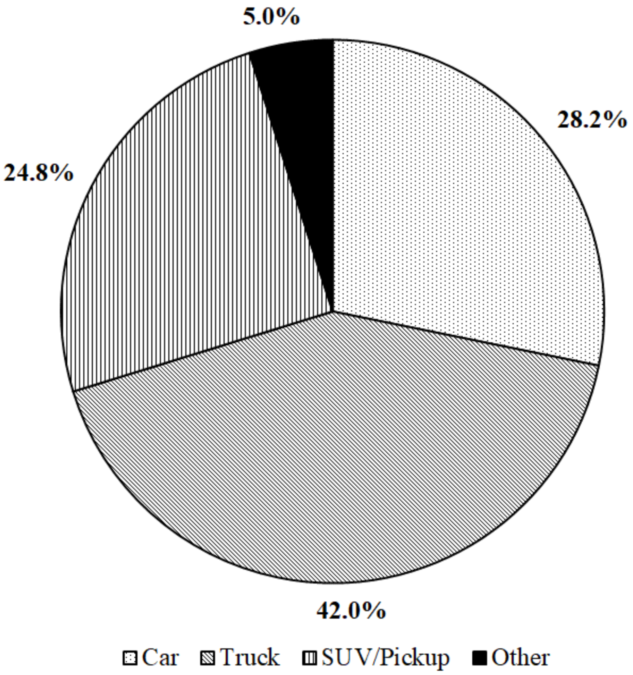


Figure 4.3. Graph. Distribution of tire failure related crashes by vehicle type.

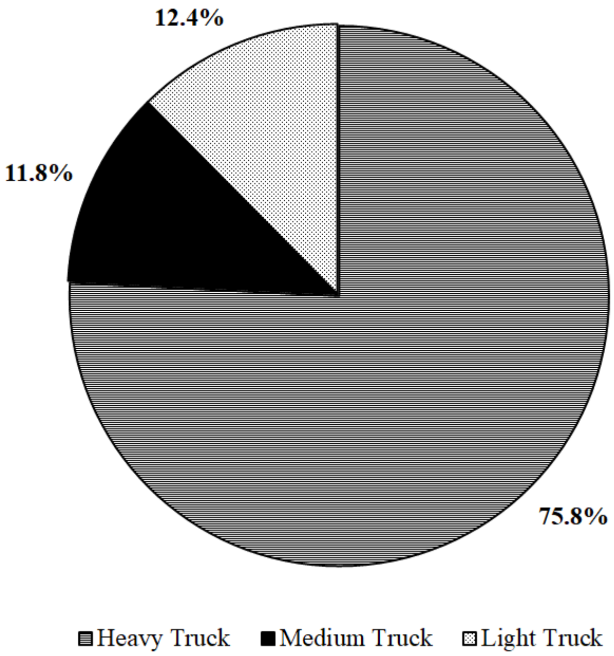


Figure 4.3. Graph. Distribution of tire failure related crashes by truck type.

The most effective countermeasure in this case would be speed enforcement for trucks, especially during summer months. Additionally, the truck drivers should be educated about the dangers related to tire failures at high speeds. An occasional VMS message to the motorist would also be useful in this case.

5. OPERATIONAL ASSESSMENT OF FREEWAY TRUCK TRAFFIC ALONG I-80, IN WYOMING

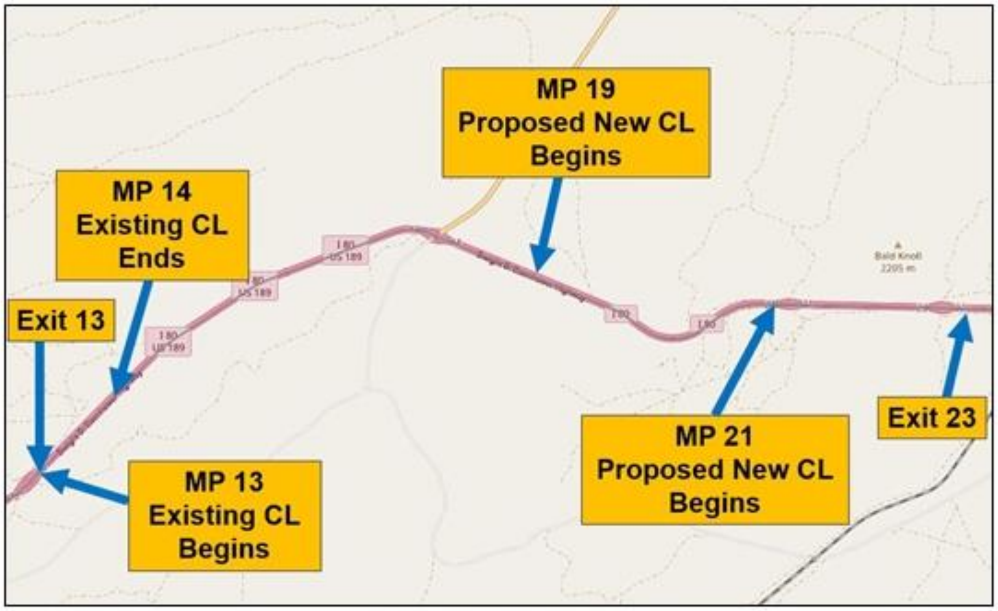
The core of the operational analysis includes developing microsimulation models for both current (year 2017) and future (year 2027 and 2037) traffic conditions. Creation of the models was accomplished by using a combination of VISUM (mesoscopic simulation model with traffic assignment capabilities) and VISSIM (microscopic simulation model). VISUM was used to develop the base geometry and calibrate existing models for traffic volumes using its built-in functions. The models were then exported to VISSIM to model the current and projected future traffic operations. In addition, the study also developed a shock-wave based methodology for a quick and easy assessment of freeway traffic conditions.

5.1. Study Locations and Scenarios

Two test sections along I-80, in Wyoming, were selected for the analysis in this chapter. The first section along I-80 is from mile post (MP) 313 to MP 323, a 10-mile eastbound segment just east of Laramie, WY. It is a gradual uphill section, with the grade exceeding five percent, where a climbing lane exists from MP 316 to MP 319. The second location is also a 10 miles eastbound section starting from MP 13 to MP 23, several miles east of Evanston, WY, where a climbing lane exists from MP 13 to MP 14. This section is characterized by a mix of significant upgrade and downgrade portions, where the upgrade portion prevails from MP 13 to MP 14, and from MP 19 to MP 21, while the downgrade portion prevails from MP 14 to MP 19, and from MP 21 to MP 23. A recent study on I-80, in Wyoming, conducted by WYDOT and HDR recommended an additional new climbing lane from MP 317 to MP 319, and from MP 19 to MP 21, as one of the high priority locations due to the similar upgrade characteristics (WYDOT 2017). Figures 5.1 and 5.2 show the selected study locations. After the methodology has been tested and proved effective for the test sections, it was applied to a total of ten different segments of I-80 using the same scenarios. This operational analysis was used to assess the cost/benefit ratio for freeway climbing lanes, and is presented later in this document.

MP 313 - MP 323

Figure 5.1. Illustration. Study location MP 313 – MP 323.



MP 13 - MP 23

Figure 5.2. Illustration. Study location MP 13 – MP 23.

The truck composition used in this analysis was 46 percent as current, and 70 percent as the worst-case scenario based on the existing data. During adverse weather conditions, such as heavy snowfall or high winds, sometimes I-80, in Wyoming, remains temporarily closed for trucks.

When the road reopens, all the trucks travel together, and therefore, the truck percentage could exceed 70 percent. This has been identified as the worst case scenario along I-80, in Wyoming. Based on this information, different alternatives were created, and microsimulation models were developed for the existing (year 2017), and projected (year 2027 and 2037) traffic volumes, each having six different scenarios, adding up to a total of 18 scenarios, as shown in table 5.1. There is a hypothetical existing and future scenario with no climbing lanes that was used to estimate what would happen if the climbing lane were to be removed.

Table 5.1. Analysis scenarios.

Year	No.	Scenario	Description
2017	1	2017 (1)	Existing traffic volume with existing vehicle composition (46% truck) having existing climbing lane
	2	2017 (2)	Existing traffic volume with 70% truck having existing climbing lane
	3	2017 (3)	Existing traffic volume with existing vehicle composition having new climbing lane
	4	2017 (4)	Existing traffic volume with 70% truck having new climbing lane
	5	2017 (5)	Existing traffic volume with existing vehicle composition having no climbing lane
	6	2017 (6)	Existing traffic volume with 70% truck having no climbing lane
2027	7	2027 (1)	Projected traffic volume with existing vehicle composition (46% truck) having existing climbing lane
	8	2027 (2)	Projected traffic volume with 70% truck having existing climbing lane
	9	2027 (3)	Projected traffic volume with existing vehicle composition having new climbing lane
	10	2027 (4)	Projected traffic volume with 70% truck having new climbing lane
	11	2027 (5)	Projected traffic volume with existing vehicle composition having no climbing lane
	12	2027 (6)	Projected traffic volume with 70% truck having no climbing lane
2037	13	2037 (1)	Projected traffic volume with existing vehicle composition (46% truck) having existing climbing lane
	14	2037 (2)	Projected traffic volume with 70% truck having existing climbing lane
	15	2037 (3)	Projected traffic volume with existing vehicle composition having new climbing lane
	16	2037 (4)	Projected traffic volume with 70% truck having new climbing lane
	17	2037 (5)	Projected traffic volume with existing vehicle composition having no climbing lane
	18	2037 (6)	Projected traffic volume with 70% truck having no climbing lane

5.2. Development of the Base VISUM Models

The initial models of existing conditions were created in VISUM and calibrated for traffic volumes using the VISUM's built-in functions. Exported maps from Open Street Map were used as the base maps for the model creation in VISUM. Roadway geometrics, speed limits, and other physical characteristics of the networks were added using Google Earth Pro. The traffic data for the selected two segments along I-80, in Wyoming, were collected from the WYDOT databases. The 24-hour traffic volumes were obtained from the Hourly Volume report for September 2017, as a representative month. The average hourly volume was calculated based on three weekdays: Tuesday, Wednesday, and Thursday, as representative weekdays. The entering and exiting traffic volumes were balanced and adjusted for the interchanges. The existing volume was projected using a growth factor of two percent, as recommended in a previous study (Parsons Brinckerhoff 2009).

5.3. Development of the VISSIM Models

After the volume calibration in VISUM, the selected freeway segment with traffic volume inputs and routing decisions was exported to VISSIM for further model development. The models were upgraded based on the actual geometrics provided by the VISSIM background maps. The geometry was also checked through Google Street View and field visits to ensure that the models represent actual conditions. Since two ten-mile upgrade sections were used for operational analysis to investigate the efficiency of climbing lanes, the accuracy of the elevation or Z coordinates was one of the vital inputs. It was thoroughly checked and adjusted using Google Earth Pro, existing KML files, and WYDOT's roadway database.

The posted speed limit for the selected roadway sections was 75 mph. In the VISSIM models, the 85th percentile of vehicle speed was selected as 75 mph, and a cumulative distribution function was developed, where the speeds ranged between 60 mph and 85 mph, based on the available field speed data. The power-to-weight ratio for trucks was modeled based on the most common truck types for this corridor. These values were used to create custom cumulative probability functions for power and weight.

The models were run for twenty hours (4:00 am - 12:00 am) with one hour of warm-up time. Different measures were extracted for the peak hours (3:00 pm – 5:00 pm) to analyze and compare the existing and future traffic conditions for different alternatives. These measures included total delay, average speed, and average spacing of the vehicles for the selected segments.

5.4. Existing Models Calibration and Validation

Existing models were calibrated and validated based on the existing traffic volumes and average speed, as shown in figures 5.3 and 5.4. VISSIM parameters were iteratively updated until the satisfactory level of matching with field conditions was achieved. The coefficient of determination (R^2) between the field and simulated traffic volumes was 0.99 for both models, representing a good calibration fit. Validation was performed for measured and observed average speed, which was compared with the simulation results. The field volume and speed data were collected from the nearest recording station along the selected freeway segments of I-80, in Wyoming. The speed distribution of trucks on upgrades was calibrated based on the power-to-weight ratio. A range of power and weights for a typical truck was created in VISSIM, and the acceleration and deceleration of the trucks were then automatically calculated by VISSIM based on the vertical grades.

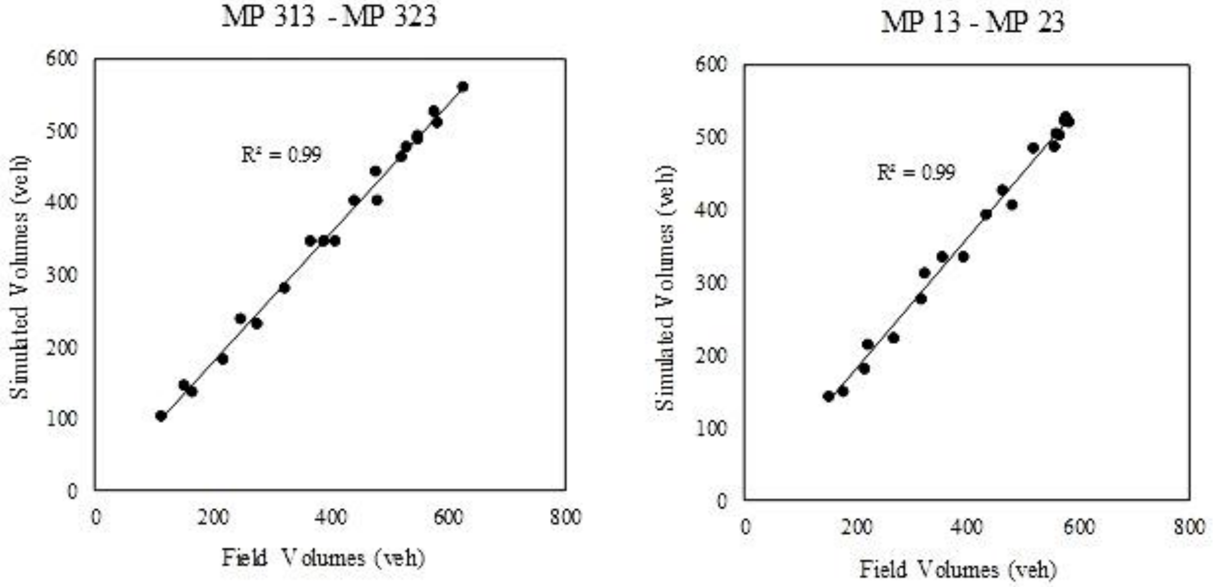


Figure 5.3: Graphs. Model calibration.

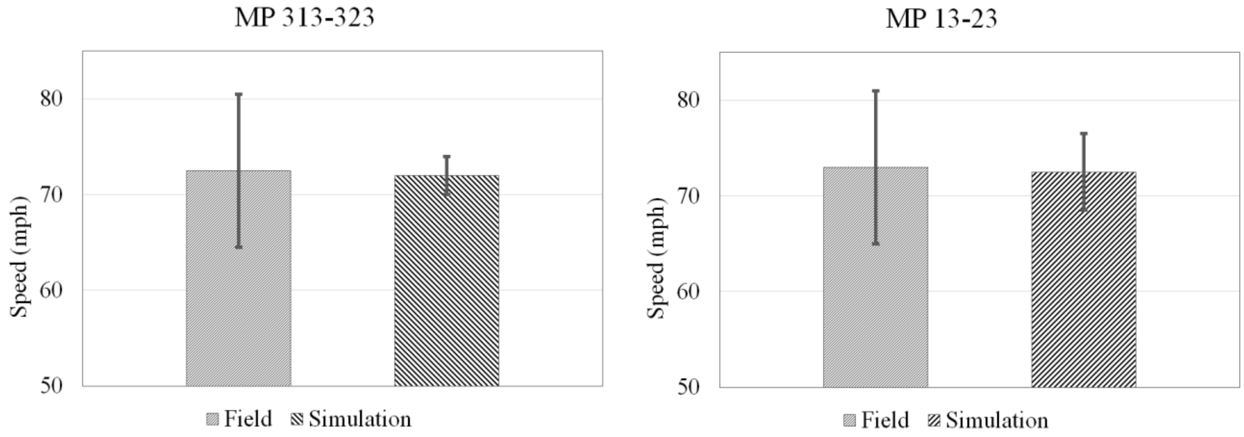


Figure 5.4: Graphs. Model validation.

5.5. Operational Analysis Results and Discussions

The simulations were run for various scenarios and the output data were extracted. The analyzed performance measures include the total delay, average speed, and vehicle spacing. The operational analysis was focused on the 2-hour PM period (3:00 pm – 5:00 pm) as the traffic volumes reached a peak during this time.

The total delay and average speed of vehicles for the two freeway sections (MP 313 – MP 323 and MP 13 – MP 23) are provided in table 5.2 and table 5.3, respectively. Comparing 2017 (1) to 2017 (2), as shown in table 5.2, the results indicated that the total delay for all vehicles and trucks significantly increased by about 60 percent, and 64 percent, respectively, while having 70 percent trucks in the composition. About 27 percent reduction in the total delay for passenger car is attributed mostly to the lower car percentage in this scenario. The average speed reduced by about 5 percent and 1 percent for all vehicles and trucks respectively, while having 70 percent trucks in the composition. However, no significant reduction in the car average speed was found in this case. A comparison of 2017 (1) to 2017 (3) shows that the total delay for all vehicles and passenger cars reduced by about 1 percent and 27 percent, respectively, when an additional new climbing lane was introduced. Very little change was found for the total truck delay in this case. Furthermore, no significant change was observed in average speed for all vehicles, passenger cars, and trucks. Compared to 2017 (2), an additional new climbing lane did not have a significant impact in increasing average speeds with 70 percent trucks in the existing traffic composition. The total delay for all vehicles and passenger cars was found to be reduced by about 1 percent and 40 percent, with a slight increase in truck delays in this case. Comparing 2017 (1) to 2017 (5) shows that the total delay for all vehicles, passenger cars, and trucks increased by about 18 percent, 365 percent, and 1 percent, respectively, when the existing climbing lane was removed. The average speed for all vehicles and passenger cars reduced by two percent and three percent, respectively, in this case. A comparison of 2017 (2) to 2017 (6) shows that the total delay for all vehicles, passenger cars, and trucks increased by about 12 percent, 489 percent, and 1 percent, respectively, without a climbing lane, and 70 percent trucks. The average speed for all vehicles and passenger cars reduced by about two percent and five percent, respectively, in this case. However, there was very little change in the average truck speed in both of this cases. This might be due to the continuous upgrade, where the trucks cannot develop higher speeds regardless of additional climbing lanes.

Table 5.2. Total delay (hr) and average speed (mph) for 2017 scenarios (MP 313 – MP 323).

Scenario	Total Delay (hr)			Average Speed (mph)		
	All Vehicles	Cars	Trucks	All Vehicles	Cars	Trucks
2017 (1)	10.06	0.48	9.58	64.98	70.65	59.09
2017 (2)	16.04	0.35	15.70	61.77	70.45	58.77
2017 (3)	9.97	0.35	9.61	65.03	70.80	59.06
2017 (4)	15.96	0.21	15.75	61.81	70.77	58.74
2017 (5)	11.88	2.23	9.65	63.96	68.60	59.03
2017 (6)	17.87	2.06	15.81	60.85	66.76	58.70

Table 5.3 shows total delays and average speeds of vehicles for MP 13 – MP 23. The results were found to be similar to the previous section. However, the total delay and the average speed for MP 13 – MP 23 was higher in most cases. This is due to the presence of a severe upgrade followed by a downgrade portion along this section. The observed speed difference between passenger cars and trucks was also lower along this section for the same reason.

Table 5.3. Total delay (hr) and average speed (mph) for 2017 scenarios (MP 13 – MP 23).

Scenario	Total Delay (hr)			Average Speed (mph)		
	All Vehicles	Cars	Trucks	All Vehicles	Cars	Trucks
2017 (1)	11.28	1.29	9.99	64.82	68.73	60.86
2017 (2)	16.11	0.71	15.40	62.93	68.71	60.75
2017 (3)	11.13	1.22	9.91	64.86	68.78	60.90
2017 (4)	15.91	0.64	15.27	62.99	68.79	60.79
2017 (5)	12.76	3.01	9.75	64.35	67.60	60.99
2017 (6)	17.11	2.18	14.94	62.63	67.02	60.92

Table 5.4 and table 5.5 present percentage increase in total delay and percentage reduction in average speed between current (year 2017) and future (year 2027 and year 2037) traffic condition for two sections, MP 313 – MP 323 and MP 13 – MP 23, respectively. In general, there was a higher increase in total delays for passenger cars than for trucks along both sections, meaning that cars are more affected by the high truck percentage and upgrades than trucks. For both sections, the maximum increase in total delays was found in scenario 5 for passenger cars (the scenario with no climbing lanes and existing truck composition), and in scenario 6 for trucks (the scenario with no climbing lanes and 70 percent truck composition). The minimum increase in total delays was found in scenario 3 for all vehicles, which was the scenario for an additional new climbing lane and existing truck composition in both sections. Therefore, the additional climbing lane has the potential to reduce the total delay for all vehicles.

The reduction in average speed between current and future traffic conditions was higher for passenger cars than for trucks in most cases, except in the scenario with an additional climbing lane for the MP 313 – MP 323 section. The highest speed reduction was observed in scenario 6 for both passenger cars and trucks, which was the scenario with no climbing lanes and 70 percent truck composition. The lowest speed reduction was recorded in scenario 3 for all vehicles, which was the scenario for an additional new climbing lane and existing truck composition in both sections. Therefore, it can be concluded that having an additional new climbing lane has the potential to improve the average speed for all vehicles, although no significant change was recorded in the average speeds. This is due to the upgrade, where cars and trucks cannot develop higher speeds regardless of additional climbing lanes.

Table 5.4. Percentage increase in total delay and percentage reduction in average speed between current and future traffic conditions (MP 313 – MP 323).

Scenario	Percentage Increase in Total Delay			Percentage Reduction in Average Speed		
	All Vehicles	Cars	Trucks	All Vehicles	Cars	Trucks
2017 (1) vs 2027 (1)	24.82%	67.01%	22.72%	0.19%	0.28%	0.22%
2017 (2) vs 2027 (2)	24.84%	66.05%	23.93%	0.28%	0.36%	0.33%
2017 (3) vs 2027 (3)	24.23%	63.79%	22.78%	0.15%	0.19%	0.23%
2017 (4) vs 2027 (4)	24.37%	64.09%	23.83%	0.23%	0.20%	0.32%
2017 (5) vs 2027 (5)	32.40%	71.10%	23.46%	0.82%	1.40%	0.33%
2017 (6) vs 2027 (6)	27.84%	53.25%	24.52%	0.67%	1.45%	0.42%
2017 (1) vs 2037 (1)	59.78%	170.05%	53.36%	0.57%	0.75%	0.57%
2017 (2) vs 2037 (2)	58.35%	172.22%	55.83%	0.73%	0.82%	0.88%
2017 (3) vs 2037 (3)	57.18%	180.62%	53.10%	0.44%	0.52%	0.53%
2017 (4) vs 2037 (4)	57.61%	183.90%	55.48%	0.62%	0.54%	0.85%
2017 (5) vs 2037 (5)	79.69%	184.36%	55.49%	1.95%	3.13%	0.82%
2017 (6) vs 2037 (6)	67.08%	142.82%	57.19%	1.62%	3.45%	1.05%

Table 5.5. Percentage increase in total delay and percentage reduction in average speed between current and future traffic conditions (MP 13 – MP 23).

Scenario	Percentage Increase in Total Delay			Percentage Reduction in Average Speed		
	All Vehicles	Cars	Trucks	All Vehicles	Cars	Trucks
2017 (1) vs 2027 (1)	27.66%	62.10%	23.20%	0.30%	0.44%	0.18%
2017 (2) vs 2027 (2)	27.00%	74.51%	24.81%	0.36%	0.49%	0.33%
2017 (3) vs 2027 (3)	26.28%	63.38%	23.03%	0.29%	0.43%	0.17%
2017 (4) vs 2027 (4)	27.44%	74.28%	24.26%	0.32%	0.43%	0.27%
2017 (5) vs 2027 (5)	56.83%	121.17%	36.98%	3.95%	4.20%	3.74%
2017 (6) vs 2027 (6)	51.13%	117.34%	41.49%	4.26%	4.70%	4.10%
2017 (1) vs 2037 (1)	67.07%	165.95%	54.28%	0.69%	1.00%	0.46%
2017 (2) vs 2037 (2)	64.59%	204.75%	55.86%	0.82%	1.16%	0.57%
2017 (3) vs 2037 (3)	56.69%	73.55%	54.62%	0.46%	0.55%	0.48%
2017 (4) vs 2037 (4)	57.27%	77.99%	56.40%	0.57%	0.65%	0.53%
2017 (5) vs 2037 (5)	78.44%	158.08%	57.86%	1.22%	2.04%	0.43%
2017 (6) vs 2037 (6)	68.01%	151.43%	58.13%	1.05%	2.31%	0.73%

The average vehicle spacing was recorded from VISSIM for two locations: the section before a climbing lane, and the section within a climbing lane. This spacing is the shortest average distance achievable between two passing vehicles without a reduction in the speed of vehicles. Table 5.6 provides the average vehicle spacing in feet for the existing scenario. The results show that the average spacing was always higher for both passenger cars and trucks when traveling through a climbing lane segment, compared to the segment without a climbing lane, which has the potential to improve both operational and safety performances. It was also found from this analysis that the average spacing was lower in MP 13 – MP 23, compared to the MP 313 – MP 323 section. This is caused by a severe upgrade followed by a downgrade portion in MP 13 – MP 23, which causes the vehicles to travel closer to each other, compared to the continuously upgrade portion in MP 313 – MP 323.

Table 5.6. Average spacing (ft) for existing scenarios.

MP 313 - MP 323							
Scenario	**Lane**	**All Vehicles**		**Cars**		**Trucks**	
		Before CL	**Within CL**	**Before CL**	**Within CL**	**Before CL**	**Within CL**
2017 (1)	1	623.52	705.15	546.46	557.01	705.42	725.68
	2	623.33	684.90	548.42	595.29	705.65	719.01
MP 13 - MP 23							
Scenario	**Lane**	**All Vehicles**		**Cars**		**Trucks**	
		Before CL	**Within CL**	**Before CL**	**Within CL**	**Before CL**	**Within CL**
2017 (1)	1	417.52	439.90	397.16	422.95	421.04	456.99
	2	401.43	445.63	403.59	448.21	405.77	446.38

The operational analyses performed through microsimulation led to the following conclusions:

- The installation of climbing lanes has the potential to improve operational performances (e.g. reduce the total delay and increase the average speed) for a 10 and 20-year planning horizon.
- No significant change in average speed was found for cars and trucks. This is due to the upgrade, where cars and trucks cannot develop higher speeds regardless of additional climbing lanes.
- Space headway of vehicles was found higher when traveling through a climbing lane segment compared to the segment without a climbing lane, which has the potential to improve both operational and safety performances.
- The operational performance of passenger cars was much more affected with no climbing lanes segments, compared to the performance of trucks.

6. TRAFFIC SHOCKWAVE MODELS FOR OPERATIONAL ANALYSIS

6.1. Traffic Shockwave and Platoon Definition

Traffic shockwave is a phenomenon that occurs in a traffic stream during the transition between two traffic states. Whenever there is a change in one of the three main traffic flow parameters (flow, density and speed), it causes a change in the other two, creating a new traffic state. The shockwave principal is illustrated in figure 3.1. State 1 is characterized by the flow q_1, density k_1 and speed u_1. In State 2, these are changed to q_2, k_2, and u_2. The transition between the two States represents the front of the shockwave, w. The shockwave moves with a speed u_w, which is computed according to the equation presented in figure 6.2.

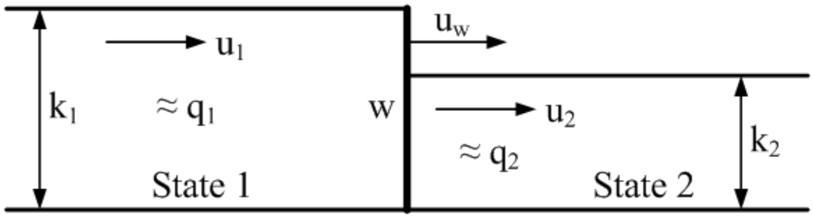


Figure 6.1. Illustration. State transition and traffic shockwave formation.

$$u_w = \frac{q_2 - q_1}{k_2 - k_1} = \frac{\Delta q}{\Delta k}$$

Figure 6.2. Equation. Shock wave speed.

Two types of traffic shockwaves that occur are the forming (transitioning to higher density), and recovering (transitioning to lower density) shockwaves. The most common cause of traffic shockwaves is the change in capacity or speed, such as bottlenecks or slow moving vehicles. Figure 6.3 shows the theoretical representation of the Greenshields' flow-density (q-k) diagram that demonstrates a shockwave that occurs between two traffic states. State 1 is characterized by the capacity C_1 and density at capacity k_1^C. State 2 is characterized by the capacity C_2, and for demonstration purposes it is assumed that its density at capacity k_2^C is the same as for State 1. State 2, with its lower capacity, typically represents a bottleneck (e.g. lane drop). The flow in State 1 is q_1, and it is lower than the capacity C_1. However, when the traffic transitions into State 2, its capacity C_2 is lower than the demand q_1 and the discharge rate becomes q_2. This causes a forming shockwave u_w which creates a moving queue at the border of the two states. Queue analysis using traffic shockwaves is a more realistic representation than the classic queuing theory.

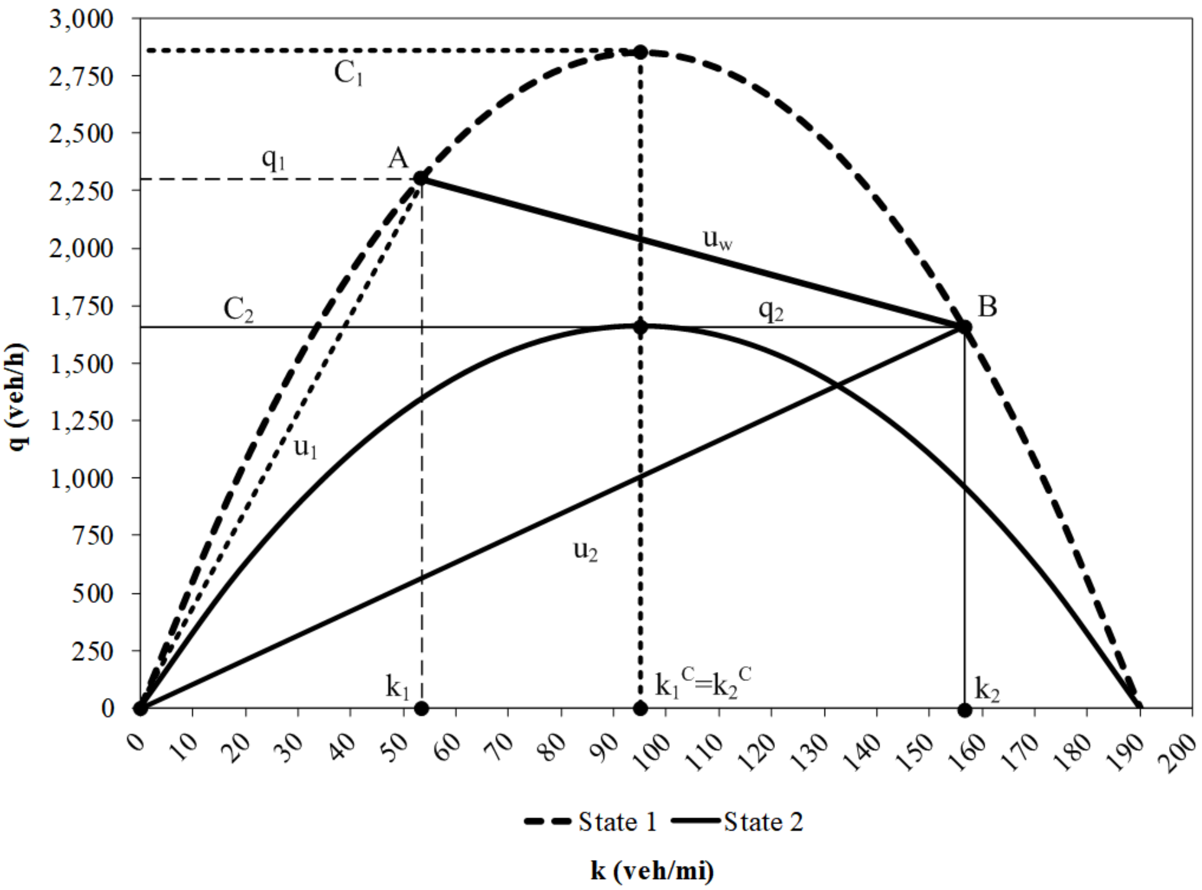


Figure 6.3. Graph. Flow-Density representation of traffic shockwaves.

To understand congestion patterns and impacts, it is important to analyze the formation and characteristics of shockwaves. Platoon is defined as a moving queue, i.e. a cluster of vehicles traversing through bottleneck. In a platoon analysis using shockwaves, there are usually three states to consider: normal conditions (undersaturated), bottleneck (reduced capacity/increased demand), and the end of bottleneck (recovery). The growth of platoon over time (in mph) is given in the equation in figure 6.4.

$$u_{pg} = u_{lead} - u_{w12}$$

Figure 6.4. Equation. Platoon growth rate.

In the previous equation, the variables are defined as follows:

u_{lead} = speed of first (leading) vehicle in platoon (the speed of traffic in State 2)

u_{w12} = speed of shockwave from State 1 to State 2

The shockwave speed between States 2 and 1 is given in figure 6.5.

$$u_{w12} = \frac{q_2 - q_1}{k_2 - k_1}$$

Figure 6.5. Equation. Shockwave speed between State 1 and State 2.

The length of the platoon L_p (mi) during the bottleneck conditions is computed according to the equation given in figure 6.6.

$$L_p = u_{pg} \cdot t$$

Figure 6.6. Equation. Length of platoon.

In the previous equation, t represents the duration of the bottleneck/congestion. The number of vehicles in the platoon N_p is computed from the equation in figure 6.7.

$$N_p = L_p \cdot k_2$$

Figure 6.7. Equation. Number of vehicles in platoon.

After the bottleneck ends, the traffic enters State 3, which is a recovery state. The shockwave between States 3 and 2 is computed according to the equation presented in figure 6.8.

$$u_{w23} = \frac{q_3 - q_2}{k_3 - k_2}$$

Figure 6.8. Equation. Shockwave speed between State 3 and State 2.

The net speed (rate) of platoon dissipation is given by the algebraic difference between the speeds of the front (uw_{23}) and rear (uw_{12}) shockwaves, as shown in figure 6.9.

$$u_{NET} = u_{w23} - u_{w12}$$

Figure 6.9. Equation. Net speed of platoon dissipation.

Finally, the time to disperse platoon is determined from the equation given in figure 6.10.

$$t_d = \frac{L_p}{|u_{NET}|}$$

Figure 6.10. Equation. Time to disperse platoon.

The platoon analysis using shockwaves is used to develop a model that estimates traffic operations on freeway grades with high percentage of heavy truck traffic. Some early researchers utilized deterministic queuing and shockwave methods to analyze freeway traffic under congestion (Chow 1976). Other researchers followed it up by determining the short-comings in the research and modified the methodology to provide more accurate results (McShane and Roess 1990, Chin 1996). Nam and Drew (1998) reexamined the deterministic queuing approach and shockwave method, and concluded that the two methods are fundamentally different and queueing analysis underestimates delays. From this research it is quite clear that shockwave analysis provides more accurate results when analyzing freeway traffic congestion.

Recent application of freeway congestion analysis included analysis of rear-end crash events using video-recorded shockwaves (Chatterjee and Davis 2016). The study determined the conditions in which a stopping shockwave would result in a rear-end crash on a congested freeway. They determined that the driver reaction times longer than their headway was a key factor in a crash outcome of a shockwave, and concluded that the relationship between reaction time and headway could reduce frequency of rear-end crashes in a shockwave. Another study where shockwave theory was utilized to evaluate macroscopic safety of platooned vehicles found that the shock propagation can be used as an index to evaluate safety of car-following (Suzuki and Matsunaga 2010). The authors in this study formulated mathematical models to evaluate vehicle platooning safety, and argue that through this approach it is possible to dynamically evaluate in real-time the safety of vehicle platoon by comparing required acceleration and the observed/estimated acceleration.

6.2. Calibrated HCM Speed-Flow-Density Relation

The HCM provides field-based relation among freeway speed, flow, and density. The flow-density (q-k) diagram is a combination of the triangular and Greenshields' diagrams and was calibrated for freeway conditions based on field data. Table 6.1 shows the relationships among the traffic flow parameters, and the q-k diagram is shown in figure 6.11.

Table 6.1. HCM freeway macroscopic traffic flow relations.

State	**Uncongested**		**Congested**
Volumes (pc/h/ln)	$0 \le q \le 1{,}000$	$1{,}000 < q \le 2{,}400$	$2{,}400 < q \le 0$
u (mph)	75	$75 - 0.00001107 \cdot (q - 1{,}000)^2$	${}^{q}/_{45}$
k (pc/mi/ln)	${}^{q}/_{75}$	$\frac{q}{75 - 0.00001107 \cdot (q - 1{,}000)^2}$	$190 - {}^{q}/_{16.5517}$

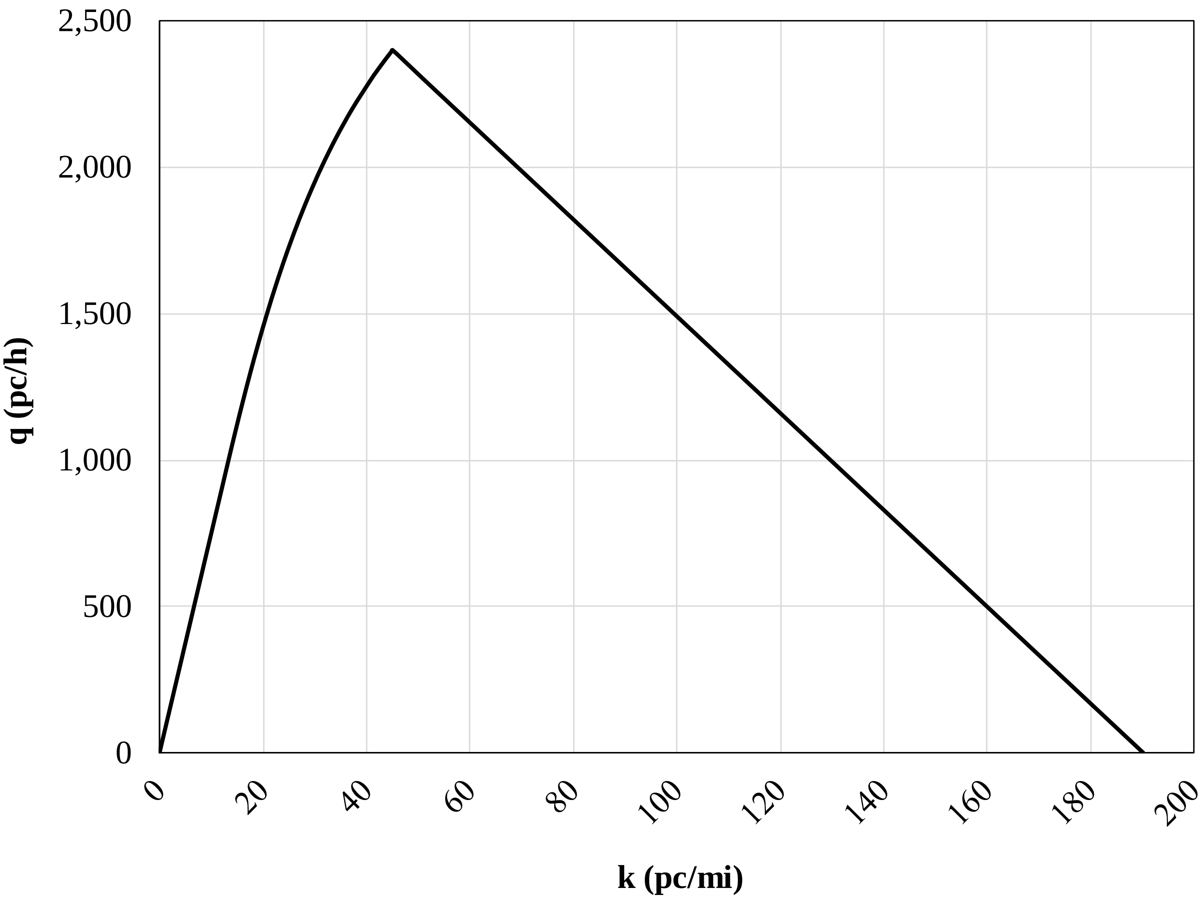


Figure 6.11. Graph. Base freeway q-k diagram.

The above relation is developed for base freeway segments and passenger cars only. In order to use the HCM speed-flow-density relation to develop the shockwave model, it needs to be calibrated for the Wyoming I-80 conditions. The calibration was performed using the HCM methodology and the Highway Capacity Software (HCS), with typical traffic conditions along I-80. The calibration resulted in the relation among the traffic flow parameters, as shown in table 6.2. The main parameters are as follows:

- Free flow speed: u_f = 73.6 mph
- Jam density: k_j = 108 veh/mi/ln
- Density at capacity: k_c = 18.61 veh/mi/ln
- Lane capacity: Q_c = 1370 veh/h/ln
- Speed at capacity: u_c = 72.1 mph
- Flow at break point: Q_{bp} = 578 veh/h/ln
- Density at break point: k_{bp} = 7.85 veh/mi/ln
- Maximum recovery shockwave speed: w = 15.33 mph

Table 6.2. Calibrated HCM freeway macroscopic traffic flow relations for WY I-80

State	**Uncongested**		**Congested**
Volumes (veh/h/ln)	0 ≤ q ≤ 578	578 < q ≤ 1,370	1,370 < q ≤ 0
u (mph)	73.6	$73.6 - 2.39 \cdot 10^{-6} \cdot (q - 578)^2$	${}^{q}/_{19}$
k (veh/mi/ln)	${}^{q}/_{73.6}$	$\dfrac{q}{73.6 - 2.39 \cdot 10^{-6} \cdot (q - 578)^2}$	$108 - {}^{q}/_{15.4}$

These parameters were used to describe State 1 (uncongested, either before or after the breakpoint, depending on the input data), and State 3 (recovery, where flow, density and speed occur at capacity). State 2 (congested) is determined using the speed of the truck behind the platoon is forming. The next section describes how the truck speed is computed.

6.3. Speed-Distance Curves of Heavy Trucks on Vertical Grades

According to the HCM, passenger cars can negotiate upgrades of four to five percent, without a noticeable loss in speeds maintained on level roadways. On the other hand, the performance of trucks is greatly affected by vertical grades. Trucks start losing their speeds at freeway grades of about one percent. Trucks generally decrease speed by more than seven percent on upgrades as compared to their operation on level terrains. The maximum speed that can be maintained by trucks on upgrades primarily depends on the length and steepness of the grade, as well as the truck’s weight-to-power ratio. The HCM and related research studies recognize the significant impact of truck performance and percentage in traffic flow through Passenger Car Equivalent (PCE) factors in computing freeway capacity and LOS.

A Policy on Geometric Design of Highways and Streets (2018) presents empirical results of truck speeds on grades as a function of the length of the grade and the grade percentage. The typical truck weight-to-power ratio is assumed to be 140 pounds per horsepower (lb/hp) as the most representative of the trucks on the road today. The chart shown in figure 6.12 is used to determine empirical equations for truck speed computation on grades that are used in the presented shockwave model.

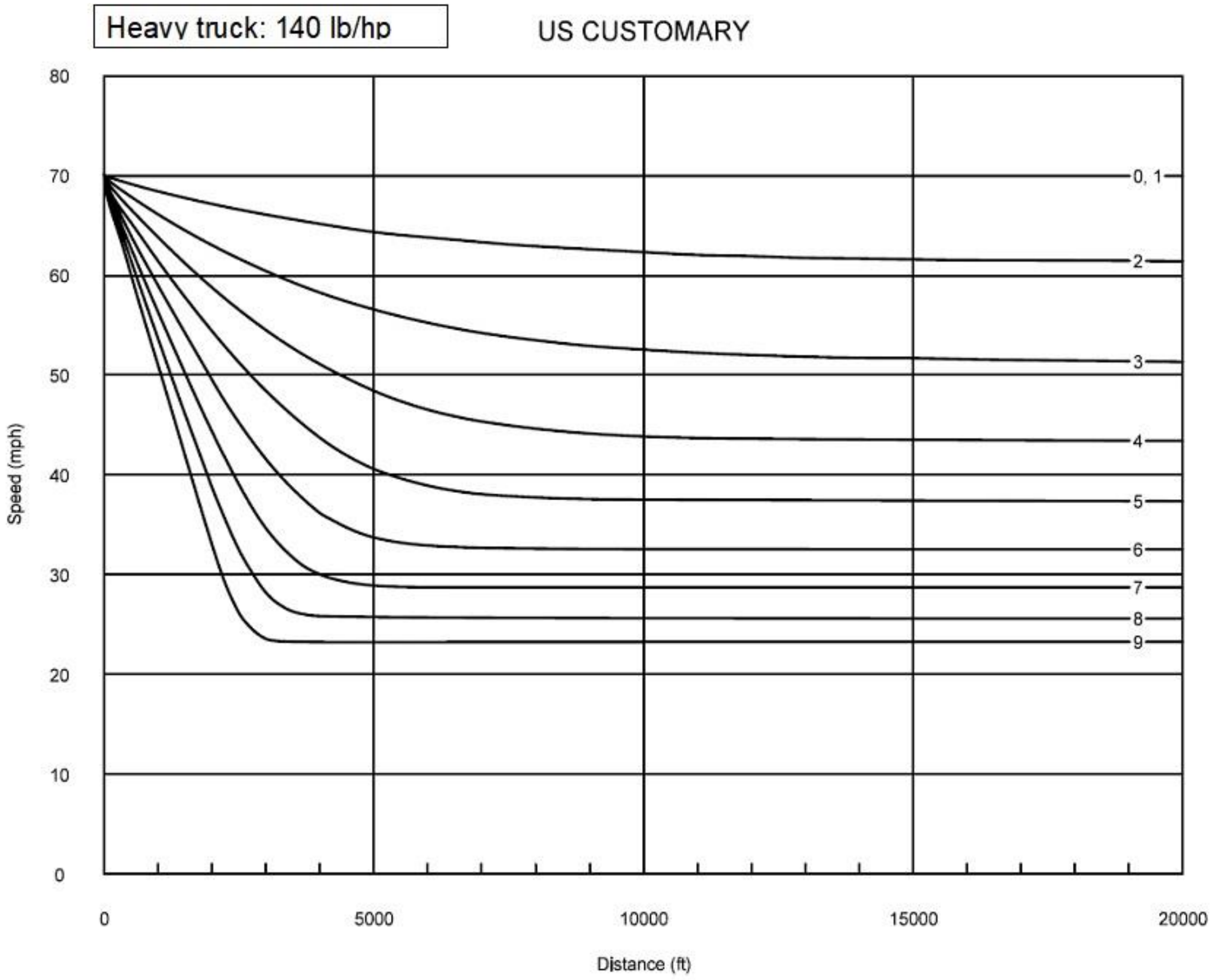


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Figure 6.12. Graph. Speed–distance curves for a typical heavy truck of 140 lb/hp

6.4. Traffic Shockwave Methodology

The traffic shockwave methodology developed in this research uses the calibrated HCM parameters for Wyoming I-80 and the speed-distance curves for heavy truck on upgrades to dynamically determine delays of traffic on upgrades caused by the slow moving trucks. The current model can compare traffic operations on an upgrade section of I-80, in Wyoming, without and with a climbing lane.

The model is using the travel direction, grade percentage, grade length, hourly volumes, truck percentage, and the presence of the climbing lanes as the main inputs. The travel direction is important for lane utilization, given as the percentage of passenger vehicles and trucks in each freeway lane. This information is obtained from field data by analyzing traffic volumes per vehicle type for several years for available measurement stations. Table 6.3 shows the lane utilization percentages for passenger cars and trucks. These percentages are hard-coded in the model, however, they can be updated as needed.

Table 6.3. Lane utilization percentages.

	Eastbound		Westbound	
	Left Lane	**Right Lane**	**Left Lane**	**Right Lane**
Lane utilization: Cars	31.1%	68.9%	37.3%	62.7%
Lane utilization: Trucks	9.0%	91.0%	10.5%	89.5%

The grade percentage and grade length are used to determine the speed of a typical heavy truck (140 lb/hp), and for the purpose of the shockwave analysis this is the truck speed at the top of the grade. Hourly volumes and truck percentage are used to compute the number of passenger cars and trucks in each freeway lane, the number of platoons in each lane, and the number of vehicles in each platoon. Furthermore, the percentage of heavy trucks in each lane is used to determine the maximum number of platoons in the lane, and therefore, compute the total delay accumulated along the grade on a lane-by-lane basis.

The procedure follows the same steps for delay calculation in the case of a presence of a climbing lane. However, in this case the delay from the climbing lane is not included since it was estimated that less than one percent of passenger cars use it. The lane utilization percentages for segments with climbing lanes are provided in table 6.4. These percentages are also hard-coded in the model, however, they can be updated as needed.

Table 6.4. Lane utilization percentages for climbing lane sections.

	Eastbound			Westbound		
	Left Lane	**Center Lane**	**Climbing Lane**	**Left Lane**	**Center Lane**	**Climbing Lane**
Lane utilization: Cars	54%	45%	1%	54%	45%	1%
Lane utilization: Trucks	0%	20%	80%	0%	20%	80%

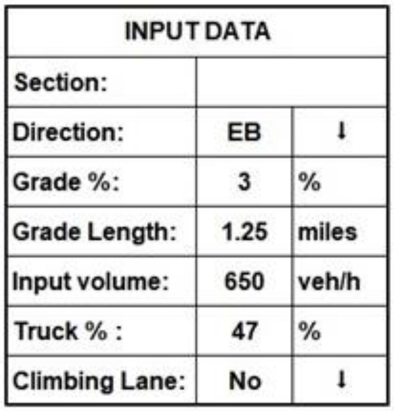
The procedure for delay calculations on upgrades using the shockwave methodology is as follows:

- Just before the beginning of the grade, all vehicles travel at the free flow speed (73.6 mph), and the density per lane is computed using the input hourly flow distributed among the lanes (Table 6.3 for regular 2-lane sections, or table 6.4 for sections with a climbing lane), and equations provided in table 3.2, assuming uncongested conditions. This is State 1.

- As the vehicles travel up the grade, the speed of trucks reduces, as shown in figure 6.12, depending on the grade length and percentage, also slowing down the passenger cars behind them. At the top of the grade, the speed of the truck is determined using equations derived from figure 6.12. The platoons created behind the slow moving trucks are assumed to be in the congested condition. Therefore, when the speed of the truck is known, flow and density can be determined using equations from table 6.2 for congested conditions. This is State 2.
- Once the platoons reach the top of the grade, their speed increases and the platoons discharge at capacity. In this case, the flow, density, and speed are equal to the values at capacity (1,370 veh/h/ln, 18.61 veh/mi/ln and 72.1 mph, respectively). The shockwave speed at discharge is equal to 15.33 mph, based on the calibrated HCM parameters. This is State 3.
- Using the speed, flow, and density information from States 1, 2 and 3, the base shockwave methodology is applied to compute the shockwave speeds, platoon growth rate, duration of bottleneck (which is equal to the travel time up the grade with a leading heavy truck), platoon length, number of vehicles in the platoon, and the platoon dissipation time.
- The total delay per platoon is computed using the number of vehicles in the platoon, and the difference between the free-flow travel time and the actual travel time.
- The maximum number of platoons is computed using the percentage of trucks in each lane. The total delay for all platoons is then determined by multiplying the number of platoons with the total delay per platoon.

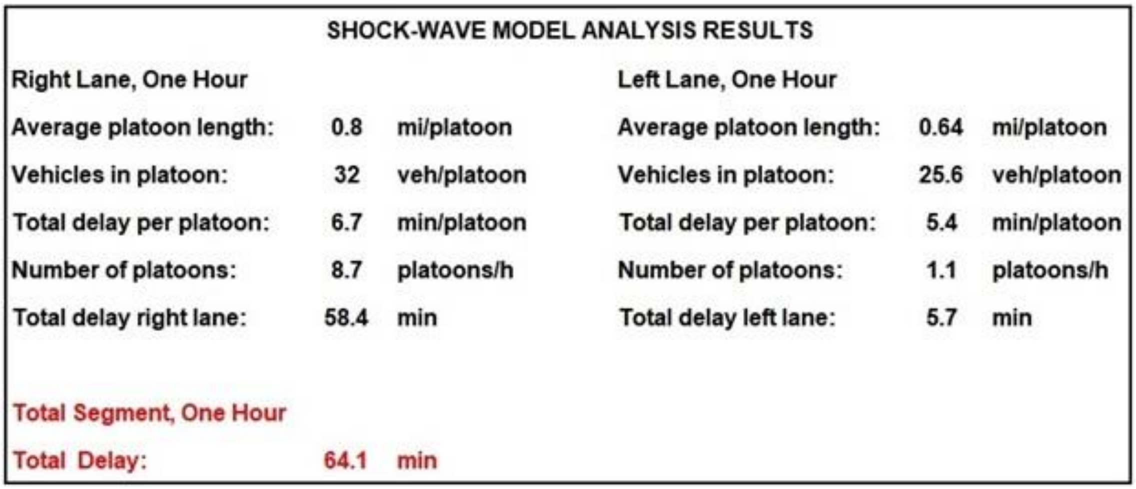
This methodology is implemented in an Excel spreadsheet (Shockwave_model.xlsx), which uses basic geometry and traffic inputs to estimate traffic delays. The input/output form is shown in figure 6.13. The user needs to input the section that is being analyzed (this is optional), and select the direction from the dropdown menu (eastbound (EB) or westbound (WB)). Then the grade information is entered as the grade percentage and grade length, in percent and miles, respectively. The input volume for the section is entered in vehicles per hour, followed by the percentage of heavy trucks, in percent. Finally, the user needs to be selected if the section has a climbing lane or not from the dropdown menu. This option can be used for a quick estimation of the operational effectiveness of a climbing lane for the analyzed segment.

As the inputs are entered into the spreadsheet, the model dynamically updates the results. For a typical 2-lane freeway section, the presented results include the average platoon length, the number of vehicles in a platoon, the total delay per platoon, the number of platoons, and the total delay for both lanes separately, as well as the total delay for the entire segment. The layout of the results is shown in figure 6.14. In the case of a segment with a climbing lane, these results are presented for the center and the left-most lane, since it is estimated that less than one percent of passenger cars travel in the climbing lane. All the results from the shockwave model are given for one hour.



INPUT DATA		
Section:		
Direction:	EB	↓
Grade %:	3	%
Grade Length:	1.25	miles
Input volume:	650	veh/h
Truck % :	47	%
Climbing Lane:	No	↓

Figure 6.13. Illustration. Shockwave model input interface.



SHOCK-WAVE MODEL ANALYSIS RESULTS

Right Lane, One Hour			Left Lane, One Hour		
Average platoon length:	0.8	mi/platoon	Average platoon length:	0.64	mi/platoon
Vehicles in platoon:	32	veh/platoon	Vehicles in platoon:	25.6	veh/platoon
Total delay per platoon:	6.7	min/platoon	Total delay per platoon:	5.4	min/platoon
Number of platoons:	8.7	platoons/h	Number of platoons:	1.1	platoons/h
Total delay right lane:	58.4	min	Total delay left lane:	5.7	min
Total Segment, One Hour					
Total Delay:	64.1	min			

Figure 6.14. Illustration. Shockwave model results interface.

7. BENEFIT-COST ANALYSIS FOR CLIMBING LANES ALONG I-80, IN WYOMING

This chapter combines safety and operational methodologies for analyzing the effectiveness of climbing lanes and provides a benefit-cost ratios for different segments where climbing lane implementations are recommended. Due to the presence of high truck percentages, I-80, in Wyoming, currently has about 14 miles of climbing lanes at different locations, approximately 10.4 and 3.4 miles in eastbound and westbound direction, respectively. WYDOT is currently interested in climbing lanes as a strategy to alleviate safety and operational issues on upgrade sections. A recent study on I-80, in Wyoming, conducted by WYDOT and HDR, proposed and ranked 11 additional new climbing lane locations based on the segments with high closure, higher safety concerns, steep grades, and length of upgrades (WYDOT 2018). The operational efficiency of climbing lanes and a benefit-cost analysis for the selected truck climbing lanes on I-80, in Wyoming, is performed in this chapter of the study. The analysis was performed from both operational and safety perspectives. This was achieved through a combination of microsimulation modeling and Wyoming-specific crash prediction models for the current and future traffic conditions along I-80.

7.1. Climbing Lanes in Research and Practice

A climbing lane is an additional roadway lane used for short distances in certain uphill areas to enhance safety, mitigate congestion, and prevent delays. It improves the mobility of large trucks along with steep grades. These lanes also facilitate the passing of slow-moving heavy vehicles without slowing other traffic on the road. Some general features of climbing lanes are (Arizona DOT 2013):

- They look the same as any other lane and have the same width.
- They are typically used on uphill segments of highways that have a steep grade (usually a five or six percent grade).
- They are marked with signage advising slower traffic to keep right.

Climbing lanes are often confused with passing lanes. However, there are some differences between the two types. A passing lane is also an added lane that is provided in one or both directions on a conventional two-way, two-lane highway to facilitate passing opportunities (Harwood 1987). Although the purpose of both passing and climbing lane is to reduce queuing of traffic behind slower-moving vehicles, the design methodologies are essentially different from one another. The design objectives of a climbing lane are based on a significant change in a grade, such as the size and length of the grade change. On the other hand, enhancing passing opportunities along the level or rolling roadway corridor is the main design principles of constructing passing lane (Wooldridge et al. 2002). Due to budget constraints, the construction of climbing lanes is often limited to rolling and mountainous regions.

The main purpose of climbing lanes is to separate the slow-moving traffic from vehicles that travel at higher speeds at upgrades. This simultaneously improves traffic operations and safety. A study performed by Polus et al. showed that a climbing lane on upgrades could provide substantial flow benefits by reducing delays and helping car platooning, which also had significant safety benefits (Polus and Reshetnik 1987). A customized microsimulation model (TRUG) was developed for this study to simulate vehicle flows on long upgrades. Another study by Polus et al. developed a model to examine the impacts of paved shoulders being used by slow-moving vehicles on the highway (Polus et al. 1999). The results indicated higher speed and throughput capacity (lanes and shoulders) of roadway sections, and a reduction of crash rate by 70 percent at the investigated sites. Morrall et al. used a customized simulation model TRARR (traffic on rural roads) to determine the impact of additional lanes in difficult terrain in Southern California (Morrall et al. 1995). The modeling result recommended 117 new additional lanes to improve operational and safety performance. Rakha et al. evaluated different truck management strategies along one of the most highly traveled sections of Interstate 81, in the state of Virginia, using the INTEGRATION traffic simulation software (Rakha et al. 2005). The study concluded that adding climbing lanes at required locations offered 30 percent and 45 percent reduction in travel times and delays respectively. The study also revealed a 42 percent increment in speed due to the installation of climbing lanes. Qin et al. examined the effects of a climbing lane on an upgrade of an existing two-lane rural highway using VISSIM microsimulation (Qin et al. 2009). The results indicated an increment in the mean speed of vehicles and reduction in speed variations when a climbing lane was added under the given traffic volumes.

Brewer et al. investigated the effects of volume, terrain, and heavy vehicles on traffic flow, and safety for two-lane highways called Super 2 highways, in Texas (Brewer et al. 2012). The results from this extended project indicated additional benefits at higher traffic volumes by reducing crashes, delay, and percent time spent following. The study also applied Empirical Bayes analysis using crash data, which revealed a 35 percent non-intersection crash reduction with injuries. Another comprehensive study, sponsored by the San Diego Association of Governments, analyzed seven truck management strategies in the state of California (IBI Group et al. 2013). It concluded that the designated truck-only lanes (e.g., truck routes, by-pass, or truck climbing lanes, etc.) are only recommended for consideration in bottleneck locations where the truck volumes and local conditions warrant this level of investment. The results obtained from the study by Alaix et al. showed improvements of LOS for climbing lane application to the selected field locations in Spain (Alaix and Garcia 2016). A study conducted by Choi et al. analyzed the operational efficiency and safety performance of climbing lanes with the use of a microscopic traffic simulator based on the Oversaturated Freeway Flow Algorithm (OFFA). The study categorized the climbing lane into the pocket type and overtaking type. The results showed that an overtaking type climbing lane provides better performance in terms of operational efficiency with a considerably small deficiency in safety performance (Choi et al. 2017). However, the operational performance drops for high traffic volumes and with the high truck ratio.

The findings of this study were compared with I-80, in Wyoming, masterplan implementation report (WYDOT 2018). In this report, the analysis used a truck percentage of 20 percent to follow the previous study by St. John and Harwood (1991), where average truck proportion prevails over 40 percent along I-80 in Wyoming. The crash reduction factor was used as 20 percent, according to the study by Lord and Middleton (2005), which was based on the New Jersey facility. Moreover, the basic queuing simulation model was used where truck speeds were estimated based on the length of the grade using a model developed in the National Cooperative Highway Research Program (NCHRP) Report 486. However, this study applied a different methodological approach by incorporating real field scenario of I-80, in Wyoming. To the best of the authors' knowledge, this is currently the only study that investigated the impacts of significantly high truck traffic percentages combined with challenging geometrical and environmental conditions.

7.2. Methodology

A benefit-cost analysis (BCA) was conducted in this study based on the guidance provided by U.S. DOT (USDOT 2019). The costs associated with new climbing lane segments were collected from I-80, in Wyoming, masterplan implementation report (WYDOT 2018). Both operational and safety benefits of climbing lanes were evaluated in this paper at the various location using microsimulation models and Wyoming-specific safety performance functions. Figure 7.1 demonstrates the methodology applied to this study.

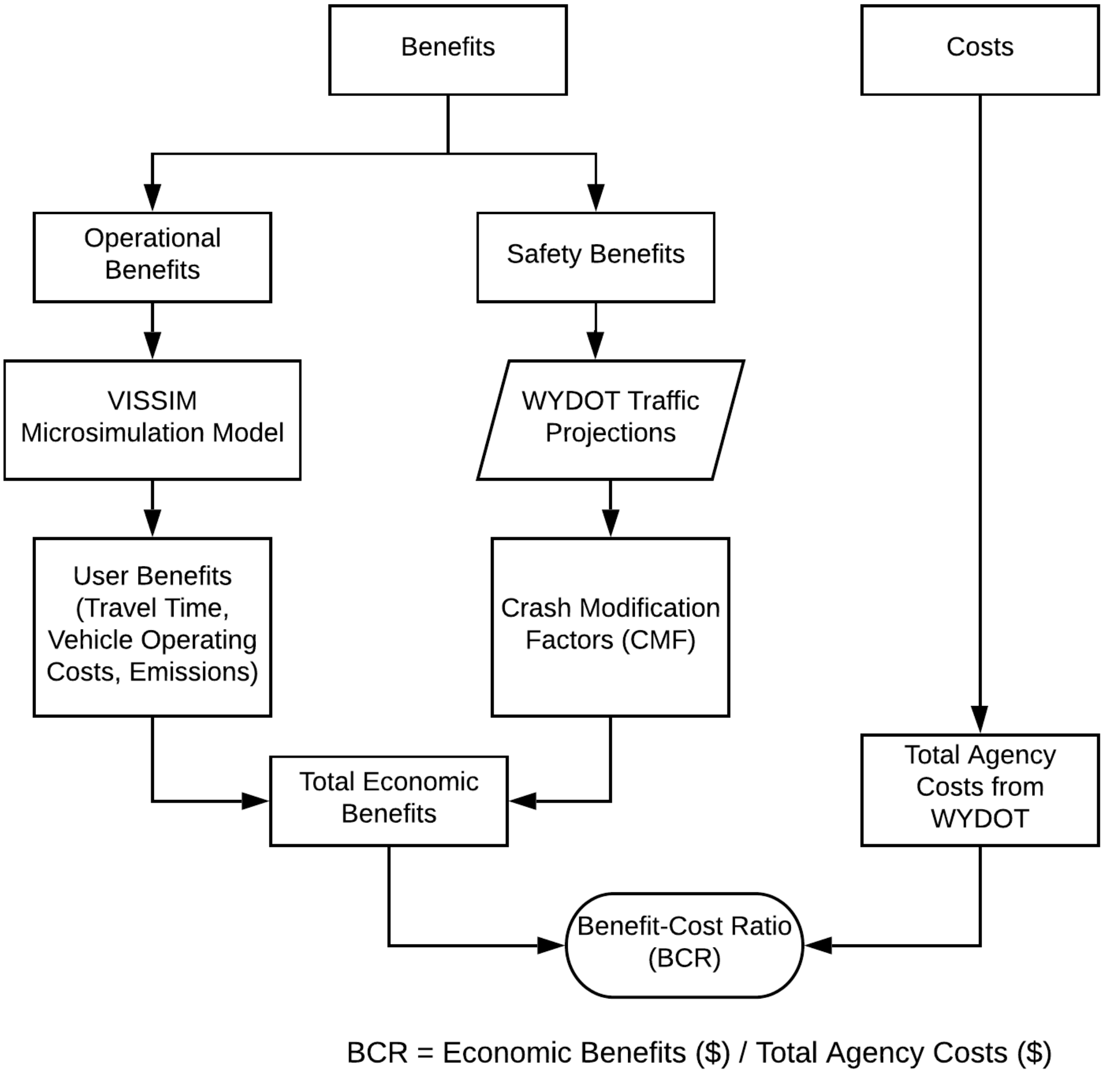


Figure 7.1. Flowchart. BCA methodology.

7.2.1. Study Locations and Scenarios

WYDOT proposed 11 new climbing lane locations in their masterplan implementation report. Among those, seven locations were selected based on the presence of severe grades, where five locations were in the eastbound, and two in the westbound direction. Table 7.1 shows the selected study locations and the climbing lane sections, as well as the associated construction costs in 2017 U.S. dollars. For this study, five 10-mile segments were chosen where those seven new climbing lanes were included.

Table 7.1. Study locations and costs associated with proposed new climbing lanes.

Study Corridor Milepost	Proposed Climbing Lane Milepost	Cost ($2017)	
		Low	High
EB (MP 13-23)	EB (MP 14.529-15.029)	$692,053	$999,632
	EB (MP 21.268-21.768)	$1,032,357	$1,491,182
EB (MP 24-34)	EB (MP 28.199-28.699)	$1,046,716	$1,511,923
EB (MP 260-270)	EB (MP 266.052-269.2)	$5,128,202	$7,407,404
EB (MP 313-323)	EB (MP 316.89-318.97)	$5,032,712	$7,269,473
WB (MP 22-12)	WB (MP 20.381-19.881)	$806,667	$1,165,186
	WB (MP 13.278-12.778)	$1,873,024	$2,705,480

The truck composition used in this analysis was 46 percent as current and 70 percent as the worst-case scenario based on the existing data. During adverse weather conditions, such as heavy snowfall or high winds, sometimes I-80, in Wyoming, remains temporarily closed for trucks. When the road reopens, all the trucks travel together, and therefore, the truck percentage could exceed 70 percent. This has been identified as the worst-case scenario along I-80, in Wyoming. Based on this information, different alternatives were created, and microsimulation models were developed for the existing (year 2017), and projected (year 2037) traffic volumes, each having four different scenarios, adding up to a total of eight scenarios, as shown in table 7.2.

Table 7.2. Analysis scenarios.

Year	No.	Scenario	Description
2017	1	2017 (1)	Existing traffic volume with existing vehicle composition (46% truck)
	2	2017 (2)	Existing traffic volume with 70% truck
	3	2017 (3)	Existing traffic volume with existing vehicle composition having new climbing lane
	4	2017 (4)	Existing traffic volume with 70% truck having new climbing lane
2037	5	2037 (1)	Projected traffic volume with existing vehicle composition (46% truck)
	6	2037 (2)	Projected traffic volume with 70% truck
	7	2037 (3)	Projected traffic volume with existing vehicle composition having new climbing lane
	8	2037 (4)	Projected traffic volume with 70% truck having new climbing lane

7.2.2. Operational Analysis

The operational analysis includes developing microsimulation models for both current (year 2017) and future (year 2037) traffic conditions. Creation of the models was accomplished by using a combination of VISUM (mesoscopic simulation model with traffic assignment capabilities) and VISSIM (microscopic simulation model). VISUM was used to develop the base geometry and calibrate existing models for traffic volumes using its built-in functions. The models were then exported to VISSIM to model the current and projected future traffic operations. This procedure was described in Chapter 5. The same approach was followed in this analysis, with the inclusion of additional segments of I-80, in Wyoming. The newly developed models were calibrated and validated for traffic volume and traffic speeds, respectively. They are then used to perform the analysis of operational effectiveness of climbing lanes.

7.2.3. Operational Benefits Methodology

Operational benefits included travel time, vehicle operating cost, and emissions savings. These savings were calculated based on the methodology, shown in figure 7.2. Average vehicle occupancies, the value of time, vehicle operating costs and damage costs for pollutants were collected from USDOT BCA guideline (USDOT 2019). Average vehicle occupancy was selected as 1.68 for passenger cars and 1.00 for trucks. Vehicle operating costs included fuel costs, repairs and maintenance. Estimated emission rate (grams per mile) by vehicle type was collected based on the Motor Vehicle Emissions Simulator (MOVES) model (KB Environmental Sciences 2019). The estimated emission rate and costs associated with travel time, vehicle operating costs, and emission savings are provided in table 7.3 and table 7.4 respectively. The benefits were estimated for a 20-year period.

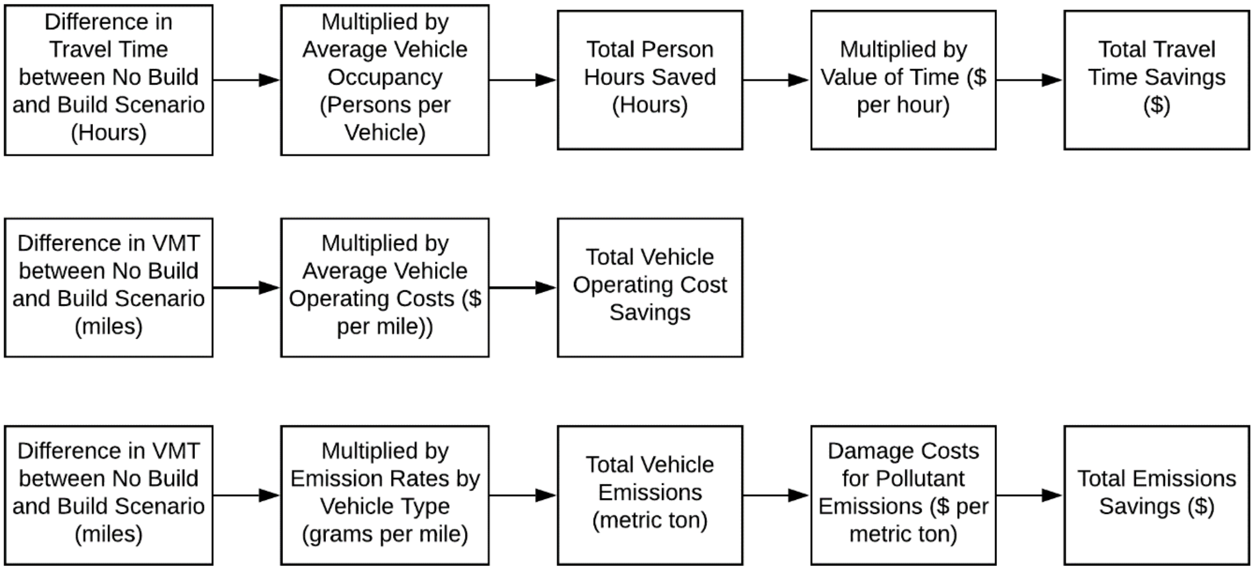
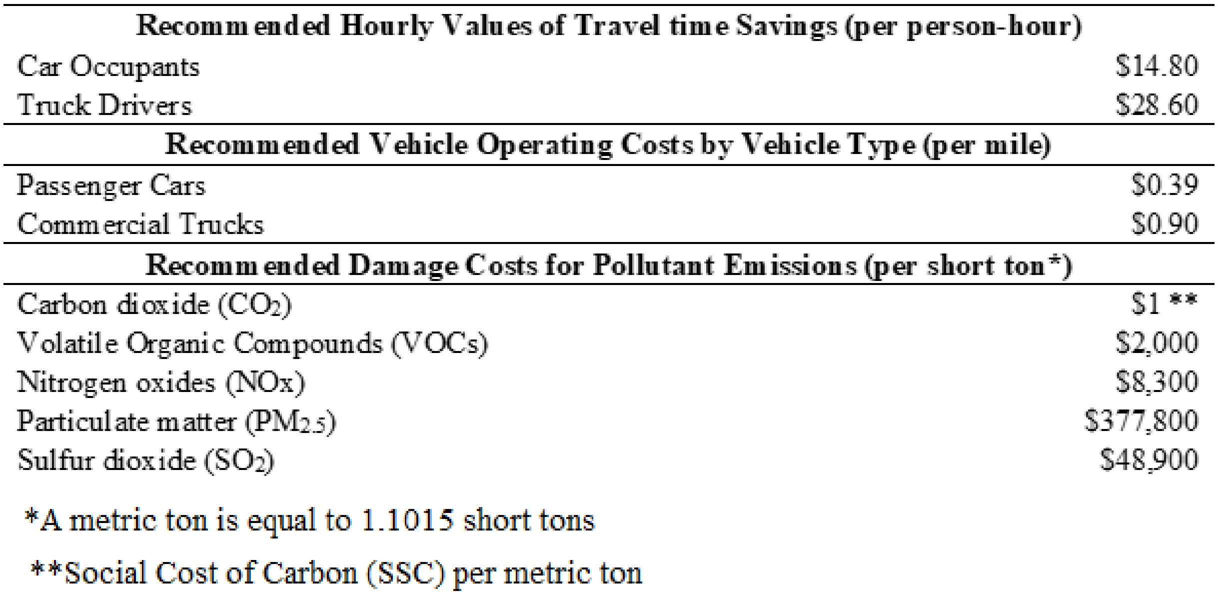


Figure 7.2. Flowchart. Operational benefits calculation methodology.

Table 7.3. Average vehicle emission rate (grams per mile) for 2016 (KB Environmental Sciences 2019).

Vehicle Type	Emission rate (grams/mile)				
	NOx	SO_2	$PM_{2.5}$	VOC	CO_2
Bike, Car and Van	0.62	0.01	0.02	0.54	368.60
2-axle SU Truck	1.43	0.01	0.07	0.26	590.80
3-axle SU Truck	5.16	0.01	0.36	0.62	839.51
Truck with single Trailer	12.31	0.01	0.47	0.55	1623.85
Truck Avg	6.30	0.01	0.30	0.48	1018.05

Table 7.4. Recommended monetized values for travel time, vehicle operating costs, and emission savings (USDOT 2018).



Recommended Hourly Values of Travel time Savings (per person-hour)	
Car Occupants	\$14.80
Truck Drivers	\$28.60
Recommended Vehicle Operating Costs by Vehicle Type (per mile)	
Passenger Cars	\$0.39
Commercial Trucks	\$0.90
Recommended Damage Costs for Pollutant Emissions (per short ton*)	
Carbon dioxide (CO_2)	\$1 **
Volatile Organic Compounds (VOCs)	\$2,000
Nitrogen oxides (NOx)	\$8,300
Particulate matter ($PM_{2.5}$)	\$377,800
Sulfur dioxide (SO_2)	\$48,900

*A metric ton is equal to 1.1015 short tons

**Social Cost of Carbon (SSC) per metric ton

7.2.4. Safety Benefits Methodology

Safety benefits result from crash reductions in the selected study locations. HSM and CMF clearinghouse do not have the CMF for a truck climbing lane. The study presented in Chapter 2 evaluated the safety effectiveness of climbing lanes using cross-sectional and propensity score methods, where the CMF for all vehicle crashes was found 0.57, attributed to the presence of a truck climbing lane. To estimate the safety improvements, the average crash frequency per year for each proposed climbing lane segment was calculated using ten years of historical crash data (2007-2016) by breaking them into various crash severities based on the KABCO scale. The number of average injured persons to each severity type was also computed. Then, Wyoming-specific SPF was developed to predict the crash frequency for current and future traffic volumes.

For simplicity, only AADT and segment length was considered in the crash prediction model, which is also supported by the HSM. Figure 7.3 represents the calculation of safety benefits using a CMF of 0.57 and crash prediction model on a year- by-year basis, accumulating for 20 years. Table 7.5 shows the monetized value of updated crash costs provided in the USDOT guideline (USDOT 2019).

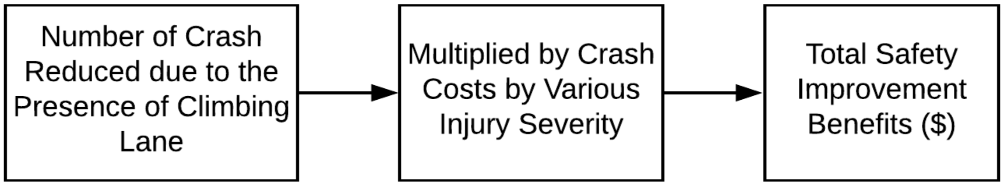


Figure 7.3. Flowchart. Safety benefits calculation methodology.

Table 7.5. Monetized value of crash cost (USDOT 2018).

Crash Type	Value of Crash Cost
Property Damage Only	$ 4,300
0 - No Injury	$ 3,200
C - Possible Injury	$ 63,900
B - Non-incapacitating	$ 125,000
A - Incapacitating	$ 459,100
K - Killed	$ 9,600,000
U - Injured Severity (Unknown)	$ 174,000

7.3. Preliminary Analysis

In the preliminary analysis, five 10-mile segments were analyzed for current and future traffic conditions, as shown in table 7.6. The operational measures were collected only for peak hours (3:00 pm – 5:00 pm). The results indicated a significant speed difference between cars and trucks for both current and future traffic scenarios. The total delay increased for trucks. Among the selected segments, MP 313-323 was found to be the worst, followed by MP 22 – 12 for all vehicles in terms of average speeds and total delay.

Table 7.6. Average speed (mph) and total delay (hour) for current and future traffic conditions.

Current Volume	**Avg Speed (mph)**						**Total Delay (hr)**					
	All Vehicles		**Cars**		**Trucks**		**All Vehicles**		**Cars**		**Trucks**	
Truck %	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**
MP 13-23	65.9	64.2	69.2	68.2	62.5	61.3	11.9	17.2	1.2	1.4	10.7	16.6
MP 24-34	68.3	66.9	71.3	70.3	65.2	64.1	7.5	11.1	0.4	0.5	7.1	10.9
MP 260-270	68.3	66.9	71.3	70.1	65.2	64.2	6.8	9.7	0.6	0.7	6.1	9.2
MP 313-323	63.6	61.7	70.5	69.3	59.0	57.7	21.7	32.7	1.1	1.1	20.6	31.9
MP 22-12	64.8	62.2	69.0	67.8	60.7	59.7	16.5	23.6	1.7	1.8	14.7	22.4
Future Volume	**Avg Speed (mph)**						**Total Delay (hr)**					
	All Vehicles		**Cars**		**Trucks**		**All Vehicles**		**Cars**		**Trucks**	
Truck %	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**	**46%**	**70%**
MP 13-23	65.4	63.7	68.6	67.6	62.1	61.8	19.7	28.3	3.0	1.7	16.7	26.6
MP 24-34	68.1	66.5	71.0	70.0	64.9	63.7	11.9	17.6	1.1	0.6	10.9	17.0
MP 260-270	67.9	66.5	70.6	69.3	65.1	65.0	11.0	15.3	1.8	1.3	9.2	14.0
MP 313-323	63.2	61.2	69.9	68.6	58.6	57.1	34.4	51.9	3.1	2.1	31.3	49.7
MP 22-12	64.2	62.1	64.3	62.2	60.2	59.7	26.9	38.2	4.4	3.2	22.5	35.0

7.4. Benefit-Cost Analysis

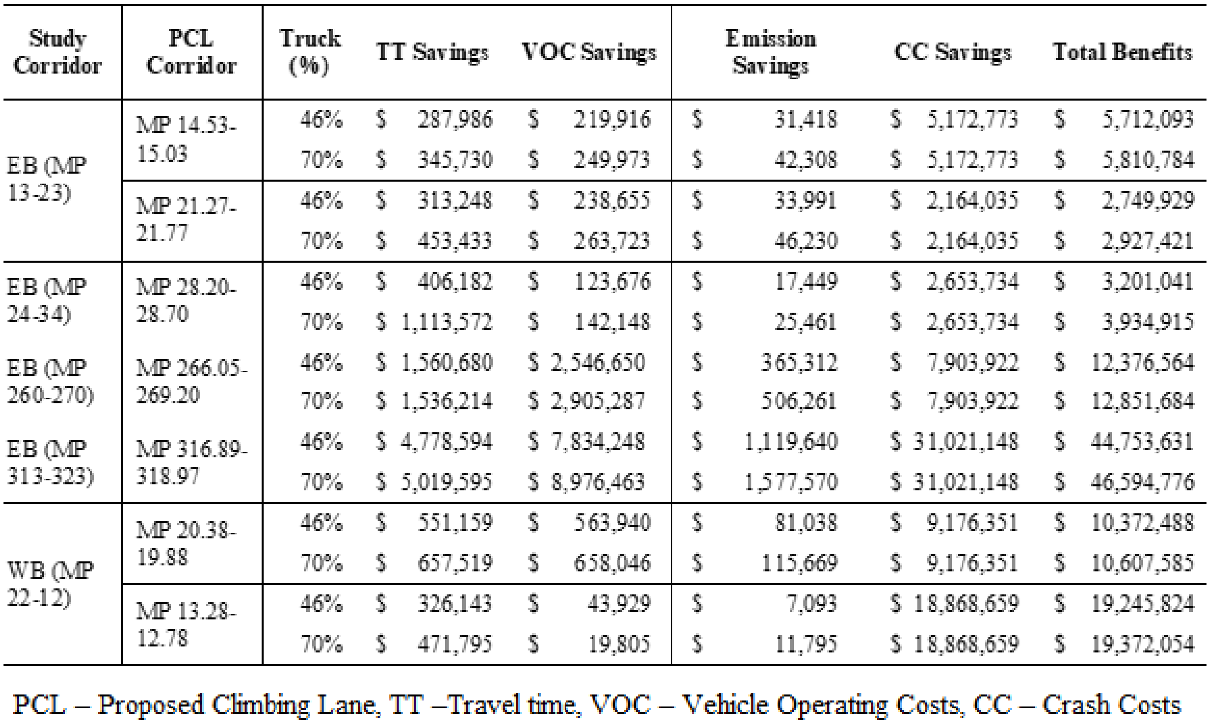
To perform a benefit-cost analysis, link results were extracted from VISSIM microsimulation, where each link represents the proposed climbing lane sections. All the measures including travel time, vehicle operating costs, and emission savings were computed for the current (2017) and future (2037) traffic condition, assuming a two percent traffic growth rate, as recommended by the I-80 Tolling Feasibility Study (WYDOT 2009). Based on these two traffic conditions, the rate of return (benefit rate) for each operational measure was determined using the equation shown in figure 7.4.

$$\text{Current Savings} = \text{Future Savings} * (1 + \text{Rate of Return})^{Time\ in\ Year}$$

Figure 7.4. Equation. Current benefit rate.

This rate of return was used to calculate yearly savings for the 20-year period (2018 to 2037). Then these yearly savings were multiplied by the monetized value provided in the USDOT guideline (USDOT 2019). It was done for both 46 percent and 70 percent truck percentage conditions. To adjust the inflation of future benefits, the study used the past 20 years of inflation rate supplied by the Bureau of Labor Statistics (2019). Table 7.7 summarizes the total benefits computed from the savings of travel time, vehicle operating costs, emissions, and crash costs due to the presence of new climbing lanes. The results indicated that safety improvements made up the majority of economic benefits for each proposed climbing lane segment.

Table 7.7. Total benefits from travel time, vehicle operating costs, emissions, and crash costs savings from 2018 – 2037.



Study Corridor	PCL Corridor	Truck (%)	TT Savings	VOC Savings	Emission Savings	CC Savings	Total Benefits
EB (MP 13-23)	MP 14.53-15.03	46%	$ 287,986	$ 219,916	$ 31,418	$ 5,172,773	$ 5,712,093
		70%	$ 345,730	$ 249,973	$ 42,308	$ 5,172,773	$ 5,810,784
	MP 21.27-21.77	46%	$ 313,248	$ 238,655	$ 33,991	$ 2,164,035	$ 2,749,929
		70%	$ 453,433	$ 263,723	$ 46,230	$ 2,164,035	$ 2,927,421
EB (MP 24-34)	MP 28.20-28.70	46%	$ 406,182	$ 123,676	$ 17,449	$ 2,653,734	$ 3,201,041
		70%	$ 1,113,572	$ 142,148	$ 25,461	$ 2,653,734	$ 3,934,915
EB (MP 260-270)	MP 266.05-269.20	46%	$ 1,560,680	$ 2,546,650	$ 365,312	$ 7,903,922	$ 12,376,564
		70%	$ 1,536,214	$ 2,905,287	$ 506,261	$ 7,903,922	$ 12,851,684
EB (MP 313-323)	MP 316.89-318.97	46%	$ 4,778,594	$ 7,834,248	$ 1,119,640	$ 31,021,148	$ 44,753,631
		70%	$ 5,019,595	$ 8,976,463	$ 1,577,570	$ 31,021,148	$ 46,594,776
WB (MP 22-12)	MP 20.38-19.88	46%	$ 551,159	$ 563,940	$ 81,038	$ 9,176,351	$ 10,372,488
		70%	$ 657,519	$ 658,046	$ 115,669	$ 9,176,351	$ 10,607,585
	MP 13.28-12.78	46%	$ 326,143	$ 43,929	$ 7,093	$ 18,868,659	$ 19,245,824
		70%	$ 471,795	$ 19,805	$ 11,795	$ 18,868,659	$ 19,372,054

PCL – Proposed Climbing Lane, TT –Travel time, VOC – Vehicle Operating Costs, CC – Crash Costs

The BCR was determined using the total benefits and total project costs shown in table 7.8. The BCR) was computed for both low and high costs, which were provided in the I-80 masterplan implementation report (WYDOT 2018), and the average value of BCR was considered for ranking, as shown in table 7.9. Based on the results from table 7.9, the most cost-effective new climbing lane location would be in the westbound direction between MP 20.38 and MP 19.88. The BCR for this location is calculated as 10.9 and 11.1, for 46 percent and 70 percent trucks, respectively.

Table 7.8. Benefit-cost ratio based on total benefits and project costs.

PCL Corridor	Truck %	Total Benefits ($ millions)	Total Project Costs ($ millions)		Benefit-Cost Ratio (BCR)		
			Low	High	For Low Cost	For High Cost	Average
MP (14.53-15.03)	46%	$ 5.71	$ 0.69	$ 1.00	8.25	5.71	6.98
	70%	$ 5.81	$ 0.69	$ 1.00	8.40	5.81	7.10
MP (21.27-21.77)	46%	$ 2.75	$ 1.03	$ 1.49	2.66	1.84	2.25
	70%	$ 2.93	$ 1.03	$ 1.49	2.84	1.96	2.40
MP (28.20-28.70)	46%	$ 3.20	$ 1.05	$ 1.51	3.06	2.12	2.59
	70%	$ 3.93	$ 1.05	$ 1.51	3.76	2.60	3.18
MP (266.05-269.20)	46%	$ 12.38	$ 5.13	$ 7.41	2.41	1.67	2.04
	70%	$ 12.85	$ 5.13	$ 7.41	2.51	1.73	2.12
MP (316.89-318.97)	46%	$ 44.75	$ 5.03	$ 7.27	8.89	6.16	7.52
	70%	$ 46.59	$ 5.03	$ 7.27	9.26	6.41	7.83
MP (20.38-19.88)	46%	$ 10.37	$ 0.81	$ 1.17	12.86	8.90	10.88
	70%	$ 10.61	$ 0.81	$ 1.17	13.15	9.10	11.13
MP (13.28-12.78)	46%	$ 19.25	$ 1.87	$ 2.71	10.28	7.11	8.69
	70%	$ 19.37	$ 1.87	$ 2.71	10.34	7.16	8.75

Table 7.9. Ranking based on benefit-cost ratio.

Ranking	Final Results			
	46% Truck		70% Truck	
	PCL Corridor	BCR	PCL Corridor	BCR
1	WB (MP 20.38-19.88)	10.9	WB (MP 20.38-19.88)	11.1
2	WB (MP 13.28-12.78)	8.7	WB (MP 13.28-12.78)	8.8
3	EB (MP 316.89-318.97)	7.5	EB (MP 316.89-318.97)	7.8
4	EB (MP 14.53-15.03)	7.0	EB (MP 14.53-15.03)	7.1
5	EB (MP 28.20-28.70)	2.6	EB (MP 28.20-28.70)	3.2
6	EB (MP 21.27-21.77)	2.3	EB (MP 21.27-21.77)	2.4
7	EB (MP 266.05-269.20)	2.0	EB (MP 266.05-269.20)	2.1

7.5. Conclusions

The goal of this section of the study was to assess the freeway climbing lane efficiency from an operational and safety perspective. The operational analysis was conducted through VISSIM microsimulation, while crash prediction models were used to perform safety analyses. I-80, in Wyoming, was selected for this research because of the high percentage of truck traffic that it carries (40 to 70 percent). This is a popular route for most freight transporting goods from the east to the west, and vice versa. Due to the presence of high truck percentages and significant vertical upgrades, I-80, in Wyoming, currently has about 14 miles of climbing lanes at different locations. WYDOT recently proposed some additional new climbing lane locations to improve safety and alleviate the operational loss. Among those, this study selected seven locations based on the severity of grades. Traffic volume, roadway geometry, and historical crash data associated with these segments were collected to evaluate the climbing lane efficiency. Several VISSIM microsimulation models were created for existing (year 2017) and projected (year 2037) traffic volumes. To understand the efficiency of truck climbing lanes, a BCA was conducted based on the USDOT BCA guideline. The analyses performed in this paper led to the following conclusions:

- The operational performance of trucks was much more affected in the absence of climbing lanes, compared to the performance of passenger cars.
- The installation of climbing lanes has the potential to improve operational performances (e.g. reduce the total delay and increase the average speed) for a 20-year planning horizon.
- Benefit-cost analysis showed that the aggregated 20-year benefits significantly outperformed the project costs.
- The most cost-effective new climbing lane location was found WB (MP 20.38 – 19.88) with a BCR of 10.9 and 11.1 for 46 percent, and 70 percent trucks respectively.
- If costs were ignored, EB (MP 316.89 – 318.97) section generated the maximum overall economic benefits.

The study has several limitations that will be addressed in future research. Emission rates usually depend on vehicle type and speed. In this study, only vehicle type was considered. Future study should develop a separate emission reduction model for the selected segments using EPA's MOVES model. The CMF used in the analysis was based on total crash reduction. Future studies should calibrate CMFs based on the injury severity and various crash types. Those condition-specific CMFs can be used to determine more accurate crash reductions. Also, a sensitivity analysis should be performed in the future to observe the change in the BCR value for a range of truck percentage or by varying climbing lane lengths.

8. CONCLUSIONS

The State of Wyoming is experiencing a high percentage of truck traffic along all highways, especially I-80, because of an expansion in oil and gas production. Interstate 80 through Wyoming was designed and constructed 60 years ago, and at that time such high truck traffic was not anticipated. The increased interactions between trucks and other vehicles have raised many operational and safety concerns. In 2016, Wyoming had the highest VMT per capita in the United States. According to WYDOT's Annual Traffic Report of 2016, truck traffic comprised approximately 21 percent of VMTs along all routes in Wyoming. The heaviest truck traffic exists along I-80, with about 47 percent truck VMTs. In 2016, 65 percent of the fatal truck crashes (medium and heavy truck) occurred on interstate highways of Wyoming, and 54 percent of these fatal crashes were observed on I-80. It was also revealed that about 58 percent of heavy truck traffic in Wyoming used I-80 as their key route, in 2015.

Trucks have significantly different physical and driving characteristics than passenger cars, especially in horizontal curves, vertical grades, and adverse weather conditions, which have impacts on operational efficiency, safety and pavement deterioration. A large portion of I-80, in Wyoming, goes through mountainous and rolling terrain, resulting in significant vertical grades. About nine percent of I-80, in Wyoming, in both directions is within vertical grades of more than three percent, where certain sections reach grades of close to seven percent. As opposed to the passenger cars, the performance of trucks is greatly affected by vertical grades. Trucks generally decrease speed by more than seven percent on upgrades as compared to their operation on level terrains. The reduction in truck speeds depends on the rate and length of grades. This causes a lot of friction between passenger cars and trucks on upgrades, with a noticeable difference in speeds. Due to the presence of high truck percentages, I-80, in Wyoming, currently has about 14 miles of climbing lanes at different locations.

This study analyzes the impacts of truck traffic on selected freeway segments along I-80, in Wyoming, as well as mitigation strategies to minimize negative impacts (with a focus on climbing lanes), through analyses of safety and operational implications that result from the interactions between trucks and passenger vehicles.

The main objective of the safety analysis in this research was to explore the effectiveness of climbing lanes and calibrate CMFs and RR for climbing lanes along I-80, in Wyoming, using cross-sectional and propensity scores safety models. The results show that the addition of climbing lanes reduces delays and increases overall traffic speeds on upgrades, and can reduce the total and truck-related crashes between 6 and 34 percent, and 1 and 16 percent, respectively, depending on the analyzed location and applied methodology. Furthermore, the study analyzed other factors contributing to truck crashes along I-80, in Wyoming. The analysis showed that 54 percent of truck crashes occurred during icy road condition, snowy weather condition and contributed about 46 percent, and driving too fast and driving in improper lane contributed to approximately 45 percent of total truck related crashes. The maximum percentage of truck crashes occurred within 4000-6000 ft curve radius range, however, this was not found to be significant. Majority of fatal crashes on I-80, in Wyoming, occurred in car-truck collisions. Impaired driving, use of alcohol or illegal drugs, not using seatbelts, fatigue, and dangerous driving were found to increase the injury severity significantly. Although higher crash frequencies occur in the vicinity of interchanges, different interchange ramp types do not have any significant impacts on crash frequencies. A large portion of truck related crashes can be contributed to tire failures, which happens more frequently during the summer months. Based on the SPFs and CMFs developed in this study, an Excel model was created with the functionality of predicting crash frequencies for segments along I-80, in Wyoming, as well as the changes in crash frequencies for updates in geometry and climbing lane installations.

The operational analysis was performed through microsimulation modeling for the current and future traffic conditions along selected freeway segments of I-80, in Wyoming. Based on these results, the study also developed a shock-wave methodology for a quick estimation of freeway conditions. Two 10-mile eastbound segments along I-80, in Wyoming (each containing a section with an existing climbing lane and a section with a proposed climbing lane as an improvement alternative) were modeled, and performance measures associated with these segments were collected to evaluate the climbing lane efficiency. Microsimulation models were developed for both current (year 2017) and future (year 2027 and 2037) traffic conditions. The performance measures (total delays, average speeds and vehicle spacing) were extracted for the peak hours (3:00 pm – 5:00 pm) to analyze and compare the existing and future traffic conditions. It was found that the installation of climbing lanes has the potential to improve operational performances for a 10 and 20-year planning horizon. Space headway of vehicles was found higher when traveling through climbing lane segments compared to the segments without climbing lanes, which has the potential to benefit both traffic operations and safety. It was also found that the operational performance of passenger cars was significantly improved with the installation of climbing lanes for the future year scenarios. An additional tool developed for operational analysis is a traffic shockwave-based Excel model. This model has the functionality of estimating platooning and delays on upgrades with and without climbing lanes.

Both the operational and safety analyses were used to perform benefit-cost analysis for climbing lanes installation on certain segments of I-80, in Wyoming. This analysis showed that the 20-year benefit-cost ratio ranges between 2 and 11, depending on the location. The results can be used to phase out the future climbing lane installation by focusing on those segments that would bring more benefits.

Findings from this study are expected to help transportation managers and policy makers to take necessary actions and decide on management strategies for I-80, in Wyoming, as well as other similar highway facilities carrying a large percentage of trucks. The benefits for WYDOT and other agencies that face similar problems on their freeway network, are in the detailed assessment of traffic conditions along the corridor, as well as the timeline of improvements that would create most benefits as the traffic increases in the future years.

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