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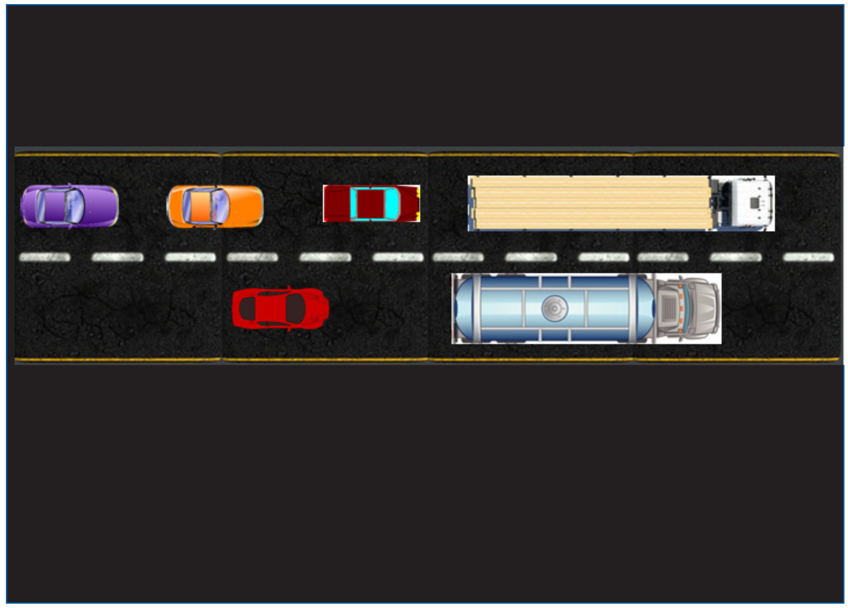
MPC 19-396 | M. Zlatkovic, K. Ksaibati, and M. Haq

Operational and Safety Analysis with Mitigation Strategies for Freeway Truck Traffic in Wyoming



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Operational and Safety Analysis with Mitigation Strategies for Freeway Truck Traffic in Wyoming

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August 2019

Acknowledgements

The authors thank the Wyoming Department of Transportation (WYDOT) and the Mountain-Plains Consortium (MPC) for funding this research, as well as the following individuals for their help and guidance in this research: Matt Carlson, WYDOT state highway safety engineer; Joel Meena, WYDOT state traffic engineer; Zorica Cvijovic, graduate assistant, University of Wyoming; and Irfan Ahmed, graduate assistant, University of Wyoming.

Disclaimer

ABSTRACT

The State of Wyoming road network is characterized by heavy truck traffic. In 2015, truck traffic was approximately 22% of vehicle miles traveled (VMTs) along all routes in Wyoming, according to the WYDOT Annual Traffic Report. The heaviest truck traffic exists along I-80 with about 47% truck VMTs. Trucks have significantly different physical and driving characteristics than passenger cars, especially on grades, which has 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. This study focuses on the benefits of climbing lanes on operations and safety of freeway truck traffic. Various methodologies were used in this assessment. 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 from 6% to 34%, and from 1% to 16%, respectively, depending on the analyzed location and applied methodology.

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EXECUTIVE SUMMARY

The goal of this study is to quantify impacts of truck traffic on selected freeway segments along I-80 in Wyoming and discuss potential mitigation strategies through analyses of operational and safety implications, which result from interactions between trucks and passenger vehicles. The focus of the analysis is on climbing lanes, due to several severe vertical grades through the mountainous terrain in Wyoming. Special attention in the study is given to the roadway geometry (horizontal and vertical alignment, existing climbing lanes) and traffic characteristics to identify impacts on traffic efficiency and safety.

The State of Wyoming's road network is characterized by heavy truck traffic. In 2016, truck traffic comprised approximately 21% of vehicle miles traveled (VMTs) along all routes in the state, according to the WYDOT Annual Traffic Report. The heaviest truck traffic exists along I-80 with about 47% truck VMTs. Trucks have significantly different physical and driving characteristics than passenger cars, especially on grades, which has 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 7% on upgrades as compared with 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 much less impacted by grades. This leads to variations in speeds between trucks and passenger vehicles, with more complex interactions between the two types.

About 9% of I-80 in Wyoming (in both directions) is within vertical grades of more than 3%, where certain sections reach grades close to 7%. 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 operational analysis of freeway climbing lanes under heavy truck traffic was performed through microsimulation. Two 10-mile eastbound segments along I-80 (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 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 with 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 significantly improved with the installation of climbing lanes for the future year scenarios.

The results of the safety analysis 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 from 6% to 34% and 1% to 16% respectively, depending on the analyzed location and applied methodology. 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 the most benefits as traffic increases in the future years.

The accompanying study sponsored by WYDOT is currently in progress. It will expand on the methodologies and results described in this report. From the operational analysis perspective, the future study will include additional segments along I-80 that will be modeled and analyzed. Also, the study will develop Excel-based tools for the shockwave models. From the safety perspective, the study will assess different crashes based on their types and severities. The results will be published in a WYDOT report.

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 networks. The State of Wyoming is experiencing a high percentage of truck traffic along all highways, especially Interstate 80 (I-80), because of an expansion in oil and gas production. I-80 was designed and constructed in 1956 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 accounted for approximately 22% of vehicle miles traveled (VMTs) along all routes in Wyoming, according to the WYDOT Annual Traffic Report. The heaviest truck traffic exists along I-80 with about 47% truck VMTs. Trucks have significantly different physical and driving characteristics than passenger cars, especially on grades, which has 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 7% on upgrades as compared with their operation on level terrains, according to the 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 U.S. economy. 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% in urban areas to 60% 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 4% to 5% 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 1%. Trucks generally decrease speed by more than 7% on upgrades as compared with 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 8% of I-80 in Wyoming (in both directions) is within vertical grades of more than 3%, where certain sections reach grades of close to 7%. 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.

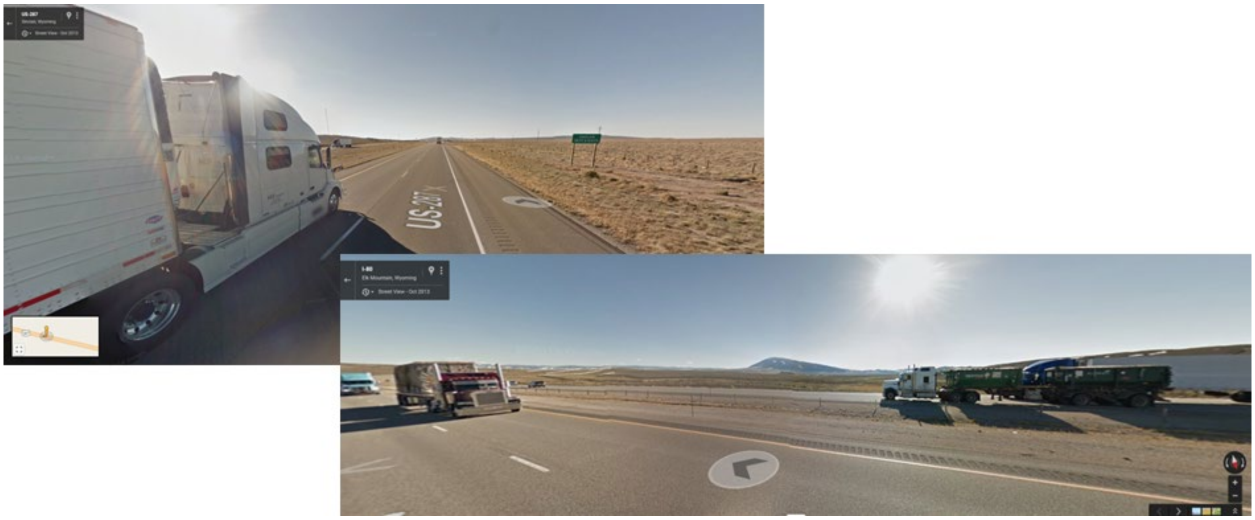


Figure 1.1 Trucks Passing and Occupying Left Lane (Source: Google Earth)

Therefore, the presence of heavy truck traffic along with vertical upgrades degrades the operational performance of the roadway system. Many researchers and practitioners recommend various 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 the introduction of additional climbing lanes, differential truck speed limits, truck lane restrictions, introducing no-passing zones for trucks, changes in horizontal and/or vertical features of the road, changes in cross sections, changes in the roadside, and installation or update of safety devices (guardrails, delineators, chevrons, speed advisory signs, pavement markings, and similar devices).

Truck safety has significant implications to motorists, transportation agencies, industry, and the public. Safety is a major consideration for the trucking industry. In 2015, of the approximately 415,000 police-reported crashes involving large trucks 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 transportation facilities should be of particular concern to state DOT engineers. This especially applies to WYDOT, which 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 WY (on average, 530 truck-related crashes occur each year), which speaks about the importance of 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 truck-related crashes include road condition, weather condition, driver condition, driver action, and crash type.

1.2 Study Objectives and Methodology

This study analyzes the impacts of truck traffic on selected freeway segments along I-80 in WY, 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 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 shockwave methodology for a quick estimation of freeway conditions. The main objective of the safety analysis is to explore the effectiveness of climbing lanes (CL) and calibrate crash modification factors (CMFs) and relative risk (RR) for CL 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 is 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 is to develop a propensity score model, which estimates the probabilities of a crash within a section with and without CLs. The final task is 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 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 the most benefits as traffic increases over the years.

2. LITERATURE REVIEW

The State of Wyoming is experiencing a high percentage of truck traffic along all highways, especially Interstate 80 (I-80), because of an expansion in oil and gas production. Wyoming ranked eighth and fourth nationally in crude oil and natural gas production, respectively, although that production rate recently went down (*1*). I-80 was designed and constructed in the late 1950s, 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. In 2016, Wyoming was ranked first in the nation for the most per-capita VMTs (*2*). According to the 2016 Wyoming Department of Transportation (WYDOT) Annual Traffic Report, truck traffic accounted for approximately 21% of VMTs along all routes in Wyoming (*3*). The heaviest truck traffic exists along I-80, with about 47% truck VMTs. In 2016, 65% of the fatal truck crashes (medium and heavy truck) occurred on interstate highways of Wyoming (*4*), and 54% of these fatal crashes occurred on I-80. It was also revealed that about 58% of heavy truck traffic used I-80 as their key route in Wyoming over other roadway systems in 2015 (*2*).

Trucks have significantly different physical and driving characteristics than passenger cars, especially in horizontal curves, vertical grades, and adverse weather conditions, which impacts operational efficiency, safety, and pavement deterioration. A large portion of I-80 in Wyoming runs through mountainous and rolling terrain, resulting in significant vertical grades. About 9% of I-80 in both directions is within vertical grades of more than 3%, where certain sections reach grades of close to 7%. According to the AASHTO Green Book, passenger cars can negotiate upgrades of 4% to 5% without a noticeable loss in speeds maintained on level roadways (*5*). However, the performance of trucks is greatly affected by vertical grades. Trucks generally decrease speed by more than 7% on upgrades, as compared with their operation on level terrains. The reduction in truck speeds depends on the rate and length of grades, as summarized and presented in the AASHTO Green Book. This creates great 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, approximately 10.4 and 3.4 miles in eastbound and westbound directions, respectively.

2.1 Climbing Lanes

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 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 include the following (*6*):

- 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 5% to 6% 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 provided in one or both directions on a conventional two-way, two-lane highway to facilitate passing opportunities (*7*). Although the purpose of both passing and climbing lanes 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 level or rolling roadway corridor is the main design principle of constructing a passing lane (*8*). According to the AASHTO Green Book, there are three criteria reflecting economic considerations that need to be satisfied to justify the climbing lane warrants (*5*):

1. When the upgrade traffic flow rate exceeds 200 vehicles per hour

2. When the upgrade truck flow rate exceeds 20 vehicles per hour
3. When one of the following conditions exists:
    - When 10 mph or greater speed reduction is expected for a typical heavy truck
    - When level of service (LOS) E or F exists on the grade portion
    - Reduction of two or more LOS is experienced when moving from the approach segment to the grade

2.2 Operational Benefits of Climbing Lanes

The main purpose of climbing lanes is to separate slow-moving traffic from vehicles that travel at higher speeds on 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 (*9*). A customized microsimulation model (TRUG) was developed for this study to simulate vehicle flows on long upgrades. A study conducted by Rakha et al. evaluated different truck management strategies along one of the most highly traveled sections of Interstate 81 in Virginia using the INTEGRATION traffic simulation software (*10*). The study concluded that adding climbing lanes at required locations offered 30% and 45% reduction in travel times and delays, respectively. The study also revealed a 42% increment in speed due to the installation of climbing lanes. Using VISSIM microsimulation, Qin et al. examined the effects of a climbing lane on an upgrade of an existing two-lane rural highway (*11*). The results indicated an increment in the mean speed of vehicles and a reduction in speed variations when a climbing lane was added under the given traffic volumes.

Another comprehensive study, sponsored by the San Diego Association of Governments, analyzed seven truck management strategies in the state of California (*12*). It concluded that the designated truck-only lanes (e.g., truck routes, bypass, 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 in LOS for climbing lane applications to selected field locations in Spain (*13*). 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 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 (*14*). However, the operational performance drops for high traffic volumes and with high truck ratios. A recent study on I-80 conducted by WYDOT and HDR proposed additional climbing lanes at several locations to improve safety and alleviate congestion by accommodating slower moving freight trucks (*15*). However, the study did not analyze operational efficiency of the added climbing lanes.

Several previous microsimulation-based studies examined the freeway operational efficiency for truck-lane restrictions (*16-21*). These studies evaluated the impacts of truck-lane restrictions in terms of average speed, speed variation, lane-changes, density, capacity, vehicle queue, travel time, etc., and showed that microsimulation can be used effectively to assess the efficiency of various truck management strategies. The study presented in this report investigated the impacts of high truck traffic on upgrades of selected freeway segments along I-80 in Wyoming and the operational efficiency of added climbing lanes. The analysis was performed for both current and future projected traffic volumes using VISSIM microsimulation modeling. This is the first study of this type along the I-80 corridor in Wyoming. Furthermore, to the best of the authors' knowledge, this is currently the only study that has investigated impacts of significantly high truck traffic percentages combined with challenging geometrical and environmental conditions.

2.3 Freeway Truck Traffic Safety Assessment

Truck safety has significant implications to motorists, transportation agencies, industry, and the public. Safety is a major consideration for the trucking industry. Of the approximately 415,000 police-reported crashes involving large trucks in 2015, there were 3,598 fatal crashes and 83,000 injury crashes in United States (*22*). The correlation between the percentage of large trucks and crash rates on transportation facilities should be of particular concern to state department of transportation (DOT) engineers. This especially applies to WYDOT, which operates facilities with large percentages of trucks on roads, such as I-80.

The Large Truck Crash Causation Study (LTCCS) performed by the Federal Motor Carrier Safety Administration (FMCSA) and the National Highway Traffic Safety Administration (NHTSA), explores the critical events and associated factors that contribute to serious crashes involving large trucks (*23*). A critical event in this study is described as the immediate reason for an inevitable collision, and is assigned to the vehicle accountable for the crash. Of the analyzed truck-related crashes, 87% were driver-related, 10% were vehicle-related, and 3% were environment-related. An additional look at the driver-related crashes showed that 38% were attributed to driver decisions, such as speeding; 28% were caused by distracted driving, 12% were non-performance, such as falling asleep, and 9% were because of poor driver performance, such as panic or overcompensating.

A paper presented at the International Driving Assessment Conference (*24*) investigated the critical reasons behind single- and multi-vehicle crashes using data from the LTCCS. The research concluded that driver choices, such as driving too fast for conditions or the lack of sleep, as well as roadway factors, were the primary reasons for single-vehicle truck crashes. Multi-vehicle crashes in heavy traffic were mostly caused by the driver's lack of attention to the surroundings. Multi-vehicle crashes where the other vehicle was at fault had similar crash contributing factors.

Another research study that applied LTCCS data to investigate the effect of large trucks on the severity of crashes is presented in (*25*). The study specifically focused on long-combination vehicles (LCV), which are trucks pulling multiple trailers. The study's model revealed that the probability for injury and fatal crashes was higher for two-trailer LCVs than that for single-trailer non-LCVs and other trucks.
Franke et al. (*26*) investigated the contribution of heavy trucks to crashes and their significance as a predictor of crash severity, and addressed the impact of large truck movement on the safety of roadways for various road classifications. The results showed the chances of a severe crash were 2.3 and 4.5 times greater when a heavy truck was involved on state and interstate highways, respectively. The severity of crashes was significantly higher during adverse weather and road conditions.

Offei et al. developed statistical models that explore the relationship between the high percentage of trucks and crash rates (*27*). The result showed that crash rates increase with an increasing percentage of trucks at various locations with specific road and weather conditions.

Increasing interactions between trucks and passenger vehicles tend to deteriorate operational and safety performance of the facility. Speed variations between passenger cars and trucks, especially on upgrades and downgrades, can significantly deteriorate traffic conditions from operational and safety standpoints. Many highway organizations have executed various truck confinement methodologies to segregate them from other vehicles along critical segments. These sorts of limitations incorporate differential speed limits, truck-only lanes, and no-truck routes. The connection between speed variation and crashes was researched by Quddus (*28*). The results showed a statistically significant correlation between variation in speeds and crash rates. A 1% increase in speed variation is followed by a 0.3% increase in crash rates. Results from the study by Peeta et al. (*29*) showed that the strategy limiting trucks to the right-most lane is an effective treatment that reduces car-truck interactions, without deterioration in traffic performance, when truck percentages are generally low (10% to 30%), and the total traffic demand is not high. However, for high truck percentages (50% to 70%) and high to very high traffic demand, congestion occurs and interactions increase.

Horizontal curves are also a significant safety issue on rural expressways. An example analysis of horizontal curve impacts on safety can be found in (*30, 31*). The results of these research efforts showed that the length of curve, degree of curve, roadway width, shoulder width, and the overall roadway condition have a significant impact on the total crash rate. A statistical analysis indicated that the length of curve, degree of curve, shoulder width, roadside hazard rating, pavement skid resistance, and shoulder type were significant factors in foreseeing low versus high accident sites (*30*).

Two comprehensive research studies by Zegeer et al. examined the impacts of horizontal curves on safety (*32, 33*). These studies focused on the safety and modifications to horizontal curves on two-path thruways. They found that a 500-ft radius bend is 200% more likely to create a crash than a comparable straight stretch of road, and a 1,000-ft radius bend is 100% more prone to produce a crash than a proportionate straight segment. Harwood et al. (*34*) found that the crash rate was more than 28 times higher for a 100-ft curve radius than for an equivalent straight section on a similar roadway.

Other studies have demonstrated that the number of crashes and crash severity increase with a sharper horizontal curve. A study by Caliendo et al. (*35*) showed that the number of total and severe crashes occurring on curves increases with the length, the curvature, and AADT. Kweon and Kockelman found that a one-degree increase in horizontal curvature results in 21% more fatalities and 13% more fatal crashes (*36*). A study presented in (*37*) showed that crash probability increases significantly within sharp curves, with a radius of less than 820 ft. The analysis showed that drivers were unable to adequately steer the vehicle within those curve sections.

2.4 Crash Modification Factors and Development Methodologies

The safety effectiveness of various countermeasures is quantified and accumulated in the Highway Safety Manual (HSM) Part D (*38*) and CMF Clearinghouse (*39*) for various roadway facilities. The development of CMFs should be site-specific. Ezra Hauer in 2012 defined CMFs as random variables that are not universal constants to always apply everywhere (*40*). It was also recommended by the Federal Highway Administration (FHWA) to develop a site-specific crash prediction model to account for local roadway conditions, crash severity, injury severity, collision manner, and weather conditions for roadway segments.

Climbing lanes are added to improve operations and safety. But sometimes it may represent a trade-off between safety and mobility when a high percentage of slower truck traffic occupies a freeway facility. The CMF for climbing lanes is only available for rural two-lane highways in the HSM. There were no CMFs developed for other roadway facilities in the HSM, such as rural multilane highways, freeways, expressways, urban arterials, and suburban arterials. According to the HSM, a passing/climbing lane has a CMF of 0.75 for all crash types when installed on rural two-lane roads (*41*). This CMF was developed using NB regression analysis with FHWA Highway Safety Information System (HSIS) data from 619 rural two-lane highway segments in Minnesota and 712 roadway segments in Washington. A study conducted in Texas revealed that the CMF of installing an additional lane on an urban freeway is 0.74 for fatal, serious, and minor injury crashes (*42*). An earlier study concluded that passing lanes on rural two-lane highways reduce total crashes by 25%, and fatal and injury (F+I) crashes by 30% in Texas (*43*). Until the conclusion of this paper, there were no such studies that developed CMFs of climbing lanes on freeway facilities. However, several studies developed CMFs for passing lanes. A study in Michigan developed CMFs for passing lanes on a rural principal arterial roadway ranging from 0.60 to 0.91 for various types of crashes. Those CMFs were based on cross-sectional analyses of sites with and without passing lanes (*44*). Another study in Michigan was carried out with an observational before/after with the EB method using 100 reference sites and 231 passing lanes (*45*). It was concluded that the passing lane segments reduce total and injury crashes by 4% and 51%, respectively. A study conducted in Wyoming found a 42% and 33% crash reduction for total and F+I crashes using observational before/after with the EB method. The study was carried out on a 26-mile rural two-lane highway segment on WY 59. The study corridor had nine passing lane segments at different locations over 10 miles (*46*). Simple SPFs were used in this study to predict the expected crash frequencies in the EB analysis where only traffic volume is considered.

The conventional methods used to calibrate CMFs for the installation of a treatment or safety countermeasure include observational before/after studies (e.g., EB method, comparison group), cross-sectional statistical modeling (e.g., Poisson regression, NB regression), and epidemiological research methods (case-control or cohort studies). The observational before/after with the EB method is considered more accurate since it properly accounts for changes in crash frequencies in the before and in the after periods at treatment sites; this may be due to regression to the mean bias (RTM). This method is also preferred over the comparison group method, as it considers the influence of traffic volumes and time trends on safety (*46*). Cross-sectional studies are used to estimate CMFs in cases where no data are available for a before/after study (*47*). This analysis does not need to take the time for an intervention of the treatment (*48*). The common approaches used to develop predictive models are conventional linear regression models, Poisson regression models, NB regression models, and zero-inflated count models. The defensible guidance on the application of these models to predict motor vehicle crashes can be found in (*49, 50*). The disadvantage of the cross-sectional method is that it does not account for the RTM bias. Therefore, it is possible to overestimate or underestimate the safety effectiveness of the treatment with this analysis.

A propensity score is the conditional probability subjected to receive the treatment rather than control, given the observed covariates. The aim of propensity scoring is to imitate what happens in randomized controlled trials (RCTs) by balancing observed covariates between control and treatment groups (*51*). Propensity scores with potential outcomes is a relatively new method used to determine the effect of treatments based on observational, non-randomized data. Although these models are common in medical, economic, political, and educational research (*52-55*), they had few applications in traffic safety. Davis first applied the propensity scores method in traffic safety research in 2000. He argued that if the selection mechanism for the treatment does not include in-traffic safety evaluation, both before/after EB and cross-sectional analysis methods become inconsistent with the true outcome (*56*).

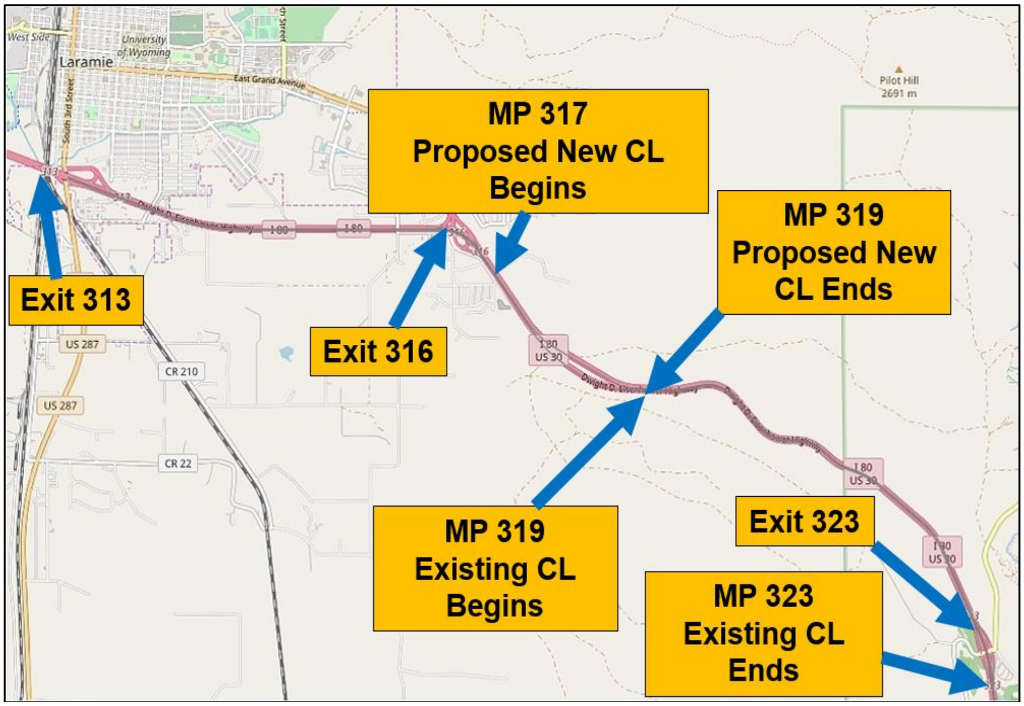
Some other applications of propensity scores in traffic safety include estimation of CMFs for signal installation (*57*), assessing the safety impacts of adding warning devices at highway-rail crossings (*58*), estimating child safety restraint effectiveness (*59*), estimation of design exception safety impacts (*60*), safety effects of intersection lighting (*61*), adjusting for bias in fatal crash samples using the FARS and NASS-GES databases (*62*), and assessing the impacts of speed cameras on safety (*63*). The propensity scores method was found to be a viable alternative to the before/after EB method and should be considered whenever a before/after study is not possible or practical (*64*).

3. OPERATIONAL ASSESSMENTS OF FREEWAY TRUCK TRAFFIC ALONG I-80

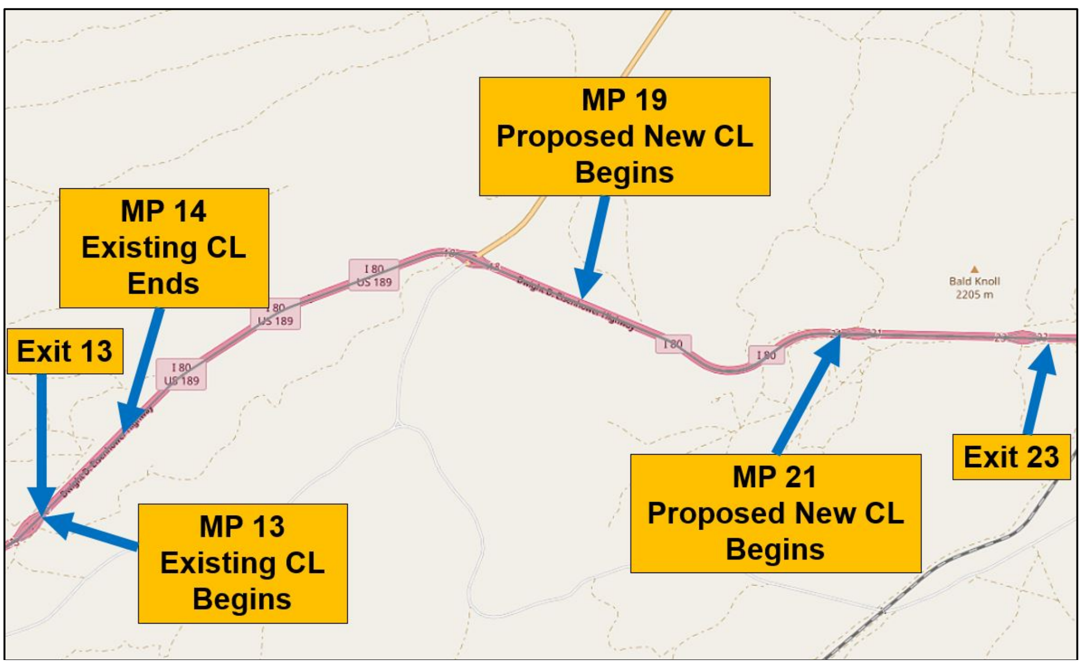
The operational analysis includes developing microsimulation models for both current (2017) and future years (2027 and 2037) traffic conditions. Creation of the models was accomplished by using a combination of VISUM (mesoscopic simulation model with traffic assignment capabilities) and VISSIM (microscopic 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 shockwave-based methodology for a quick and easy assessment of freeway traffic conditions.

3.1 Study Locations and Scenarios

Two sections along I-80 in Wyoming were selected for the analysis in this study. The first 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 5%, where a climbing lane exists from MP 316 to MP 319. The second location is also a 10-mile 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 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 (*65*). Figure 3.1 shows the selected study locations.



MP 313 – MP 323



MP 13 – MP 23

Figure 3.1 Study Locations

The truck composition used in this analysis was 46% as current and 70% as the worst-case scenario based on existing data. During adverse weather conditions, such as heavy snowfall or high winds, I-80 sometimes remains temporarily closed for trucks. When the road reopens, all trucks travel together, therefore the truck percentage could exceed 70%. This has been identified as the worst-case scenario along I-80. Based on this information, a number of alternatives were created, and microsimulation models were developed for the existing (2017) and projected years (2027 and 2037) traffic volumes, each having six different scenarios for a total of 18 scenarios, as shown in Table 3.1. An existing hypothetical and future scenario with no climbing lanes was used to estimate what would happen if the climbing lane were to be removed.

Table 3.1 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

3.2 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 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 2%, as recommended in a previous study (*66*).

3.3 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 10-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 85^{th} 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. Figure 3.2 shows an example of vehicle speeds on an upgrade, as well as the power and weight settings in VISSIM.

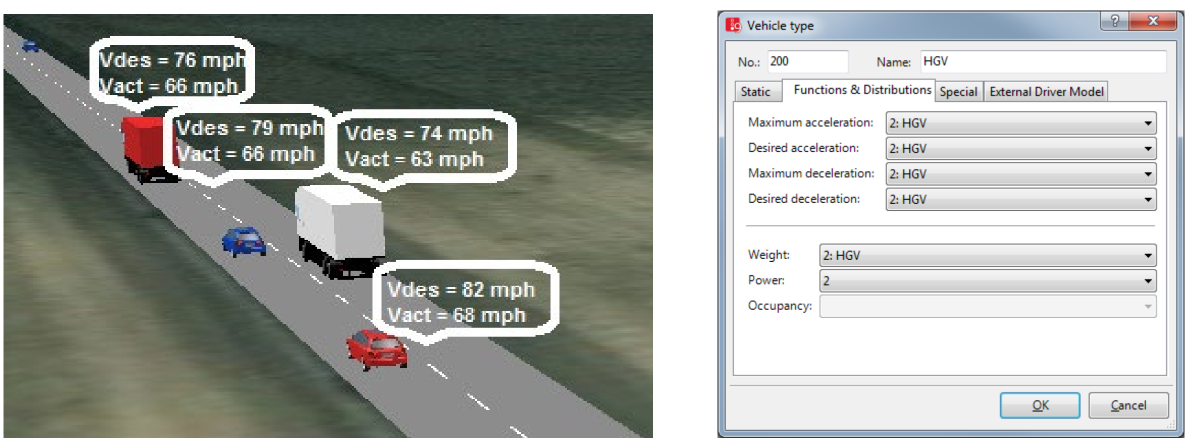


Figure 3.2 Truck Speeds Based on P/W ratio and Grade

The models were run for 24 hours (4:00 am – 12:00 am) with one hour of warmup time. Various 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.

3.4 Existing Models Calibration and Validation

Existing models were calibrated and validated based on the existing traffic volumes and average speed, as shown in Figure 3.3. 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. 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.

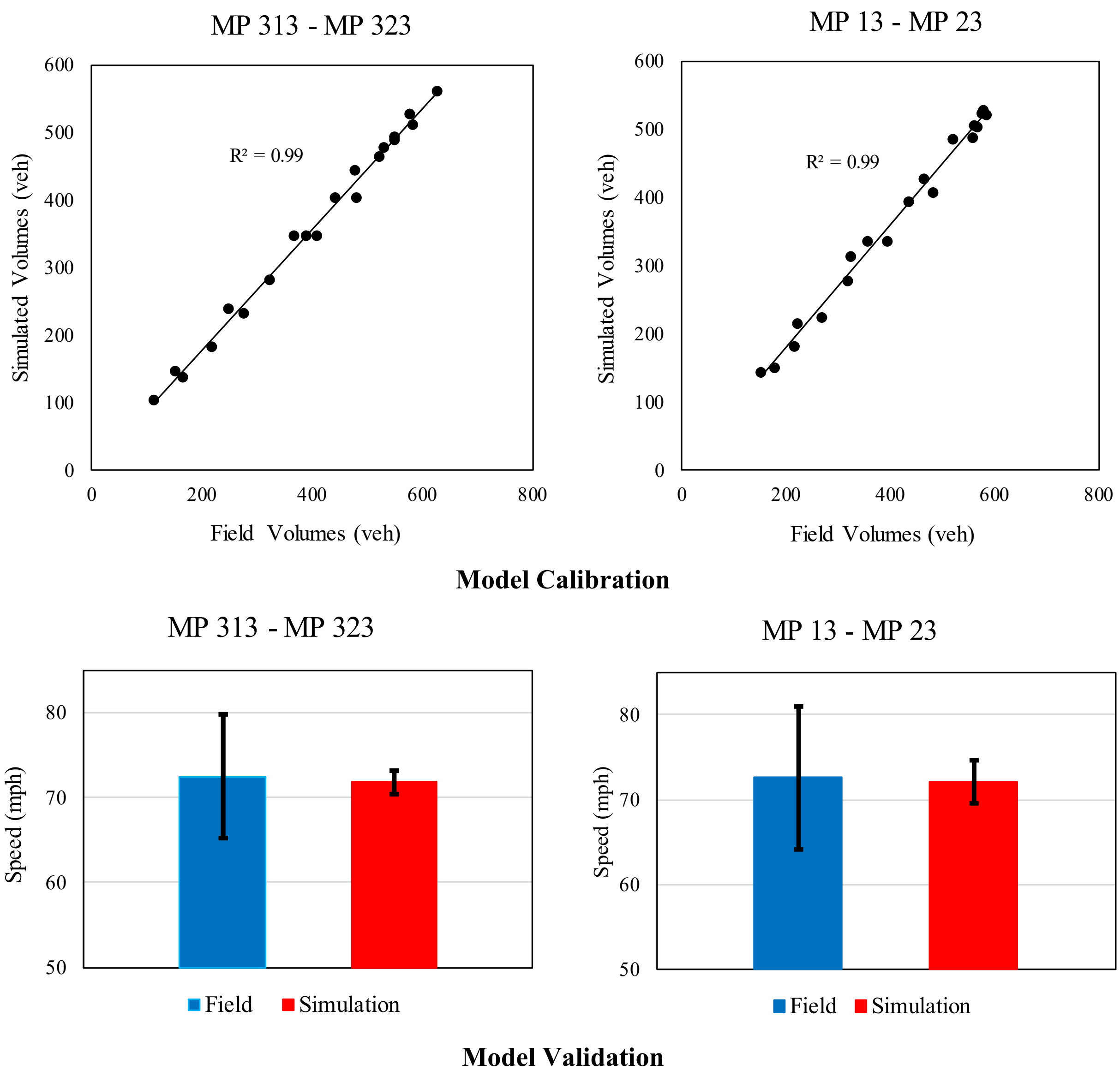


Figure 3.3 Model Calibration and Validation

3.5 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 two-hour afternoon period (3:00 pm – 5:00 pm) as the traffic volumes reached a peak during this time.

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 3.2 and Table 3.3, respectively. Comparing 2017 (1) to 2017 (2), as shown in Table 2, the results indicated that the total delay for all vehicles and trucks significantly increased by about 60%, and 64%, respectively, while having 70% trucks in the composition. About a 27% 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% and 1% for all vehicles and trucks, respectively, while having 70% 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% and 27%, 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 with 2017 (2), an additional new climbing lane did not have a significant impact on increasing average speeds with 70% trucks in the existing traffic composition. The total delay for all vehicles and passenger cars was found to be reduced by about 1% and 40% with a slight increase in truck delays in this case. Comparing 2017 (1) with 2017 (5) shows that the total delay for all vehicles, passenger cars, and trucks increased by about 18%, 365%, and 1%, respectively, when the existing climbing lane was removed. The average speed for all vehicles and passenger cars reduced by 2% and 3%, respectively, in this case. A comparison of 2017 (2) with 2017 (6) shows that the total delay for all vehicles, passenger cars, and trucks increased by about 12%, 489%, and 1%, respectively, without a climbing lane and 70% of trucks. The average speed for all vehicles and passenger cars reduced by about 2% and 5%, respectively, in this case. However, there was very little change in the average truck speed in both of these cases. This might be due to the continuous upgrade, where the trucks cannot develop higher speeds regardless of additional climbing lanes.

Table 3.2 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 3.3 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 were 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 3.3 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 3.4 and Table 3.5 present the percentage increase in total delay and percentage reduction in average speed between current year (2017) and future years (2027 and 2037) traffic conditions 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, which was the scenario with no climbing lanes and existing truck composition, and in scenario 6 for trucks, which was the scenario with no climbing lanes and 70% 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% 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 3.4 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 3.5 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 3.6 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 with 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 with 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 with the continuously upgrade portion in MP 313 – MP 323.

Table 3.6 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 higher when traveling through a climbing lane segment compared with 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 with the performance of trucks.

Potential future work includes evaluating the measures of effectiveness, such as segment capacity, distribution of vehicle speeds and headways, variations in speeds, densities, the percentage of time spent following, and the LOS. This analysis is currently in progress for the accompanying WYDOT study. The results from the simulation models would be beneficial to identify potential locations for climbing lanes and ranking them, so time optimization can be achieved during implementation.

3.6 Traffic Shockwave Models for Operational Analysis

Traffic shockwave is a phenomenon that occurs in a traffic stream during the transition between two traffic states. 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 (such as bottlenecks, or slow moving vehicles). Figure 3.4 shows the most commonly used flow-density (q-k) diagram to represent traffic shockwaves that occur between traffic states.

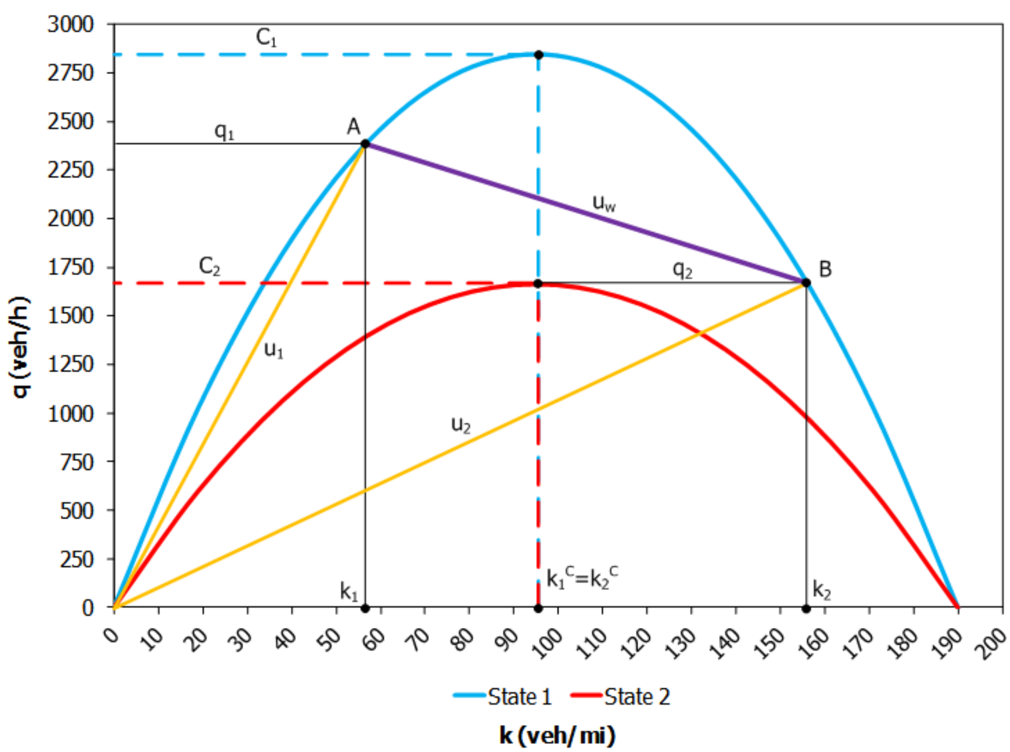


Figure 3.4 Flow-Density Representation of Traffic Shockwaves

To understand congestion patterns and impacts, it is important to analyze the formation and characteristics of shockwaves. The data requirements for shockwave analysis include vehicle movements and interactions over time and space, which were obtained in this study using traffic simulation as discussed previously.

Platoon is defined as a moving queue, i.e., a cluster of vehicles traversing through a bottleneck. In a platoon analysis using shockwaves, there are usually three states to consider: normal conditions (undersaturated), bottleneck (reduced capacity/increased demand), and end of bottleneck (recovery). The growth of platoon over time (in mph) is given by (3.1):

$$u_{pg} = u_{lead} - u_{w12} \qquad (3.1)$$

Where,
u_{lead} = speed of first (leading) vehicle in platoon
u_{w12}= speed of shockwave from state 1 to state 2

The shockwave speed is given by the following equation (3.2):

$$u_w = \frac{q_2 - q_1}{k_2 - k_1} = \frac{\Delta q}{\Delta k} \qquad (3.2)$$

Where,
q_i= flow in state i
k_i= density in state i

The following equation (3.3) is used to determine the length of platoon (mi) during bottleneck conditions:

$$L_p = u_{pg} \cdot t \qquad (3.3)$$

Where,
t = duration of the bottleneck/congestion

Number of vehicles in platoon can be found using equation (3.4):

$$N_p = L_p \cdot k_2 \qquad (3.4)$$

The net speed (rate) of platoon dissipation is given by the algebraic difference between speeds in front (uw_{23}) and rear (uw_{12}) shock waves, equation (3.5):

$$u_{NET} = uw_{23} - uw_{12} \qquad (3.5)$$

Finally, the time to disperse platoon can be determined using equation (3.6):

$$t_d = \frac{L_p}{|u_{NET}|} \qquad (3.6)$$

The first analysis in this study was carried out in order to observe the differences in traffic flow on the uphill and downhill segments. In general, the results indicated that heavy vehicles reduced speed significantly on the uphill segments, as compared with downhills, with the combination of severe vertical grades and the high truck percentage. For instance, Table 3.7 and Table 3.8 represent performance measures of link 55 (uphill) and link 14 (downhill) with following traffic flow parameters: density, speed, and relative delays.

Table 3.7 Link 55, Uphill Segment Summary (3:00-5:00 pm)

Link 55	**Density (vpmpl)**		**Relative Delay**		**Speed (mph)**	
	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane
All Vehicles	19.24	19.18	37.92%	37.71%	44.26	44.42
Cars	9.90	9.89	34.20%	33.94%	46.94	47.15
Trucks	9.34	9.28	41.78%	41.70%	41.49	41.53

Table 3.8 Link 14, Downhill Segment Summary (3:00-5:00 pm)

Link 14	**Density (vpmpl)**		**Relative Delay**		**Speed (mph)**	
	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane
All Vehicles	12.08	12.41	3.24%	3.30%	68.85	68.76
Cars	6.48	6.90	3.64%	3.52%	68.67	68.66
Trucks	5.61	5.51	2.77%	3.03%	69.05	68.88

According to results from Table 3.7, the density for all vehicles was about 20 vehicles per mile per lane (vpmpl) and almost the same for passenger cars and trucks. There was no significant difference between the left and right lanes. A similar situation was found with speed as another traffic stream parameter. Relative delay, which is the ratio of average delay time to average travel time, was found to have some noticeable values, especially for trucks.

Using the HCM and density for this segment, the LOS C was determined. Although density is considered the main parameter to determine LOS for freeway segment, it doesn’t represent real traffic flow conditions in this case. Speed as another important traffic flow parameter (used indirectly to determine LOS) is about 30 mph lower than the posted speed on the segment. The third parameter, referring to lost time during travel, is the relative delay. It is expressed in percentage, and on uphill segment 55, for all vehicles with values of 37.92% and 37.71% for the left and right lane, respectively.

On the other hand, the results in Table 3.8 represent the downhill link, with the same percent of heavy vehicles. The changes in density were insignificant and, according to the HCM, the computed LOS is LOS B. The results also showed that other observed parameters, speed, and relative delay significantly changed. The speed was found near the posted speed and relative delays were reduced by about 10 times.

The differences in various performance measures between two (very often adjacent) links invoke further analysis and attempts to discover the impacts of high truck traffic for similar road configurations. Attention has been given to the shockwaves, queue determination, and platoon effects, which are the expected phenomenon, as well as to the overarching safety.

The inability to overtake heavy vehicles in the desired moment is the reason to form shockwaves and platoons. Shockwave speeds for all consecutive vehicles with a 200-ft or shorter distance among them were determined from the position of the vehicles using vehicle records output from VISSIM. For platoon forming, three or more consecutive vehicles were considered, and it was done only as a one-time step, with an interval of 10 seconds. An empty place after calculation referred to the vehicles with spacing more than 200 ft. In this case, the assumption was made that the vehicle was moving at free flow speed.

The same calculation was conducted for both lanes in the eastbound direction to compare results. Twenty and 46 platoons were found in the right and left lane, respectively, which is the summation of platoons for different time intervals. For each of these platoons, the following parameters (growth of platoon, speed of leading vehicle, length of platoon, duration of the bottleneck conditions, number of the vehicles in the platoon, net speed, and time necessary for platoon to disperse) were calculated. Table 3.9 and Table 3.10 provide different shockwave parameters for the right and left lanes, respectively. First, the growth of platoon (u_{pg}) was calculated for further analysis. All platoons with negative growth were eliminated, which resulted in six and nine platoons in the right and left lane, respectively.

Table 3.9 Shockwave Platoon Analysis, Right Lane

Growth of Platoon, u_{pg} (mph)					
8.84	9.79	2.65	6.16	4.59	3.53
Number of Vehicles in the Platoon, N (veh)					
15	15	15	14	14	14
Duration of the Bottleneck Condition, t (min)					
1.57	1.18	3.99	1.27	1.59	2.03
Length of the Platoon, L_p (mi)					
0.23	0.19	0.18	0.13	0.12	0.12
Time to Disperse Platoon, t_{pd} (min)					
0.69	0.43	0.37	0.32	0.25	0.25

In the right lane, platoons contained 14 or 15 vehicles, while in the left lane, this number varied from four to 16. The trucks usually used the rightmost lanes for moving, especially on upgrades. The results from Table 3.9 indicate that the length of platoon and time to disperse were less than one mile and one minute, respectively. On the other hand, duration of the bottleneck condition was between one and four minutes.

Table 3.10 Shockwave Platoon Analysis, Left Lane

Growth of Platoon, u_{pg} (mph)								
8.42	7.59	8.62	10.21	6.89	12.98	9.81	6.99	5.39
Number of Vehicles in the Platoon, N (veh)								
14	14	6	6	16	10	9	4	4
Duration of the Bottleneck Condition, t (min)								
1.42	1.48	0.48	0.31	2.29	0.44	0.31	0.13	0.04
Length of the Platoon, L_p (mi)								
0.20	0.19	0.07	0.05	0.26	0.09	0.05	0.01	0.00
Time to Disperse Platoon, t_{pd} (min)								
0.46	0.13	3.2	1.09	3.78	1.95	0.79	0.13	0.01

Table 3.10 shows a significantly greater number of platoons in the left lane, which was not expected, because it should be free lane for passing (the vehicles with higher speed). Obviously, these expectations cannot be applied for uphill segments with a high percent of heavy vehicles. Frequent passing maneuvers and low speeds cause many delays and jeopardize traffic safety. The length of platoon was still less than half a mile, while the time needed to disperse platoon increased to four minutes. Duration of the bottleneck condition was between one and three minutes. Overall conditions of traffic stream in the left lane were found to be worse than in the right lane.

The time space diagrams for both lanes are provided in Figure 3.5 and Figure 3.6. Shockwaves with all phases, forming, bottleneck moving, and recovery shockwave, were visible on the diagrams and are marked with red circles.

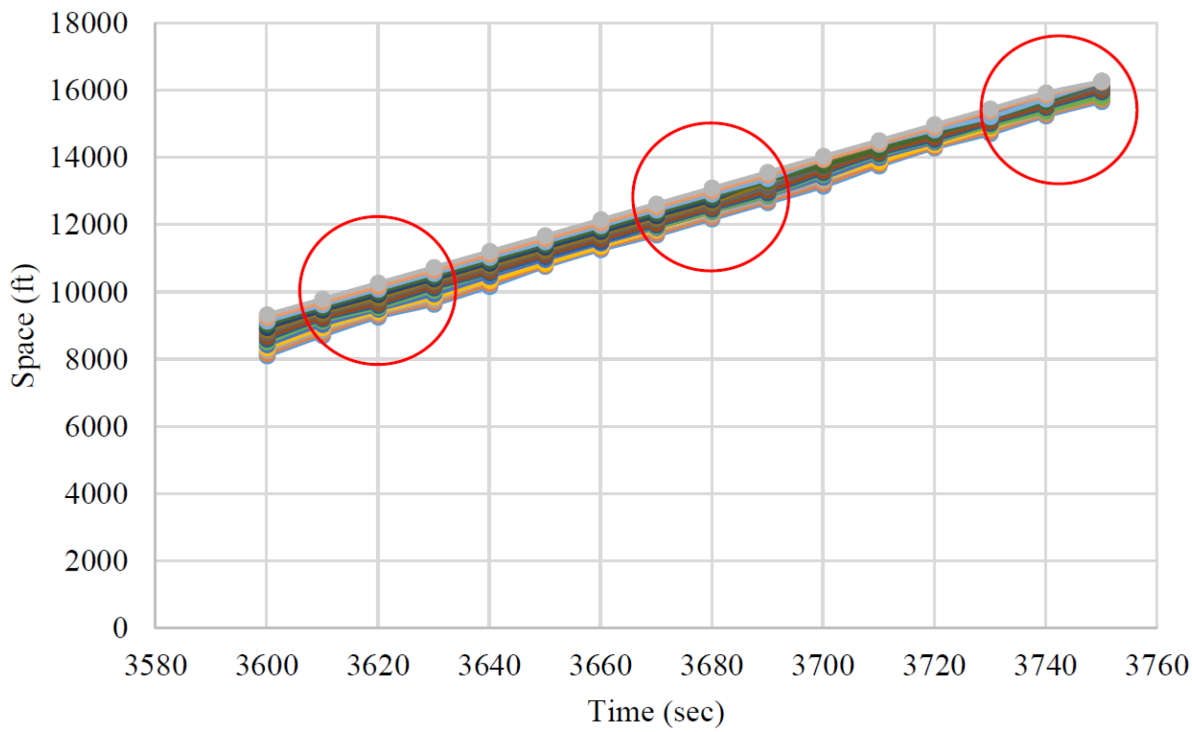


Figure 3.5 Time-Space Diagram, Right Lane

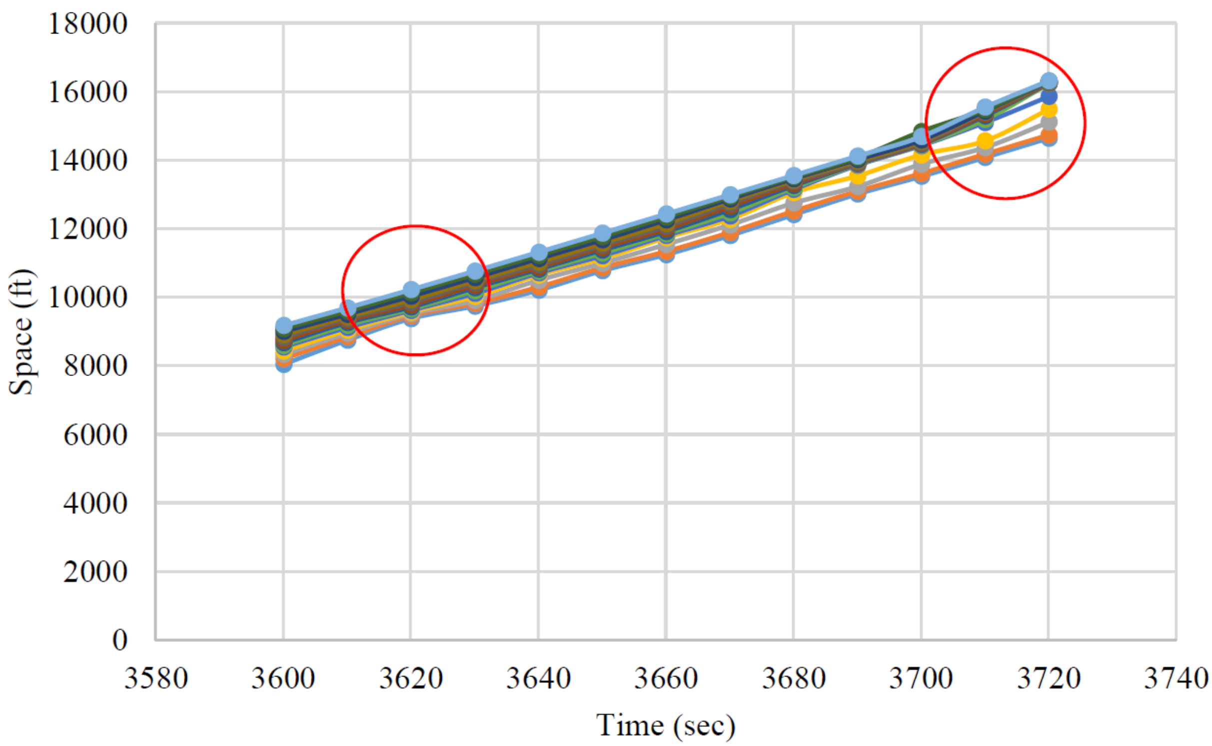


Figure 3.6 Time-Space Diagram, Left Lane

The shockwave model developed using microsimulation results can be implemented in the same way using the lane-by-lane volume and speed data collected from the freeway automatic traffic recorders. This model is currently being expanded and implemented in an Excel-based spreadsheet. Future model improvements should include developing a relationship between driver kinematics (e.g., perception-reaction time) and average headway of vehicles in a congested freeway to determine the probability and possibility of drivers making lane changes (a more stochastic approach to the shockwave model). These models can also be used in some established mesoscopic and macroscopic simulation models.

4. SAFETY ASSESSMENTS OF FREEWAY TRUCK TRAFFIC ALONG I-80

This chapter presents a safety analysis of I-80 in Wyoming, with a special focus on truck traffic because of the high percentage of cargo movement that this corridor carries. It is a popular route for freight transportation between the east and west coasts. 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 (*67*).

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

Crash data and accompanying information were acquired for the nine-year study period, 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, and 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 crash rates on all analyzed sections.

4.1 Descriptive Analysis

For this study, I-80 in Wyoming was divided into 20 sections, each having approximately 20 miles, as shown in Table 1. Since horizontal curves are a significant safety issue on expressways, horizontal curve parameters were also used in the analysis. As seen in Table 4.1, I-80 in Wyoming includes many horizontal curve segments; out of 402.78 miles of roadway, about 23% is within horizontal curves.

There were 4,945 truck crashes recorded along I-80 in Wyoming during the analyzed nine-year period. The classification of crashes by crash severity is shown in Table 4.2. Three types of crash severity included property damage only (PDO), injury, and fatal. On average, about 81% of the truck crashes were PDO crashes, while injury crashes accounted for about 17.5%. Fatal and other unknown severity accounted for the rest of the crashes. During the nine-year study, the greatest number of truck crashes recorded was in 2008. The second largest number of total truck crashes recorded was in 2016, the year that also had the highest number of fatal crashes.

The analyzed contributing factors for the truck-related crashes included road conditions, weather conditions, driver condition, driver action, and crash types, as shown in Table 4.3. The results showed that, on the nine-year average, 54% of crashes occurred during icy road conditions, and 32% of crashes occurred during dry road conditions. Snowy and wet road conditions contributed to 8% and 4% of crashes, respectively. The analysis of the impacts of weather conditions on crashes showed that about 46% of crashes occurred during snowy weather conditions. About 6% and 4% of crashes occurred during strong wind and cloudy conditions, respectively.

Table 4.1 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 4.2 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**

Table 4.3 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

The analysis of driver condition showed that about 90% of the crashes occurred in apparently normal states. Falling asleep contributed to approximately 2% of crashes. Emotion, fatigue, sickness, alcohol, and other driver conditions accounted for the rest of the crashes. The next contributing factor was driver action. It indicated that driving too fast and driving in an improper lane contributed to approximately 45%

of crashes. About 25% of crashes showed no apparent improper driving. Following too close, running off road, and other improper driving actions accounted for about 19% of crashes. This analysis can provide some guidelines for the mitigation strategies to be considered in order to reduce truck-related crashes.

The manner of collision presented in Table 4.3 shows different crash types, such as angle, head on, single vehicle, rear end, sideswipe, etc. The analysis showed that about 64% of the truck crashes along I-80 were single vehicle crashes. The rear end and sideswipe collision contributed to about 18% and 11%, 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 types of collisions accounted for the rest of the crashes.

4.2 Crash Frequency Analysis

A crash frequency analysis was performed separately for all vehicles and trucks for the 20 analyzed sections of I-80. A separate analysis was performed for portions of the roadway within horizontal curves. Tables 4.4 and 4.5 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% of all crashes.

Table 4.4 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 section 13 and 14, accounting for approximately 28% of all truck-related crashes. A comparison of results in Tables 4.4 and 4.5 shows that sections 5, 13, and 14 were the most dangerous, contributing to the highest percentage of crashes. Those sections must be given priority when taking necessary actions for roadside safety improvements. A more detailed analysis into those sections is needed to identify contributing factors, as well as suitable countermeasures. This is currently part of an ongoing research effort.

Table 4.5 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 between 50 ft and 33,000 ft. The crash frequency was analyzed for different curve radius ranges, as shown in Tables 4.6 and 4.7. Table 4.6 shows the number of all vehicle crashes within different curve radius ranges. The results indicate that about 40% of all vehicle crashes occurred within curves of 4,000-ft to 6,000-ft radius; 25% of crashes occurred within curves that have a radius of more than 9,000 ft; while about 27% all vehicle crashes occurred within curves of a 1,500-ft to 4,000-ft radius. Table 4.7 shows the number of truck-related crashes within different curve radius ranges. The results indicated that about 45% of truck-related crashes occurred within curves of a 4,000-ft to 6,000-ft radius; 25% occurred within curves with a radius of more than 9,000 ft; and 24% occurred within curves of a 1,500-ft to 4,000-ft curve radius.

A comparison of all crashes and truck crashes from Tables 4.4–4.7 indicates that out of all 4,951 vehicle crashes that occurred within horizontal curves, approximately 30% 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 a 4,000-ft to 6,000-ft radius. Therefore, safety improvements on that portion of highway curves need to be established to reduce those crashes.

Table 4.6 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 4.7 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**

4.3 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 4.8 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 4.8 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 greatest in 2008, with close to 1.7 crashes per million TMT for overall section. The lowest crash rate for trucks (close to 1.0) occurred in 2015. A similar trend can be seen for all vehicles crash rates. The analysis of crash rates within horizontal curves shows similar trends for all vehicles and trucks.

4.4 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 most suitable for local conditions. The negative binomial (NB) or Poisson-gamma regression model has been the most widely used model for crash prediction (*28*). 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 equation 4.1.

$$\lambda_i = \exp(\beta_0 + \beta_1 X_{1i} \dots\dots\dots\dots\dots \beta_p X_{pi}) \quad (4.1)$$

Where,
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 equation 4.2:

$$P(Y = y) = \begin{cases} w + (1 - w)e^{-\lambda} & for\ y < 0 \\ \frac{(1-w)\lambda^y e^{-\lambda}}{y!} & for\ y > 0 \end{cases} \quad (4.2)$$

where y = number of crashes, and w can be represented by a probability model that incorporates the effects of covariates.

4.4.1 Data Preparation and Description

In this study, nine years of crash data, roadway geometrical characteristics, and weather data were collected from several sources for the 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 average daily traffic (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 Crash Analysis Reporting Environment (CARE). The CARE database provides detailed information about crashes in Wyoming starting from 1994. Finally, weather data were extracted from the National Oceanic and Atmospheric Administration (NOAA) website. For this study, the average number of rainy, snowy, and windy days per year for each freeway segment was used as the main weather factor to predict crashes. These data were retrieved from the nearest weather stations along the I-80 corridor. 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, which 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 Highway Capacity Manual (HCM). A minimum length criterion of 0.1 miles was considered to avoid low exposure problems 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 4.9 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; vertical grade was divided into four categories: downgrades less than -2% as VG (1), VG (2) if the downgrades range from 0 to -2%, VG (3) when the upgrades range from 0 to 2%, and upgrades greater than 2% 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% during the study period. The weather data were shown as the average number of days per year. The largest numbers of observed rainy and snowy days per year 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 14 miles of climbing lanes along I-80 in both directions at different locations due to the severe upgrade sections. The presence of climbing lanes was also considered an independent variable in truck-related crashes.

Table 4.9 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

4.4.2 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 4.10 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% 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%, 49%, 54%, and 52%, respectively, compared with VG (3) sites. Moreover, in comparison with VG (3), VG (2) was found to increase the mean TTC, STC, MTC, and TRWC by 17%, 14%, 24%, and 31%, respectively; and VG (4) was found to increase TTC, STC, MTC, and TRWC by 42%, 28%, 67%, and 42%, respectively. A one-unit increase in curve radius decreases the mean of TTC, MTC, and TRWC by 0.01%. 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 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%. 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; hence, they were removed from the models. A one-day increase in rainy days per year was found to increase the estimated mean of TTC, STC, MTC, and TRWC by 1.20%, 1.10%, 1.20%, and 1.45%, 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%, 69%, and 73%, respectively. Therefore, climbing lanes are an effective countermeasure with a significant potential to reduce truck-related crashes along sections with steep vertical grades.

Table 4.10 Parameter Estimates of Wyoming-Specific SPFs for various Truck Crash Types using ZINB Models on Interstate 80

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 10 years (2007-2016) were first extracted from the CARE database to develop the SPFs. The data quality for 2007 was not consistent, 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.). A large amount of weather data were missing from the NOAA website. The common issue associated with this database was the unavailability of 12 months of weather data in a one-year period. Moreover, wind speed data were rare for most of the weather stations.

4.5 Safety Effectiveness of Truck Climbing Lanes

This section describes the analysis of effectiveness of climbing lanes (CL), and the calibration of crash modification factors (CMFs) and relative risk (RR) for CL 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 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 is 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.

4.5.1 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. The NB or Poisson-gamma regression models have been the most widely used model for crash prediction (*12*). If the dataset contains several zero truck crashes, ZINB models would be more appropriate. The general form of the NB regression model is given in equation 4.3:

$$\lambda_i = \exp(\beta_0 + \beta_1 X_{1i} \dots\dots\dots\dots\dots \beta_p X_{pi}) \tag{4.3}$$

Where,
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 NB distribution is given by equation 4.4:

$$P(Y = y|x) = \frac{\Gamma(y+\alpha^{-1})}{(y!\Gamma(\alpha^{-1}))}\left(\frac{\alpha\mu(x)}{1+\alpha\mu(x)}\right)^{y}\left(\frac{1}{1+\alpha\mu(x)}\right)^{\alpha^{-1}} \tag{4.4}$$

Where P is probability distribution, y is the expected number of crashes, and α is the overdispersion 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 CL, then the SPFs for freeway segments including CL as a variable can be expressed as:

$$Y_i = e^{(\widehat{\beta}_0+\widehat{\beta}_1 \times CL)} \tag{4.5}$$

For the segments with and without CL, the resulting equation can be defined by assigning CL=1 and CL=0 in equation 4.5, respectively.

The CMF for having climbing lanes can be determined as:

$$CMF = e^{(\widehat{\beta}_1)} \tag{4.6}$$

The propensity scores-potential outcomes approach estimates the probability of 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 relative risk (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 in equation 4.7.

$$P_n(i) = \frac{\exp(\alpha_i x_n)}{1+\exp(\alpha_i x_n)} \tag{4.7}$$

where x_n is the set of covariates, α_i is a vector of parameters to be estimated, and $P_n(i)$ is the probability that a location receives the treatment.

The goal of this model is to balance the covariates, 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 Equation 4.6. 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 0 indicating otherwise. Once the expected probabilities of crash occurrences were estimated for both treated and untreated groups, the RR was estimated as follows:

$$RR = \frac{E[P_{nUT}]}{E[P_{nT}]} \tag{4.8}$$

where 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.

4.5.2 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 period 2008 to 2016. Roadway geometric characteristics, cross-section elements, pavement type, and traffic data were extracted from the WYDOT Roadway Data Portal (RDP). Other non-traditional data sources, such as Google Earth Pro® and Google Maps®, were used to check, confirm, and obtain missing data.

The CAREdatabase was used to obtain total crash and truck-related crashes. Weather data were extracted from the NOAAwebsite. 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, 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 to warrant climbing lanes is a truck speed reduction in excess of 10 mph, as discussed previously. It also indicates that having a continuous one-mile upgrade of 4% reduces heavy truck speed significantly. Therefore, the sites having upgrades of 4% 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 problems 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 totaled 1,062 segments. Tables 4.11 and 4.12 show the descriptive statistics for the variables used in the cross-sectional and propensity scores analysis, respectively.

Table 4.11 Variables Used in 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 4.12 Variables Used in 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

4.5.3 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 4.13. 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% and 88%, respectively.

Table 4.13 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, which 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 annual average daily traffic (AADT). Among these, vehicle miles traveled (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% confidence level.

4.5.4 Propensity Scores-Potential Outcomes Framework

The propensity score model developed for the treatment (presence of climbing lanes) is shown in Table 4.14. Propensity scores were estimated using binary logistic regression where only two treatment levels (presence vs. absence of CL) 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 4.14, the variables associated with a lower probability of a climbing lane present 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 climbing lane presence are VMT, truck percentage, delta, right shoulder type, and average number of rainy and windy days per year.

Table 4.14 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 4.13. 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 a caliper value of 0.05σ are shown as an example below in Table 4.15. 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 sites, provided 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 a climbing lane in comparison segments increases the probability of occurrence of a truck-related crash by approximately 16%, compared with the treated segments with climbing lanes.

There was 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 there is no treatment).

Table 4.15 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 under-estimate the effectiveness of a treatment, since it does not account for the RTM 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 1 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% – 34% and 1% – 16% effective in reducing total and truck-related crashes, respectively, for different caliper values. This method uses the dual modeling approach, which makes it more accurate than cross-sectional analysis. Both the CMF and RR provide the results, which represent directly or indirectly the safety effectiveness of climbing lanes; and it was found effective in reducing total and truck-related crashes, which makes 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 studies 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 levels 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.

5. 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. I-80 was designed and constructed in the late 1950s, 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. In 2016, Wyoming was ranked first in the nation as the most per capita vehicle miles traveled (VMT) statewide. According to the Wyoming Department of Transportation (WYDOT) Annual Traffic Report of 2016, truck traffic accounted for approximately 21% of VMTs along all routes in Wyoming. The heaviest truck traffic exists along I-80, with about 47% truck VMTs. In 2016, 65% of the fatal truck crashes (medium and heavy trucks) occurred on interstate highways in Wyoming, and 54% of these fatal crashes were observed on I-80. It was revealed in 2015 that about 58% of heavy truck traffic used I-80 as their key route in Wyoming than another roadway system.

Trucks have significantly different physical and driving characteristics than passenger cars, especially in horizontal curves, vertical grades, and adverse weather conditions, which impacts 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 9% of I-80 in both directions is within vertical grades of more than 3%, where certain sections reach grades of close to 7%. As opposed to passenger cars, the performance of trucks is greatly affected by vertical grades. Trucks generally decrease speed by more than 7% 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 WY, 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. Two 10-mile eastbound segments along I-80 (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.

The main objective of the safety analysis is to explore the effectiveness of climbing lanes (CL) and calibrate crash modification factors (CMFs) and relative risk (RR) for CL along I-80 in Wyoming using Cross-sectional analysis and Propensity scores-potential outcomes framework, respectively. Overall, 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% – 34% and 1% - 16% respectively, depending on the analyzed location and applied methodology. 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.

The accompanying study sponsored by WYDOT is currently in progress. It will expand on the methodologies and results described in this report. From the operational analysis perspective, the future study will include additional segments along I-80 which will be modeled and analyzed. Also, the study will develop Excel-based tools for the shockwave models. From the safety perspective, the study will assess different crashes based on their types and severities. The results will be published in a WYDOT report.

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