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Evaluation of Feasibility of Deployment of Runaway Truck Detection and Warning Systems at Truck Escape Ramps

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16. Abstract

Despite the presence of properly signed and well-located runaway truck ramps, crashes involving trucks with overheated or otherwise failed brakes continue to occur downhill from the ramp locations. A recently deployed experimental truck warning system on Wolf Creek Pass on westbound SH160 shows some promise of effective crash reduction. The intent of this research project is to conduct observational before and after study at Wolf Creek truck escape ramps and evaluate feasibility of deployment of this system at all truck escape ramps in Colorado.

Implementation:
A methodology to evaluate safety performance by direction using Colorado-specific crash prediction models for the mountainous environment has been developed. The effectiveness of a detection and warning system for runaway trucks can be quantified. The findings of this research have the potential to reduce runaway truck crashes in the mountainous environment in Colorado and elsewhere.

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Abstract

It is widely recognized that truck escape ramps (TERs) contribute to reducing the frequency and severity of runaway truck crashes. However, despite properly signed and strategically located TERs, crashes due to failed brakes continue to occur downhill from ramp locations. The intent of this research project was to conduct an observational before and after study at the Wolf Creek truck escape ramps, where an experimental truck warning system has been recently deployed on westbound SH-160. The degree of crash reduction which can be expected due to a TER is not known to the same level of precision as other crash reduction factors, and to our knowledge, neither have observational before and after studies with proper correction for the regression to the mean bias been conducted to evaluate their effectiveness. In conjunction with this, a simultaneous objective was to examine the feasibility of deployment of a similar truck warning system to that on Wolf Creek Pass at all TERs in Colorado. Furthermore, the findings of this research have the potential to reduce runaway truck crashes not only in Colorado mountainous environment but elsewhere nationally.

Implementation:

As a result of this study, the Colorado Department of Transportation (CDOT) now has tools to evaluate safety performance *by travel direction* using Colorado-specific crash prediction models for the mountainous environment. The analysis enables quantification of the benefits of the experimental signing, detection and warning system for trucks and escape ramps, and results examined the feasibility of its deployment at all TER locations within Colorado. Finally, the study findings have potential to reduce runaway truck crashes not only in the Colorado mountainous environment but also in other locations nationally.

Executive Summary

The intent of this research project is to conduct an observational before and after study of the recently constructed experimental truck detection and warning system on Wolf Creek pass and evaluate the feasibility of deployment of this system at all truck escape ramps in Colorado.

Review of extant literature revealed that most of the research around TERs and runaway commercial vehicles crashes is centered on details of geometric design, gradation of the aggregate in the arrester bed, design of the dragnet, drainage requirements, signing and striping, driver education, ramp types, provisions for the removal of vehicles and other issues. To our knowledge no observational before and after studies with proper correction for the regression to the mean bias have been conducted to evaluate the effectiveness of truck escape ramps or assess the effectiveness of ITS.

Since truck escape ramps prevent crashes in one direction only it is critically important to develop methodology for evaluating safety performance in one direction. An analytical framework for conducting Safety Performance Function (SPF) Analysis by direction with correction for the regression to the mean was developed. This tool was subsequently implemented in the completion of an observational Before and After study of the effectiveness of the experimental truck signing, detection and warning system on Wolf Creek Pass.

The study results suggest that the warning and detection system has been effective for westbound commercial vehicle crashes. However, not all vehicles that should use the escape ramps are doing so.

Despite this, the system likely contributed to a reduction in severe westbound commercial vehicle crashes over time. The analysis found a 41% decrease in total crash frequency and a 39% reduction in severe injury crash frequency. Fatal crashes showed no change.

An assessment of all TERs in Colorado using directional SPF analysis revealed mixed results in terms of ramp performance over a typically 10-year study period, with some ramps having seen multiple recorded uses and others having seen zero. It was determined that because site specifics vary so widely across locations, particularly in terms of available infrastructure such as electricity supply and fiber cable network, the most sensible approach to project ranking was the Breakeven Analysis method. Two locations (Loveland Pass and Slick Rock Hill) were determined to be unlikely to be economically feasible for deployment of the system, as such it is not recommended that the measures be deployed at those locations, however other safety improvement recommendations were made. The remaining locations showed Breakeven cost estimates range from $1,029,672.83 (Mount Vernon Canyon TER) to $6,131,719.26 (Upper and Lower Vail Pass TERs).

Implementation Strategy

To incorporate the findings of this report into CDOT's procedures and methodology, directional SPF analysis will be added to the safety management software used by CDOT for safety performance analysis. Additionally, quantifying the effectiveness of the experimental signing, detection, and warning system, along with ranking the feasibility of deploying such a system across all Colorado TERs, will help CDOT prioritize safety improvement projects. This will enable better adaptation of project designs, maximizing safety benefits, and improving cost-effectiveness in resource allocation.

Chapter 1 – Introduction And Literature Review

Truck escape ramps (TERs) are typically found on routes which experience heavy truck traffic in mountainous downgrades to stop and contain runaway commercial vehicles. It is generally accepted that the occurrence of runaway commercial vehicles (trucks) is due to brake overheating, mechanical failure of brakes or driver failure to downshift appropriately. In the case of runaway trucks, a TER offers an opportunity for safe deceleration and arresting of the vehicle away from the mainline traffic. Typical types of TER include gravity, sand pile, arrester bed and more recently, dragnet systems. While each type has its individual merits as well as drawbacks, it is widely accepted that the arrester bed type is the most desirable. These are common in Colorado and involve a bed of increasing depth filled with an appropriate aggregate, typically 'pea' gravel, whose dragging force against the wheels of the truck slow the vehicle and whose material properties allow compression of the aggregate which promotes sinking and arresting of the truck.

This research is focused on evaluating the feasibility of deploying a new detection and warning system on all Colorado TERs which is based on the recently implemented system at the Wolf Creek Pass on westbound SH-160A between mile points 159.60 and 166.60. This new system would include advance warning diagrammatic signs showing hairpin curves, escape ramp locations and enhancement of signs with flashing beacons and blank outs to provide commercial vehicle speed advisory, which together offer real time feedback and guidance to runaway commercial vehicles. The literature review to support this research had the objective of surveying extant literature on the topic of effectiveness of truck escape ramps and the use of Intelligent Transportation Systems (ITS) on TERs.

The findings of the literature follow, however, in the course of our evaluation we found that most extant literature around truck escape ramps and runaway commercial vehicles is centered on details of geometric design, gradation of the aggregate in the arrester bed, design of the dragnet, drainage requirements, signing and striping, driver education, ramp types, provisions for the removal of vehicles and other issues. To our knowledge no observational before and after studies with proper correction for the regression to the mean bias have been conducted to evaluate the effectiveness of truck escape ramps or assess the effectiveness of ITS.

Literature on the Topic of Truck Escape Ramps (TERs)

Hayden, R.L., Mt. Vernon Canyon Runaway Truck Escape Ramp (1982)

In 1982 Hayden prepared a report for the then Colorado Department of Highways on the Mt. Vernon Canyon truck escape ramp (Hayden, 1982). The escape ramp is of the gravel arrester bed type, located on the I-70 corridor in Colorado and has a downgrade of over 5%. Hayden looked at the crash history on the ramp from its completion in 1979 to the time of publication in 1982, he found that there were 53 usage incidents of the ramp by runaway trucks recorded in the 3-year period. Remarkably no injuries or fatalities were recorded. Hayden draws the reader's attention to the opposing statistics for trucks which did not use the ramp. These latter statistics are notably different: 18 truck crashes were recorded in which the escape ramp was not used, including 7 fatalities and 24 injuries.

The report itself is concerned with evaluation of the performance of the escape ramp, including the performance of the gravel arrester bed. Hayden begins his report by outlining the rather bleak history of runaway truck crashes on Colorado mountainous roads prior to the construction of truck escape ramps within the state, which began in 1976. As part of the background description Hayden outlines the demonstrated success of the Rabbit Ears Pass TER as witnessed by the number of potentially serious incidents which were prevented.

The Mt. Vernon Canyon Ramp is studied by Hayden because at the time it was the only downgrade arrester bed in use. The report is concerned primarily with operational performance in terms of rolling resistance, aggregate contamination, entry speed, deceleration and the effects of a curved approach to the arrester bed. Because of the downgrade characteristic of the ramp, the arrester bed was required to be 2,000 feet long and the additionally, due to geometric characteristics of the site, is not visible to truck drivers as they enter the TER approach.

Hayden describes the use of the CCTV system which is in place at the Mt. Vernon Canyon ramp, as being used primarily to gather information on the performance of the arrester bed material and vehicle entry speeds by recording captured footage upon truck entry to the ramp. A series of loop detectors provide information on vehicle speed and deceleration. The report goes on to describe operating problems encountered with the CCTV system soon after adoption, related to the loop detectors. The malfunctions encountered with the CCTV system meant that data could not be gathered as design intended on entering trucks.

This report is not the only one consulted as part of our literature review in which reference was made to non-commercial vehicles using TERs casually or recreationally. The report and others highlight the diminishing effects on performance of the gravel arrester bed this can have, and hence the potential safety implications, as the bed does not slow and stabilize the truck as intended and rutting can cause trucks to bounce severely. All of this may have the further knock-on effect of an unsuccessful TER usage dissuading truck operators from using the ramps. Thus, it seems that as part of any TER design consideration should be given to measures which can be taken to prevent non-commercial vehicles from using the ramps in order to maintain the best possible operational performance.

The study goes on to provide more detailed narrative information related to specific usage incidents on the Mt. Vernon Canyon Ramp. One incident involved jackknifing within the ramp, however it was speculated that this may have been caused by application of truck brakes within the arrester bed. Another incident describes use by a driver unfamiliar with the route, this would seem to indicate that the presence of diagrammatic signs as advance warning signs would be beneficial in these cases. There is more than one case recorded where the tuck having entered the TER is bounced around and hits the retaining wall. In cases such as this where there is a downgrade arrester bed, this might be indicative of the need for additional edge cushioning to be provided by way of crash cushions, guardrails or retaining walls.

Rolling Resistance and Deceleration

Hayden goes on to analyze rolling resistance and deceleration specifically on the Mt. Vernon Canyon Ramp. He emphasizes that "rolling resistance and the deceleration rate that the gravel arrestor bed material imparts to a runaway truck is one of the key parameters needed for design." Hayden refers to the Colorado Roadway Desing Manual as a source for standards and specifications related to arrester bed design of TERs. In this section Hayden reiterates how the problems encountered with the CCTV loop detector system caused the quality and quantity of data gathered on truck entry characteristics to be diminished, as described previously. Hayden describes an alternative system of calculation which was developed to estimate distance-time and speed-time curves for entering trucks and obtain the information needed to study the arrester bed performance, however it is notable that there are gaps in the approach and results may not be entirely accurate. The results of Hayden's analysis indicated that deceleration within the bed increases over time. Correction factors were used to counter the gravitational effects of the arrester bed being on a downgrade. Hayden concludes that the design value set out in the Colorado Roadway Desing Manual of 0.2 G's for arrester bed rolling resistance seems to be adequate for average entry speeds, but is less confident about making any definitive conclusion for entries at higher speeds.

Aggregate Contamination

Appropriate aggregate properties and characteristics are essential to successfully slow and stop runaway trucks in arrester beds. Contamination is one such way in which the properties and characteristics of bed aggregate are negatively impacted. Hayden describes fines infiltration contamination of aggregate, which causes the gaps between gravel pieces to become filled in and reduces the ability of a truck to sink into the gravel. Contamination was found to have been particularly well prevented at the Mt. Vernon Canyon Ramp. Hayden found that a winter maintenance practice which involved keeping a snowbank along the highway mainline side of the ramp during winter prevented sand drift from the roadway onto the arrester bed. Hayden recommends that expensive aggregate replacement can be avoided by monitoring the distance traveled by trucks which have entered the TER and their entry speeds. In this way if trucks of similar entry speeds are taking longer to slow and stop than previous similar entries, the need to replace, clean or refresh aggregate can be anticipated and managed more effectively and economically.

Maximum Entry Speed

Entry speed is one of the factors that is used in determining the appropriate arrester bed design length required, along with the specific ramp geometrics and the aggregate rolling resistance. For this reason, Hayden indicates that an accurate estimate of entry speed is important for successful design. Hayden states clearly that estimated entry speed by truck operators is not reliable, although the degree to which is not clear. Other sources which were reviewed refer to design entry speeds of 80-90 mph, although Hayden seems to indicate that these are very conservative figures.

Hayden's study includes information on the profiles of truck operators which were recorded as part of the incident reports at the Mt. Vernon Canyon Ramp. In the case of this ramp for the 3 year-study period which was available, it was found that the average operator experience was 5 years. This echoes similar results to another paper by Valdes Vasquez et al. for CDOT published in 2018 (Valdez Vasquez, Strong, & Shuler, 2018) related to other TERs on the I-70 corridor (a review of which follows in this literature review). Brake overheating was found to have been the most common cause for use of the TER.

Hayden concludes his report by stating that the Mt. Vernon Canyon Ramp has been effective, while taking the opportunity to reemphasize the importance of maintaining optimal rolling resistance in the arrestor bed of downgrade escape ramps. Although focused exclusively on a downhill arrester bed style escape ramp, the paper makes strong and relevant points relating to the factors which pertain successful ramp design and operation generally, and it raises considerations around the regulation of ramp usage by non-commercial vehicles and the necessity of an appropriate and well-functioning ITS system.

The State Department of Highways, A Report on Truck Escape Ramp Use in Colorado (1982)

This 1982 report (Branch, 1982) produced by the then State Department of Highways, for the state of Colorado describes the usage of the existing TERs in Colorado at the time of publication. A 3-year crash history for 1976-1979 was considered as part of this report. While the report is not focused on quantifying the safety benefits of TERs in terms of Crash Reduction Factors (CRFs), it does make reference to the number of injuries and fatalities in that 3-year period which were as a result of runaway truck crashes and offers an estimated economic cost.

The report provides background information on the existing ramps at the time of publication which includes ramp type, arrester bed specifics, construction costs and the number of recorded usages of the ramp. One of the TERs discussed, Mt. Vernon Canyon, was at the time of the report unusual in that it has a downgrade arrester bed and had CCTV which allowed video capture of truck behavior. While technology has since advanced, at the time this was novel.

The report states that the "Truck Escape Ramp Reports" which were consulted provide "important data for assessing the performance of ramps." A cursory review of the sample reports suggests that the information contained in contemporary crash reports would also prove invaluable in determining the performance of escape ramps. The authors provide a summary of information they obtained from ramp usage reports at the time. There were some interesting observations to be made in the summary they provide. Firstly, it is clear that most trucks which used the ramps were from eastern U.S. states, indicating drivers may be unfamiliar with the area and with changing driving conditions in mountainous environments. The data also indicated that driver inexperience was likely a contributing factor to crashes. The seasonal variations in the ramp usage reports were as might be expected, that is that recorded usages are highest in the summer months when temperatures would be higher and brake overheating might be expected to occur more readily. Notably, entry speeds were wide ranging from 5 mph to 110 mph. In terms of arrester bed performance, 72% of entering vehicles stopped within 600ft of the entrance, however it is not clear how this is related to ramp types.

This report, as with others we reviewed, draws attention to unauthorized ramp usage. At the time of this report, it appears that there was an average of less than 6 recorded such unauthorized usages per year for all ramps in the state.

A Benefit-Cost-Analysis

As outlined above, while this State Department of Highways report is not focused on quantifying the safety benefits of TERs in terms of Crash Reduction Factors (CRFs), it does include a Benefit-Cost-Analysis (BCA). The Benefits were measured as the annual cost of prevented crashes. This was estimated by using the average cost of a runaway truck crash before ramp installation, while the number of annual crashes which were prevented was estimated based on the recorded ramp usages. The Costs were measured based on the annualized ramp construction costs, annual maintenance costs and costs of maintenance involved post-crash. **Figure 1-1** shows the calculation used in the report, which resulted in a B/C ratio of 3.20 indicating that the authors determined the implementation of TERs in Colorado to be cost effective, and it can be inferred, also to carry a safety benefit.

$$\text{B/C Ratio} = \frac{\sum A_i}{\sum R_i}$$

A_i = Annual cost of prevented accidents (ramp usages) at each ramp location @ \$33,342 each. This is an average cost of runaway truck accidents before ramp placement (derived from figure 1, page 2).

R_i = Annual amortized ramp construction cost + maintenance cost + after accident cost for each ramp.

then $\text{B/C Ratio} = \frac{\$\ 2{,}621{,}280}{\$\ \ 818{,}494}$ (Sum of Accident Cost saved by Ramp Usage) / (Sum of Ramp Cost)

B/C Ratio = 3.20

Figure 1-1: Benefit-Cost-Ratio Calculation of TER Usage in Colorado *(Branch, 1982)*

The report includes a section outlining the design of TERs which is based on a publication by the FHWA from 1979 which was to serve as an interim guideline. It can be assumed that this is now outdated and has since been replaced, with most sources we reviewed typically consulting the AASTHO Green Book.

Ramp Location

The report stipulates that ramp location is generally determined by topography; however, we know an element of subjectivity is also involved in the selection process based on individual case circumstances. The report recognizes this and states that a review of crash history for the 9 ramps that existed in Colorado at the time of this publication resulted in the authors drawing several general conclusions:

- The ramp location selected should capture the greatest possible number of runaway trucks,
- Crashes near the summit are less severe, conversely runaway trucks on a steep downgrade probably reach a probable point where the speed they have attained will cause a "catastrophic" accident,
- The placement of ramps prior to horizontal curves is preferred and
- Ramps located 3-4.5 miles from the summit capture 70-80% of runaway trucks.

While this report is dated, it provides a basic guide to TER types and forces involved in their operation. It also serves to highlight the importance of the information contained in crash reports for informing ramp design, but also ramp improvements. Additionally, the information contained in the report related to historical crashes and stakeholder feedback provides interesting data on the contributing factors behind crashes, which indicate that there is perhaps a human element to be considered which might be addressed by increased information, warning, and education.

Pigman, J. G. and Agent, K. R., Evaluation of Truck Escape Ramps (1985)

This report was produced by the Kentucky Transportation Research Program at the University of Kentucky for the Kentucky Transportation Cabinet (Pigman & Agent, 1985). It discusses the historical context of severe crashes which resulted in construction of two truck escape ramps in Kentucky, one at Hyden and one at Beattyville.

Initially warning signs with flashing lights were installed at the Hyden location (8% downgrade), however fatalities continued to be recorded, as such a truck escape ramp was constructed. Beattyville, the second location has a more severe downgrade of 13%.

An arrester-bed type escape ramp with gravel was implemented at Hyden. with gravel. Delineator posts and overhead lighting for nighttime incidents were also included in the design of the ramp at Hyden. Downgrade warning signs are also present. The ramp at this location is on a downgrade.

The escape ramp system at Beattyville is a combination of the gravity style and arrester-bed style. The ramp at this location is mostly on an upgrade. Signs for a TER are present.

The researchers gathered records for when the ramps were reported to have been used. Their results indicated that Hyden had been used 4 times in 5 years at the time of publication. Crashes at this location included two brake failures and one involved adverse winter weather. Beattyville records indicated it had been used once in 5 years at the time of publication and the incident was related to brake failure.

The authors state that the records indicate both ramps were used successfully to design and no injuries occurred. Incidents of fatalities were noted to have stopped in the 5-year study period implemented.

This report provides a basic evaluation of two truck escape ramps in Kentucky with positive results, although the data is somewhat limited and dated.

Tritsch, S.L., A Review of Truck Escape Ramps for HPR-PL-1(31)280, Evaluation of Arrester Bed Performance (1987)

This report was produced for the Arizona Department of Transportation (ADOT) to further knowledge on the field of arrester-bed design (Tritsch, 1987). Tritsch provides a brief contemporary review of the design of TERs and the historical experience of other states which have TERs, with a specific view towards arrester bed aggregate materials and forces.

Tritsch surveys contemporary research into arrester bed materials and concludes by providing recommendations for future research specific to ADOT needs, such as field testing correlated with laboratory testing of the arrester bed drag force (the momentum transferred from a truck into the gravel and the shear energy generated by the moving gravel).

This report, like others referenced as part of this literature review, refers to the AASHTO "A Policy on Geometric Design of Highways and Streets" (1984) as the deferred standard for states when it comes to designing TERs where any more specific design standards lack. The report primarily focuses on the structural mechanics involved in the use of a TER, such as the forces involved and the arrester bed materials and configuration, the latter which is currently dated due to more recent research into aspects such as the optimal gravel depth.

Witheford, D.K., Synthesis of Highway Practice 178, Truck Escape Ramps (1992)

This report was produced for the Transportation Research Board (TRB) as part of the National Cooperative Highway Research Program (NCHRP) (Witheford, 1992). It is a synthesis of reviewed DOT literature from across the states regarding TER technology. It sets out a summary of practices around and recommendations for location, design, operation and maintenance of TERs. Its primary focus is on the Grade Severity Rating System outlined by FHWA whose "objective is to calculate vales for "Weight Specific Speed" (WSS) signs that instruct drivers on the maximum safe speeds on grades for vehicles of different weight."

The report states that escape ramps of the gravel arrester bed type are most popular.

This report is another that finds that "advance signing and brake check areas at the top of grades contribute importantly to safe operations" and that "adequate maintenance is essential to the effective operation of truck escape ramps" in terms of aggregate maintenance and its refreshment post use, as well as removal of impurities and contaminants.

As part of the section which discusses operational considerations, the report makes heavy references to the relevant section of the Manual on Uniform Traffic Control Devices (MUTCD) published by the FHWA regarding the implementation and placement of advance signage for truck escape ramps. Also, as part of this section is the only reference made to ITS, that is to one of the surveyed states using a manufacturer's system which detects the presence of a truck in the arrester bed and activates an upstream warning sign. Misuse of truck escape ramps was found to be common and to negatively affect their performance. One incident is described where the bed had not been maintained after being disrupted by improper entry from a 4-wheel drive, and this caused a subsequent runaway truck to bounce severely upon entering the arrestor bed. Furthermore, in terms of operational considerations, the survey of literature performed by Witheford found that reduced truck speed limits of 20mph were an effective safety measure on downgrades, if trucks were compliant. Witheford's report indicates that at the time of publication this is not widely practiced, and perhaps more widespread adoption of truck speed regulations would be warranted.

The report made by Witheford involved surveying several states to ascertain details on the use of their TERs. Mixed results were returned with some states reporting next to little usage and others reporting 4 to 5 uses per month. Results were complicated by the reasons behind the usage of the escape ramps often involving casual misuse by non-commercial vehicles, versus needful use. Additionally, usage varied from ramp to ramp within states.

In terms of signing this report makes a couple of observations which tie into our research effort:

- Witheford refers to findings from the Grade Severity Rating System report (Johnson, DiMarco, & Allen, 1982) which indicated that a pilot study of special signing along the length of a downgrade in California which guided truck drivers down the Donner Pass with special graphic and text messages indicating grade steepness, curvature, escape ramp locations etc., found the provision of signing to be "very important."
- Another study this report refers to is from Virginia (Eck & Lechok, 1980), which indicates that truck driver responses confirmed that special signing, particularly graphical signing indicating steepness of grade, alignment and escape ramp locations, would be more helpful than typical speed limit signing.

One of the main conclusions the authors draw from their survey of state literature and the surveys they carried out as part of their research, is that regulatory signing should be provided so that it is sufficient to discourage the misuse or casual use of the ramps by vehicles other than runaway commercial vehicles, "…special advance signing especially (….) at grade summits, is highly desirable according to both researchers and truckers."

Even at the time of publication of this article (1992) one of the recommendations for future research recognized the need for benefit-cost-analysis of the costs of TERs compared to the "probable cost of accidents that might otherwise have occurred." It is telling that 30 years on there is still not a significant body of literature on this, as such our research may prove highly valuable to the field and industry.

HDR Engineering, Truck Escape Ramp Study, Final Report (2003)

This report, published in 2003, was funded by Arizona Department of Transportation (ADOT) to support research into the requirements for installation of truck escape ramps along specific routes within the state (HDR Engineering, 2003). The report contains a compilation of data on seven existing TER sites such as geometry, traffic characteristics and crash history, as well as data for sites where TERs may be implemented. At the same time, the publication makes a review of policies for TERs in other state agencies in mountainous states to identify the contemporary state of practice regarding TER construction and operations.

The report provides detailed information on seven existing TERs including as-built plans. When making a review of crash history for the escape ramps, the authors elected to utilize a distance of 4 miles in each direction of the ramp (upstream and downstream). The crash data was utilized to inform an evaluation of the suitability of the placement of a TER as well as an evaluation of the relationship between crashes, alignment, and downgrade.

All ramps which were studied in Arizona were of the arrester-bed type, and most were located on a downgrade. Additionally, all ramps that were included in the study have “last chance” mounds at the terminus of the ramps. One finding of the author’s review of existing ramps was that the design of arrester-beds was inconsistent both in terms of width and depth.

State of Practice (2003)

To determine the state of practice by other state agencies with regard to TERs the researchers used the following sources: internet, federal and state agencies, professional societies and publications. From their consultation of internet websites, the authors found that brake failure was cited as the primary cause of runaway trucks, and that websites tended to promote vehicle arresting barriers such as dragnets, as part of the TER system. The federal agencies they consulted were the U.S. Department of Transportation (USDOT), the Federal Highway Administration (FHWA) and the American Association of State Highway Transportation Officials (AASHTO). This section of the report outlines the signage requirements for escape ramps set out in the MUTCD by the FHWA, as well as general geometric and material guidelines stipulated in the AASHTO "Green Book," A Policy on Geometric Design of Highways and Streets. The primary finding of the authors is that specific guidelines are lacking regarding TER design, and rather we are left with general recommendations at the federal level.

Their research into practices at ADOT itself refers to a 1996 publication, "Roadway Design Guidelines" which offers minimal guidance, it does indicate that gravity type TERs are preferred in Arizona and that ramps within 3-4 miles of a summit have been found to intercept 80% of runaway trucks. A summary of technical reports produced by ADOT with regard to TER standards is also provided in this section of the publication. Some interesting points from the summary include:

- "Truck Emergency Escape Ramps, August 1985" notes most crashes involving runaway trucks occurred on grades over 5% and on a distance longer than 2 miles.
- "Truck Escape Ramps in Arizona – A Comprehensive Evaluation, December 1991," reports on the 70 instances the TERs in Arizona were used. Three minor injuries resulted. Some crashes involved non-commercial vehicles using the ramp. Four of the seven locations showed a reduction in the number of runaway truck crashes after the installation of the escape ramps. The conclusion was TERs were proven successful in reducing the severity of runaway truck crashes.
- "Candidate Location for an Operations and Safety Evaluation, US60 MP 289.00 to MP 293.00, Salt River Canyon, November 1998," found "improved warning signage should be installed to encourage operators to use lower gears," based on crash history at this location. The authors highlight a point made in this report, which is that Benefit Cost Analysis (BCA) for TERs is difficult and unusual in that compared with other remediation measures on highways which do not require any action on the part of motorists, a TER requires deliberate action by the driver to make use the TER, an interesting concept.

The report summarizes the state of practice in ADOT by stating that the value ADOT places on TERs is determined based on a combination of the amount of usage they get along with the reduction seen in severe runaway truck crashes.

While assessing the state of practice around TERs across other state agencies, including Colorado DOT, the researchers focused mainly on Western states with environments similar to

Arizona. The most interesting summary was based on Californian practices. They summarize that the California state entity responsible for transportation, CALTRANS, published "Traffic Bulletin No. 24 (1986), Design Guide for Truck Escape Ramps," which cites increased trucking, increased truck load weights, reduced maintenance efforts to improve profit margins and more out-of-state truck operators being employed who are unfamiliar with local terrain, as common factors related to an increased number of runaway truck crashes. The bulletin from California states, "proper signing of the entrance to the TER is essential," and recommends illumination of overhead ramp signs, and blank-out or changeable message signs upstream of TER to alert other truck operators if the ramp is occupied.

The author's review of state practices resulted in the conclusion that there is no clear methodology for determining the need and location of TERs nationwide, and that CALTRANS and Washington State DOT had their own standards regarding TERs, while other states relied on "NCHRP Synthesis of Highway Practice 178 – Truck Escape Ramps" and the AASHTO "Green Book" book.

Some of the professional societies and publications reviewed in this report included the American Association of Civil Engineers (ASCE) and the Transportation Research Board (TRB). Reference is made to a TRB article "State Practice and Experience in the Use and Location of Truck Escape Facilities (TRR 736)" which makes a statement that TERs have proven effective crash countermeasures.

Ultimately, this report produced by HDR for ADOT is concerned with determining the need, location and design of truck escape ramps, and not with quantifying their efficacy.

Florida Department of Transportation, Update of Florida Crash Reduction Factors and Countermeasures to Improve the Development of District Safety Improvement Projects, Final Report (2005)

This 2005 report prepared by Florida Department of Transportation (FDOT), had the goal of updating existing Crash Reduction Factors (CRFs) for FDOT for use in benefit-cost-analysis and constructing an online automated web tool ("CRASH") available on the FDOT intranet permitting continuous updating of the CRF database as new information becomes available (Florida Department of Transportation, 2005). The report also offers a review of the state-of-practice of development methods for CRFs and a survey of how CRFs are obtained by other states across the nation. Also included is a review of the efforts the Federal Highway Administration (FHWA) made regarding the application of the Empirical Bayes Method to the development of CRFs based on before-and-after studies to overcome regression-to-the-mean problems.

The review of CRF development performed by FDOT found that before-and-after and cross-sectional study methods were the most commonly used. Because the former was found to be the most commonly used method, the researchers made a further examination of the simple before-and-after method; the before-and-after method with a comparison group and the before-and-after method with the Empirical Bayes (EB) method. At the time of publication FDOT used the simple before-and-after method to determine CRFs but acknowledged that this approach suffers from the Regression-to-the-Mean (RTM) statistical phenomenon which can cause selection bias and overestimation of the degree of crash reduction achieved. The EB method is now widely accepted and considered to overcome the RTM problem.

Before-and-After Studies

This paper asserts that in seeking to recognize and remove hazardous locations in terms of highway safety two of the most important steps involved are the identification of the causes of crashes and the ability to predict the crash reduction brought about through safety improvements. As outlined above the report makes a thorough assessment of the three types of before-and-after studies used to develop CRFs. It addresses the major common concerns around simple before-and-after studies, for example the RTM phenomenon. One of the points made in this assessment of before-and-after studies is that clearly discerning between crash reduction brought about solely by the treatment applied and crash reduction which might be due to other external factors such as weather, reporting methods, crash trends in general etc., is difficult to determine accurately in order to obtain the true percentage crash reduction offered by a treatment. Nevertheless, the report defends the simple before-and-after study method for several reasons amongst which are that it is widely used so CRFs can be compared and verified and because it has a statistical precision that is not seen with any other study type. Regarding the before-and-after comparison group method, the report indicates that its success depends on the similarity of the comparison sites with the treatment sites, which subsequently presents an obvious difficulty if an adequate number of comparison sites cannot be found. The report also asserts that the before-and-after study EB method addresses the RTM problem which is "generally considered the most serious" and is recognized as being the most precise method.

CRF State-of-Practice

The nationwide survey which the researchers administered regarding CRFs and BCA returned responses from 42 states. The following tables summarize the general results of the survey; however, it should be noted that the time of survey was 2002 and the time of report publication was 2005, were response to be gathered today, results may vary.

Table 3-1. CRF Development Status in Different States

CRF Status	States
Developed their own CRFs or part of CRFs	Alaska, Arizona, California, Florida, Idaho, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Montana, New York, Ohio, Oklahoma, Oregon, Texas, Vermont, Virginia
Updating or developing CRFs at the time of survey	Connecticut, Florida, Kentucky, New York, Ohio, Oregon, Virginia
Use CRFs from literature and other States	Alabama, Colorado, Connecticut, Indiana, Kentucky, Louisiana, Michigan, Montana, Nebraska, North Carolina, Pennsylvania, South Carolina, South Dakota, Virginia
Adopted CRFs completely from other states	Delaware, Maine, Maryland, Nevada, West Virginia
Did not indicate how their CRFs were developed	Idaho, Iowa, Minnesota, Montana
Do not use CRFs	Arkansas, Hawaii, Massachusetts, Mississippi, North Dakota, Utah, Wisconsin, Wyoming
Did not respond to survey	Georgia, Illinois, Kansas, New Hampshire, New Mexico, Puerto Rico, Rhode Island, Tennessee, Washington

Figure 1-2: CRF Use by State, FDOT Survey Findings

Table 3-2. CRF Methods Used by States

Before-and-After Method	Alaska, Arizona, California, Florida, Idaho, Indiana, Iowa, Kentucky, Minnesota, Montana, New York, Ohio, Oklahoma, Texas, Vermont
Cross-Sectional Method	Missouri, Oregon

Figure 1-3: CRF Development Methods by State, FDOT Survey Findings

Additionally, it was noted that "CRF reports from Kentucky, Florida, New York, and FHWA were adopted by the other states the most often." While a further point to note was that states were found to apply CRF types differently: for example, some states applied CRFs by total crashes, crash severity and crash type, while others applied CRFs by crash type and crash severity only. The study period was found to be three years generally for before-and-after studies.

The authors provide summary tables which offer a synthesis of the CRFs which they identified through their nationwide survey. **Figure 1-4** shows an excerpt from these tables where the truck escape ramp countermeasure is listed. Note that these CRF figures are those which are presented by the FHWA in their CRF Desktop Reference Guide publication (U.S. Department of Transportation Federal Highway Administration, 2007).

Table 3-7. CRFs for Construction/Reconstruction Improvements (cont.)

Improvement	Crash Reduction Factor (%)															
	I	II			III										IV	V
	All	F	I	PDO	HO	RE	RA	SS	LT	RT	FO	Ped	ROR	OT	WP	N
Shoulder bus lanes					50(MN)		34(MN)	27(MN)	42(MN)				27(mn)			
Truck escape ramp	18(AZ)					33(AZ)							75(CA)			
Truck escape lanes	100(VT)															
New turning pockets						90(AK)		90(AK)								

Figure 1-4: Synthesized CRFs for Truck Escape Ramps, FDOT

Further consultation of the appendix of this FDOT report shows that the TER CRFs developed by Arizona (**Figure 1-5**) were broken down in applicability to "All crashes", crashes involving "deficient brakes" (i.e. runaway truck scenarios), and "Rear ends." While **Figure 1-6** shows that those developed by California are for application to scenarios involving runaway trucks only.

The legend provided by FDOT indicates that figures in parentheses indicate an increase in the crash rates, while figures which are underlined indicate statistically significant numbers. Considering this, it can be understood why the CRFs related the "deficient brakes" i.e. runaway truck scenarios from Arizona were not summarized as part of Table 3-7 in the FDOT report, nor were they included in the FHWA CRF Desktop Reference Guide (U.S. Department of Transportation Federal Highway Administration, 2007), as these CRFs indicated an increase in crashes, instead the general number of 18% was adopted as applied to all crashes occurring on a highway at all levels, as this number was found to be statistically significant. Conversely, the California number of 75% as applicable directly to runaway truck crashes was adopted for inclusion in both the FDOT summary Table 3-7 and the FHWA desktop publication. Although the California numbers are not underlined to indicate statistical significance, one can assume that both FDOT and the FHWA found good reason for their adoption over the Arizona number for a CRF applicable to runaway truck scenarios.

It is also worth noting that the Arizona TER CRFs for Injury and Fatal level Rear-End collisions were found to be 71% and statistically significant at this figure.

State: Arizona
Source: Arizona Department of Transportation

Improvement	Reduction Factor (%)				
	All	Fatal	Injury	Fatal and Injury	PDO
ROADWAY IMPROVEMENTS					
LANE ADDITION					
All crashes	25	39	23	23	27
Rear-end	32	67	28	28	35
Run-off-road	44	55	44	45	44
Side swipe/same direction	30	100	36	37	28
Side swipe/opposite, and head-on	53	100	39	70	59
LANE WIDENING					
All crashes	56	58	57	57	54
Run-off-road	49	100	35	41	54
Side swipe/same direction	52	0	43	43	54
Side swipe/ opposite, and head-on	70	0	100	100	25
SHOULDER WIDENING					
All crashes	57	48	59	58	57
Run-off-road	60	25	57	54	65
Side swipe/same direction	41	100	75	78	28
Sideswipe/ opposite, and head-on	75	33	80	72	83
Pedestrian	71	86	57	71	0
TWO-WAY LEFT-TURN LANE					
All crashes	30	40	20	20	35
Rear-end	36	0	38	38	34
Left-turn	33	100	0	2	48
Run-off-road	37	100	(3)	0	49
Pedestrian	19	0	19	18	50
Sideswipe/ opposite and head-on	36	0	50	50	27
REALIGNMENT					
All crashes	48	33	56	55	42
Run-off-road	66	33	71	69	62
Rear-end	37	0	42	42	34
Sideswipe/ opposite and head-on	85	67	89	83	87
Sideswipe/same direction	54	0	57	57	53
SHOULDER GROOVING					
All crashes	18	15	18	18	17
Run-off-road	27	12	27	26	26
OVERLAY					
All crashes	9	2	4	4	13
Rear-end	19	25	18	18	20
Run-off-road	13	(16)	11	10	15
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TRUCK ESCAPE RAMP					
All crashes	18	(75)	28	20	16
Deficient brakes	(14)	(100)	0	(100)	20
Rear-end	33	0	71	71	(100)

Figure 1-5: Arizona TER CRFs, FDOT Appendix

State: California
Source: Caltrans Highway Safety Improvement Program

Improvement	Reduction Factor (%)
New signals	20
Modified signals	20(1)
Flashing beacons	20
New left turn channelization	
A. Signalized Intersections	
1. Without left-turn phase	15 (2)
2. With left-turn phase	35 (2)
B. Non-signalized Intersection	35 (2)
C. Two-Way Left-Turn Lanes	25 (2)
New safety lighting	15 (3)
Curve correction	50 (2)
Rumble strip	50 (4)
Superelevation correction	50 (5)
Truck escape ramp	75 (6)
Shoulder widening on narrow 2-lane roads (24 feet wide or less)	
A. Widening (ADT less than 400)	15 (2)
B. Widening (ADT 400 to 1499)	30 (2)
C. Widening (ADT 1500 to 3000)	30 (2)
Truck climbing lane for 2-lane roads	30 (2)

Notes:
(1) Calculate the appropriate reduction factor. Not to exceed 20% for all intersection types.
(2) Of all accidents.
(3) Of night accidents.
(4) Of drift off the road accidents. (Sleepy, under influence). Inattention
(5) Of run-off the road accidents.
(6) Of run-away truck accidents.

Figure 1-6: California TER CRFs, FDOT Appendix

The report gives a brief overview of the various approaches taken to the calculation of the benefit of project selection as weighed against project costs across the states it surveyed. The overview makes it clear that while the Benefit-Cost Ratio method is the most commonly used, there are many different variations in how it is implemented, with some states counting all crashes, others just those involving fatal and injury crashes and yet other states opting to use an entirely different method altogether for project selection.

The report ends with a detailed description of the web-based tool that FDOT developed to automatize the recording and updating of safety projects across the state, as well as some observations for future development. As part of those developments the report refers to the FHWA goal of composing a national system of default crash modification factors.

This report provides a comprehensive review of the development and use of CRFs across the nation at the time of publication in 2005. It also provides a robust review of the Before-and-After method for the evaluation of safety projects, particularly when the EB method for correction for RTM is employed and supports its use in economic evaluations. The report provides several CRFs related to truck escape ramps, as determined by the states of Arizona and California.

However, detailed information regarding the study types, parameters and conditions is lacking and there appears to be some counter-intuitive findings in the case of Arizona and the effects of TERs on crashes involving deficient brakes.

Henry, M. and Wendtland, M., ITS Concepts for Rural Corridor Management (2007)

This report was prepared by Arizona DOT to review and recommend ITS concepts that might be deployed within rural areas of the state (Henry & Wendtland, 2007). While not exclusively concerned with truck escape ramps and associated ITS solutions, during their research, the authors did identify TER monitoring or "ITS-instrumented ramps" as one state-of-the-art practice which might be deployed.

The technology that is described in this report is more concerned with the detection of a truck on the truck escape ramp and the subsequent alert to other motorists of this condition, rather than with alerting truck operators of the presence of and location of a TER on the downgrade. The warning system described would detect trucks on the ramp, activate warning signs and have the potential to follow this up with email alerts sent to maintenance staff as well as snapshot images. The report describes how blank-out signs on the shoulders in advance of the TER are activated in this situation so that other drivers are made aware of the presence of a truck on the TER.

The authors identify two benefits: recognition by other truck drivers that the ramp is occupied, so that dual usage is not attempted; and the need for maintenance is also recognized following intrusion onto the ramp. The report subsequently identifies one primary challenge to any ITS deployment on TERs as being the availability of infrastructure to establish the necessary communications network, such as power and internet.

U.S. Department of Transportation Federal Highway Administration, Desktop Reference for Crash Reduction Factors (2007)

The publication by the FHWA serves as a quick reference guide for transportation planners, engineers and other stakeholders in determining and appropriate Crash Reduction Factor (CRF) for a proposed safety countermeasure (U.S. Department of Transportation Federal Highway Administration, 2007). A CRF as defined by the authors is an estimate of the "crash reduction that might be expected if a specific countermeasure or group of countermeasures is implemented with respect to intersection, roadway departure and other non-intersection crashes, and pedestrian crashes."

In some instances, a specific countermeasure may have more than one CRF associated with it, due to multiple applicable research studies producing slight variations in results of "potential effectiveness," which can be due to environment, traffic volumes and other such input being varied. As such the document is not a hard rule on the applicability of CRF but rather a best guide to support sound engineering judgment, as is indeed also clearly stated by the authors. The reference guide is clear in making it known that as part of any countermeasure application, the degree of crash reduction needs to be considered not just on the generalized CRF but also on specific elements such as geometrics, environment, operational conditions etc.

The manner in which the CRFs for associated countermeasures is logical, as well as helpful, in that that authors have constructed the tables such that any CRF presented in bold indicates to the reader that the study on which it was based meets rigorous scientific methods, while on the opposing end, any CRF that is not bold indicates the study was less rigorous. Coupled with the supply of standard errors for CRFs, this permits the reader to make informed choices and decisions regarding the application of CRFs.

The report dedicates a substantial amount of space at the beginning to describing to the reader by way of example how to interpret the information presented in the tables for each of CRF sub-types (Intersections, Roadway Departure and Pedestrian).

Review of the desktop reference guide revealed a CRF for provision of Truck Escape Ramps (TERs). As part of the second section of this reference guide which sets out CRFs related to roadway departure crashes, “Table 6: Geometric Countermeasures” (see **Error! Reference source not found.**) contains information related to the installation of a TER. It can be seen there is a range of CRFs provided for TERs as a countermeasure, varying based on the crash type being considered (run-off-the-road, rear-end, or all crash types). It is also apparent that the CRFs are applicable for all crash severity levels. Notably, the range of expected crash reduction is quite wide, from 18% when all crashes are considered, to 33% for rear-ends, and up to a much higher 75% when run-off-the-road (ROR) crashes are considered. Intuitively these figures make sense, a 75% reduction in run-off-the-road crashes appears reasonable because we expect most runaway truck scenarios to result in a run-off-the-road i.e. roadway departure crash and we also expect most drivers to elect to utilize and successfully access the escape ramp, while at the same time we recognize that runaway truck crashes do not account for all roadway departure crashes on highways. Similarly, a runaway truck scenario could result in a rear-end collision if the truck does not use a TER or one is not available, however, with truck traffic generally encountered at less than 10%, we expect these types of rear-end collisions to be less frequent than rear-ends involving all other vehicles and so we do not expect so large a CRF for rear-end collisions in general. Finally, the same can be said for application of the TER CRF to “all crash types,” we expect runaway truck crashes to comprise a small amount of all crash types along a mountainous highway, as such the general crash reduction to all crashes by implementation of a TER would be expected to be much lower, as seen here at 18%.

Following reference “15” found in the table (**Figure 1-7**) provided by the authors, it can be found that the CRF figures in the table for TERs are extracted from a 2005 study performed by Florida Department of Transportation (FDOT) (Florida Department of Transportation, 2005) to update the state’s CRF database and develop a state online system that allows for updating of the CRF database when new research and studies become available. When the FDOT report was consulted it led to the finding that the CRFs outlined for TERs were originally obtained from the Arizona Department of Transportation and the California Department of Transportation. Examination of the FDOT report did not provide specifics as to how these CRFs were arrived at, and the original reports from Arizona and California could not be obtained.

Desktop Reference for Crash Reduction Factors — Roadway Departure Crashes

Countermeasure(s)	Crash Type	Crash Severity	Area Type	Road Type	Daily Traffic Volume (veh/day)	Effectiveness: Ref	Effectiveness: Crash Reduction Factor / Function	Effectiveness: Std Error	Effectiveness: Range Low	Effectiveness: Range High	Study Type
Install passing/climbing lane	All	All	All	All		1	20				
	All	Fatal/ Injury	Rural	2-lane		38	33				
Install shoulder	All	All				15	9				
Install shoulder bus lanes	Head-on	Fatal/ Injury				15	50				
	Head-on	PDO				15	86				
	Left-turn	Fatal/ Injury				15	42				
	Left-turn	PDO				15	57				
	ROR	PDO				15	27				
	Right-angle	Fatal/ Injury				15	34				
	Right-angle	PDO				15	31				
	Sideswipe	Fatal/ Injury				15	27				
	Sideswipe	PDO				15	8				
Install truck escape ramp	All	All				15	18				
	ROR	All				15	75				
	Rear-end	All				15	33				
Lengthen culverts	All	All				15	44				
	All	All				15	40				
	All	All				15	48				
	All	All				15	30				
Narrow cross section (4 to 3 lanes with two way left-turn lane)	All	All	Urban	4-lane highway	8,000-17,400	17	**37**	1			EB Before-After
	All	All		4-lane		42	26		23	28	
	All	Fatal/ Injury	Urban	4-lane highway	8,000-17,400	17	**0**	2			EB Before-After
	All	PDO	Urban	4-lane highway	8,000-17,400	17	**46**	1			EB Before-After

Figure 1-7: Truck Escape Ramp CRF, Table 6: Geometric Countermeasures, Desktop Reference for Crash Reduction Factors

In addition to this TER CRF, several other CRFs are found in the desktop reference guide which may be applicable to our interests as we consider the implementation of ITS technology including Variable Messages Signs (VMS) with speed advisory and enhanced diagrammatic advance warning signs with flashing beacons as part of the upgrading of TERs within Colorado. Two of the CRFs seen in “Table 9: Signs/Markings/Operational Countermeasures” as part of the second section, Roadway Departures, of this guide are:

- Curve advance warning signs with flashing beacons and
- DMS/VMS with speed advisory warnings

Figure 1-8 shows the relevant excerpt from Table 9 of the reference guide. While the CRFs are not applicable exclusively to runaway truck crashes, they might be considered in a composite fashion to be applied to all highway crashes in a mountainous environment where an enhanced ITS truck warning system is implemented. Consideration would need to be given to the more local environment and conditions, as it can be seen that while the CRF for installation of curve advance warning signs with flashing beacons is advised at 30%, in the case of VMS for speed advisory there is a standard error provided such that the range for 46% or 41% is in fact more variable.

Desktop Reference for Crash Reduction Factors — Roadway Departure Crashes

Countermeasure(s)	Crash Type	Crash Severity	Area Type	Road Type	Daily Traffic Volume (veh/day)	Ref	Effectiveness: Crash Reduction Factor / Function	Std Error	Range Low	Range High	Study Type
Install curve advance warning signs (flashing beacon)	All	All				15	30				
Install delineators (general)	All	All				15	11				
	Head-on	All				15	67				
	Night	All				15	25				
	ROR	All				15	34				
	Sideswipe	All				15	67				
Install dynamic/variable accident warning signs	All	Injury		Freeways		5	44	17			Meta Analysis
	Rear-end	Injury		Freeways		5	16	10			Meta Analysis
Install dynamic/variable queue warning signs	Rear-end	PDO		Freeways		5	-16	15			Meta Analysis
Install dynamic/variable speed warning signs	All	All				5	46	17			Meta Analysis
	All	Injury				5	41	62			Meta Analysis
Install guide signs (general)	All	All	All			15	15				
Install guideposts or barrier reflectors	All	Fatal/ Injury	Rural	2-lane		38	8				
Install illuminated signs	All	All				15	15				
Install lane assignment signs	Rear-end	All				15	10				
	Sideswipe	All				15	20				
Install nonvehicular (animal) reflectors	All	All				15	10				
	Night	All				15	25				

Figure 1-8: Advance Warning Signs CRFs, Table 9 of the Desktop Reference for Crash Reduction Factors

This desktop reference guide is one of the most relevant pieces of literature related to our interests and provides useful starting data in terms of potential CRFs which might be considered and tailored for the enhanced truck escape ramp guidance system which is being proposed. It is also one of the only sources that provides directly a suggested CRF for implementation of a TER.

AECOM, Feasibility Study, US 421 from US 221 in Watauga County to SR 1301 in Wilkes County, Truck Escape Ramps and Improvements (2009)

This study (AECOM, 2009) describes in detail the feasibility of upgrading existing truck escape ramps on US 421 in North Carolina, which is a 4-lane rural arterial with grades of between 4% and 9%. The 2008 ADT was 8,700 vpd with 10% truck traffic. Some of the more relevant improvements for our purposes are upgrades to signing and provision of ITS features. Signage improvements included enhancing signs with truck specific information regarding the downgrade and the location of the TERs, while ITS features included devices to detect truck entry onto a ramp and subsequent alerting of emergency services and truck drivers.

The two existing ramps are of the sand pile type. AECOM examined a ten-year study period for crashes on the relevant section of US 421. Of all 239 recorded crashes, 51 (21%) involved trucks. There were 3 fatalities involving trucks, which made up 43% of all recorded fatalities.

Seven of the truck crashes occurred on the western escape ramp and 28 occurred on the eastern ramp. This implies that over 68% of truck crashes involved use of the TERs.

As seen in other publications which were reviewed as part of this literature review, this study also relies partly the AASHTO "Green Book" and the NCHRP report, "Synthesis 178 Truck Escape Ramps: A Synthesis of Highway Practice," to formulate designs for changes to the existing escape ramps and a proposed escape ramp.

One of the proposed changes which the study explores is the placement of a truck stop at the summit of the downgrade (the pre-existing stop was not at the summit), to allow cooling of truck brakes before descent of the downgrade and for truck drivers to gather adequate information. It was considered at the time if the stop should be legislatively made mandatory. The truck stop which was considered as part of this study included for dynamic message signs in advance of the stop, as well as dynamic message signs at the stop to describe weather travel conditions.

As part of the detailed description provided on the upgrading of the pre-existing sand pile escape ramps to arrester bed types, the authors state that arrester bed types are preferred because "they reduce the speeds of trucks more gradually." The main body of the report is concerned with setting out the technical specifications for alternative designs of the four new truck escape ramps, regarding aspects such as design entry speed, arrester bed length and width, location of ramps and construction and right of way costs. AECOM addresses challenges to meeting design criteria, potential design exemptions, and describes the reasoning behind design proposals as part of this technical section.

For each ramp location the ITS elements included as part of the design by AECOM were:

- An advance dynamic message sign prior to the ramp
- A microwave vehicle presence detector
- A CCTV camera and
- Communications equipment

The ramp designs described by AECOM also include ramp lighting, a paved service road and anchors for truck removal.

One obstacle which was addressed as part of this study was horizontal curve flattening, because curves were negatively impacting sight distance in some locations, as well as causing trucks to cross over the central median. This is an important consideration certainly for CDOT also, however, in a narrower mountainous environment where facilities are perhaps two lanes rather than a wider 4-lane rural environment, such as here in North Carolina, this may not be as readily achievable.

As part of their study for the North Carolina DOT, AECOM divided their recommendations into near-term and longer-term items. Those items which they included under "near-term" recommendations were considered "top priorities needed to reduce the frequency and severity of truck crashes" along US 421. These recommendations are generally focused on the construction of TERs at the locations which witnessed the most crashes and most severe crashes, however it is interesting to note that one of the more immediate recommendations proposed is for the implementation of a truck stop/information station (including advance dynamic signage) at the summer of the downgrade, thereby emphasizing how this study perceives this element to be crucial to the enhanced safety of the truck escape ramp system. In conjunction with this, AECOM emphasizes that the ITS improvements they are recommending at the TERs are top priorities, including the vehicle detection described previously.

As part of their general recommendations, AECOM state that it is important to ensure trimming of foliage along the route to ensure maximum visibility of warnings, critical information and arrester beds. This is one of several studies reviewed as part of this literature review in which public outreach was recommended to further education around truck escape ramps, increase awareness of their presence and purpose. In the case of the latter collaboration with the freight industry and law enforcement is suggested.

While this study is focused on a location in North Carolina, whose environment may not be exactly replicate of those in Colorado, it points to the importance that the industry places on the presence and purpose of advance signage and the implementation of ITS as related to truck escape ramps.

Valdes Vasquez, R. et al., Emergency Escape Ramps (EER) Improvements (2018)

This research was performed for the benefit of the Colorado DOT (CDOT) with the objective of developing design and operational recommendations for CDOT regarding TERs (Valdez Vasquez, Strong, & Shuler, 2018). The primary focus was to reduce instances of jackknifing, roll-back and rollovers by commercial vehicles which enter a TER, in order to maintain trucks upright and prevent hazardous spillages and injuries. To achieve this the researchers used a combination of analysis of the materials and designs of arrester beds, evaluation of crash reports, field observations, and interviews with stakeholders along the I-70 corridor and CDOT staff. Primary focus was given to the Lower Straight Creek truck ramp on I-70.

The report outlines that the current standards for construction of TERs within Colorado are found as part of "CDOT Standard Specifications for Road and Bridge Construction," which was influenced by a condition assessment of existing TERs and the experience of other state agencies. It also states that since 2006 CDOT has aggregate specifications for materials used in arrester beds.

One interesting concern of CDOT which is raised in this report is around the failure of commercial vehicle drivers to utilize TERs.

The report describes types of TERs and refers to what is outlined in AASHTO's "Green Book," that is that gravity type TERs are least attractive because while they slow the vehicle, they do not capture it, hence the truck can still roll back and jackknife. Meanwhile sandpile types are outlined as being less attractive in adverse weather, a large factor in a Colorado climate.

A review of the current state of practice by the authors includes a discussion on dragnet TERs which are relatively new. While they appear to be more expensive due to possible sub-ground heating requirements as well as the cost to replace steel tubes/nets after use, they provide a smoother stop, and hence less chance of secondary injuries for drivers, and they help retain the vehicle such that jackknifing and overturning are prevented.

The authors discuss various approaches to determining the need for and locational placement of a TER, such as the FHWA Grade Severity Rating Scale guide which is based on limiting the temperatures experienced by braking of commercial vehicles. Also discussed is the design of TERs including ramp length and aggregate selection, which are generally based on the AASHTO "Green Book" from 2011.

In terms of operation and maintenance the authors highlight that for successful operation of a TER, advance warning to commercial vehicle drivers of the conditions ahead is necessary along with mandatory brake-check areas and speeds set by truck weight. Here again we see a reference made to the advance signage requirements set out in the MUTCD regarding escape ramps. This paper is another one in which the importance of delineators and lighting for nighttime ramp use is highlighted. The authors states that Colorado is among one of the states that has published material on TERs for truck drivers to outline the concept, provide usage guidelines and increase awareness. The report makes a point of emphasizing the importance of proper maintenance of ramps to ensure successful performance, e.g. after use the aggregate needs to be fluffed, contaminants need to be removed regularly from the aggregate and moisture needs to be removed. The authors indicate that the effectiveness of arrester beds is reduced if snowmelt carrying fines infiltrates the aggregate and drainage system.

The report goes on to analyze incident reports involving trucks for 2005-2017 along the Colorado I-70 corridor, which included five TERs. The analysis showed an average of 1.7 "truck-use" incidents per month (other uses which generated a report were wildlife incidents or downed trees for example). Focus was given to the Lower Straight Creek Ramp as this had the highest incident record. Surprisingly, less than 2% of incidents involved severe crashes. Seasonal influences appear to be significant, as usage in summer months for the 2015-2016 year was almost three times greater than in winter months. The author's hypothesis is that temperatures in winter prevent brake over-heating while trucks are also traveling more slowly due to winter conditions. Based on their analysis the authors determined that truck usage of TERs on I-70 has increased steadily since 2005.

The production of the report also involved field observation at the Eisenhower Tunnel of operations and video monitoring capabilities, as well as an observation of four TERs on I-70. Ramps are monitored by cameras and the presence of a truck activates a contact switch. Visibility is diminished at nighttime making monitoring more difficult without infrared capabilities on cameras. Maintenance and operations personnel can deploy static or dynamic signs when ramps are closed. The report refers to observation of a "story sign" in advance of one of the ramps, as well as observed poor lighting and heavy vegetation.

In the case of one ramp location, it was observed that only the first 1/3 of the ramp was being utilized by runaway trucks, while at a second location approximately 2/3 of the ramp was being utilized. Both locations are ascending arrester bed types. The researchers also made observations of insufficient gravel depth at some ramp entrances as well as fines intrusion.

Another observation included witnessing other vehicle types using the dedicated ramp lane to overtake slower moving vehicles, and as such the authors comment that realignment and signage in these cases would be beneficial. This highlights the importance of ensuring proper signage and pavement markings regarding the purpose of the ramp for emergency usage by trucks only, as well as the prohibition of other vehicular traffic in a ramp lane.

The report goes on to provide a section on the analysis of materials and design of arrester beds based on methods adopted by other state agencies and historically published research. This section draws attention to an important consideration around the design of TER arrester beds, that is the balance between providing an aggregate that provides a high degree of rolling resistance, which is necessary to stop runaway vehicles, and the rapid deceleration caused by these materials. Rapid deceleration poses more potential for injury to drivers as there is potential for the trailer to accelerate into the slowed cab and jackknife. The authors indicate that this may be one reason why drivers are deterred from using TERs. Tapering the depth of the bed from the entrance over the first 100 to 200 feet might be one way to reduce the abrupt deceleration as suggested in this report.

Details of the interviews with stakeholders (e.g. Colorado Motor Carriers Association), along the I-70 mountain corridor and CDOT personnel are discussed by the authors. The meetings were focused on obtaining information related to: law enforcement response to ramp usage; reasons for differences in the amount of usage between ramps; improving efficacy of lighting/signage/shoulders; reasons for avoidance of ramps by truck drivers; and suggestions from stakeholders for improvements to ramp effectiveness. Increased driver awareness and education were cited as a contributing factor to increasing TER usage by truck drivers. Improvements to TER signage were particularly well received. Details of the meetings showed that the Colorado Motor Carriers Association (CMCA) confirmed that drivers do not receive training specific in the use of TERs. Interestingly, the most frequently used ramp in the state, the Lower Straight Creek ramp, seems to show usage by drivers with less experience according to CMCA feedback.

A second stakeholder meeting attended by the researchers included discussion regarding the need for "dynamic speed signage and flashing signage for hot brakes." A survey was performed, although there were only 8 respondents, stakeholders were well represented between CDOT, freight carriers, law enforcement and design consultants. In terms of ramp awareness and advance signage, survey results showed there was agreement that signage indicating ramp entry as well as "story signs" (i.e. diagrammatic depictions) in advance of ramps would be beneficial. Additionally, guardrails or some other device to act as a channelizing method at ramps was a well-received recommendation. Provision of lighting at ramp entry points and outreach to commercial truck drivers to improve education around escape ramps, were also aspects which received positive feedback in the surveys.

Finally, the report looked at the performance of ramps based on hazmat spills as the governing criteria. Data evaluated by the authors showed that spills had occurred not on ramps but in the vicinity of ramps. This section of the report is primarily concerned with understanding the cleanup process and techniques as well as the post-clean-up verification across other western states, within Colorado, and by emergency responder companies.

The report draws several conclusions regarding TERs in Colorado. Of note is the statement by the authors that the escape ramps along I-70 have performed well since their implementation with 1 fatality and 5 injuries recorded at the time of publication in 2018. Problems/factors influencing performance of escape which were observed by the team include a ramp having a sharp angle of departure for from the mainline, intrusion of fines into arrester bed material due partly to poor maintenance, sub-optimal aggregate being employed and insufficient aggregate depth. Another of their conclusions includes a re-statement of how increasing awareness and education amongst truck drivers was perceived by stakeholders to assist in promoting their use of TERs.

One of the conclusions made which may connect directly with this research was based on the stakeholder surveys, that is that signage improvements and dynamic advisory speed signs were the most important improvements for ramp design and/or operation in the eyes of stakeholders. Designated ramp entrance and pavement markings, as well as lighting were also determined to be important factors in improving ramp effectiveness and usage.

The paper ends with detailed recommendations for the four specific ramps on I-70 which were part of the field observations. Aspects which merited attention with a view to improving performance, and which might tie into this research, were as follows:

- Development of a maintenance schedule to include aggregate sampling and testing to ensure integrity and optimal performance of arrester bed material by removal of contaminants and fluffing.
- Camera system upgrades to a sophisticated ITS system, that is a "camera that has both thermal and digital imaging capabilities along with data collection and transmission."
- One theory described by the authors in an effort to explain hazmat spillages, is that abrupt deceleration leads to jackknifing or rollover. Because of this they recommend research into deceleration rates on TERs.
- Research into deceleration rates on TERs because the fear of rollover may be one reason why drivers are hesitant to utilize ramps. Guardrails or concrete barriers lining the edge of ramps would make them more inviting.
- To deter use by non-commercial vehicles the authors suggest red and white checkering of pavement markings on the ramp entry lane as well as a sign indicating "ESCAPE RAMP ENTRANCE: NO TRAFFIC" or similar.
- Addition of flashing beacons to overhead ramp entrance signs as per the Rabbit Ear Pass, which are solar powered.

This report offers information and findings specific to Colorado and CDOT and provides valuable insight into improving escape ramp operations which may prove beneficial for this research effort, particularly in terms of advance signing.

Moomen M. et al., Evaluating the Safety Effectiveness of Downgrade Warning Signs on Vehicle Crashes on Wyoming Mountain Passes. (2019)

In his paper Moomen (Moomen, Rezapour, Ngah Raja, & Ksaibati, 2019) refers to several articles which make some interesting points related to our research. An article produced by Lill in 1977 (Lill, 1977) which found that the primary factors involved in severe truck crashes on downgrades included:

- Inexperienced drivers or drivers unfamiliar with the area
- Speeding
- Impairment
- Defective brakes and
- Inadequate signage

Moomen highlights Lill's finding that warning signs might be effective in these situations: "…warning signs caution drivers about the locations and dangers associated with hazardous sections of highways." Moomen also refers to a 1994 study by Middleton (Middleton, 1994) which found that flashing lights added to warning signs targeted at trucks resulted in reduced truck speeds.

The goal of this study was to assess the safety effectiveness of advance downgrade warning signs in reducing downgrade crashes. The study looked at locations on Wyoming highways meeting MUTCD criteria for hazardous grades which qualified for steep grade warning signs. The research methodology utilized a negative binomial regression model to overcome over-dispersion of data. MUTCD truck escape ramp warning signs were amongst those included (MUTCD W7-4, W7-4b, W7-4c). Also included were speed advisory signs specific to commercial vehicles.

The results of Moomen's research found that a unit increase in an escape ramp sign saw the expected number of crashes decrease by 1- exp (-0.572), equating to 43.6% i.e. increased presence of warning signs for TERs was associated with a decrease in truck crash frequency on downgrades. The paper indicates there is ambiguity as to whether the warning sign alone propagated this or whether the presence of the ramp itself results in less crashes, as in general crashes were observed to be less on segments where ramps were present.

Meanwhile a curve warning coupled with a speed advisory sign was found to be associated with a 32% decrease in truck downgrade crashes.

Moomen further emphasizes as others have that "trucks are more prone to crashes on downgrades due to brake failure." He adds to this by outlining that changes in superelevation also increase truck crashes because the risk of overturning due to a high center of gravity is higher along with poorer control on curves.

The analysis found that overall passing lanes were most effective at reducing truck crashes on downgrades. While in terms of signage exclusively, downgrade warning signs, curve warning sings coupled with truck speed advisory signs, and advance warning signs for TERs, were most effective at reducing truck crashes on downgrades. "The study found that there is empirical evidence to justify the installation of advance warning signs for downgrades."

The primary findings of Moomen's research can be summarized as follows:

- Signs are more effective when installed in advance of the downgrade section rather than within section itself,
- Curve warning signs when accompanied by truck speed advisory signs are most effective at reducing truck downgrade crashes,
- Warning signs function as a system and not individually, this concept and its implications was not pursued in this study,
- An evaluation of the safety effectiveness of warning signs specifically as related to the importance truck operators place on them should be made and
- The effects of downgrade warning signs on crash severity should be studied.

Zhao, X. et al., On the Effective Speed Control Characteristics of a Truck Escape Ramp Based on the Discrete Element Method (2019)

This paper states that truck escape ramps are "the most efficient way to prevent" brake failure accidents involving trucks (Zhao, Liu, Yu, Shi, & Ye, 2019). It also notes that extant research on the topic typically focuses on location, geometry and materials.

This research focuses on the dampening characteristics of TERs provided by bed aggregate materials, with a view to preventing trucks overshooting the ramp bed and overturning. The research involved simulation and laboratory testing using the discrete element method (DEM) to investigate the tire-soil relationship.

The authors tested different bed depths and truck loads based on models of pebble they developed. A road test was also performed in China. In conjunction they simulated trucks running into an arrester bed. The road test and simulation results were similar with a 2.39% error.

A tire-pebble DEM model simulated trucks running onto TERs under different loads and for different depths of beds. Trucks speeds were seen to drop sharply then stabilize. Results indicate that "at the entrance of the TER, the truck speed is mainly determined by the laying depth." In other words, the heavier the truck load, the more difficult it was to stabilize the truck. Laying depths tested ranged from 0.2m to 0.6m.

The main finding of this paper was that when the material in the arrester bed gets to a depth of 0.6m and deeper, the dampening properties of the aggregate remain around the same. A thicker laying depth of aggregate was found to cause a faster speed decrease. It was also found that speed at the entrance to a ramp was mainly determined by the laying depth of aggregate. Finally, the tire tread pattern was found to have little influence.

STANTEC, Escape Ramp Site Evaluation and Conceptual Design: Eastbound I-70 from Genessee to Denver West (MP 257 to MP 264) (2021)

This report produced by STANTEC in 2021 for the benefit of CDOT outlines the evaluation of sites and design alternatives for a new TER on eastbound I-70 in Colorado (STANTEC, 2021). Consideration is also given to improvements to an existing brake cooling station or the construction of a new one. The environment of the proposed ramp is a mountainous downgrade of over 5% with frequent sharp curves. The study limits in question for this report include truck traffic which ranges from 6.5% up to 7.9% of ADT, and ADT ranges between 77,000 and 112,000, approximately, depending on which particular segment within the study limits is being considered.

Existing Mt. Vernon Canyon Escape Ramp

This study incorporates the Mt. Vernon Canyon Ramp, which was evaluated in 1982 by Hayden (Hayden, 1982), the report for which has been reviewed earlier in this literature review. As alluded to in the 1982 report by Hayden, the sharp horizontal curve on the approach to the Mt. Vernon Canyon ramp has been found to be a challenge to navigate for truck drivers whose vehicles are out of control, as indicated by this 2021 report. In fact, crash reports which were studied as part of this 2021 report show that crashes were recorded on the curve leading into the escape ramp, noting also that the ramp is not always used when needed, which implies truck drivers may find it difficult to navigate or are deterred from using the ramp due to the curved approach. This was confirmed by the Colorado Motor Carriers Association (CMCA) who indicated that the "sweeping curve" combined with the steep grade caused some truck operators to be unable to use the ramp. As such, it appears that the success of a TER is not based solely on the design of the ramp itself but also relies on the characteristics of the surrounding environment. In terms of ITS, the study briefly describes a pilot program by ITS and freight groups at CDOT which by way of Bluetooth and license plate readers, identify trucks and communicate speed warnings to the drivers by way of overhead VMS and in-cab information as they approach downgrades.

Design Considerations

The report assesses various ramp locations by one-mile increments along the study limits. The challenges posed by the location specific characteristics are described, such as steep cross slopes, adjacent rock walls and residential/commercial development, and presence of extended auxiliary lanes for example. Traffic queueing was another aspect which STANTEC considered, and which made certain locations unsuitable for runaway trucks. Due to the unique and varied nature of the geometric and other site-specific challenges and hazards posed by the locations which were evaluated, the design team elected to focus on left shoulder/median placement of a potential TER. The report highlights an obvious challenge to this proposal, which is the unorthodox placement of an escape ramp in the median posing an unfamiliar situation to truck operators who may be thrown off by this and find it difficult to navigate their way to the ramp successfully.

As part of their evaluation STANTEC and CDOT observed traffic habits in the field at proposed ramp locations. This appears to be a valuable consideration when determining the location of any potential ramp, which is largely subjective in and of itself. Field observation at one segment in particular allowed the team to recognize that truck operators tended to occupy the center through lane, rather than the left or right through lane, to avoid heavy occupancy in the right through lane by vehicles which planned to make an upcoming exit. Field observation of traffic habits can also help to identify traffic queueing, which as outlined above, poses unfavorable conditions for placement of a TER.

Stakeholder (law enforcement, EMS, trucking industry and local communities) feedback indicated that amongst the factors considered important for successful TER operation, was adequate and clear advance signage as to the position of the ramp. Emergency responders also pointed to the availability of water sources being an important factor in ramp design in addressing any potential hazardous ramp uses.

VISSIM Simulation

Evaluation of alternatives was made based on simulation using VISSIM software, which simulated worst-case scenarios in terms of peak-hour traffic volumes, steep downgrades and limited ability of truck operators to perform necessary maneuvers to change lanes before being aware that the new ramp is located on left/median. The model also allowed varying the location of advance warning signs as to the location of the median escape ramp, runaway truck speed and route selection. Input parameters for the model were further informed by stakeholder feedback. Results of the simulation indicated that advance warning signs with critical information for truck drivers are pertinent to the successful access and use of the escape ramps. Being able to alter the advanced warning distances in the simulations "helped inform the design team about where the signage for the new escape ramp should likely be placed." Ultimately, early warning of ramp location provided the ability to maneuver appropriately and have that result in successfully reaching the ramp. Some limitations of the VISSIM modeling included unrealistic results, for example incidents of other vehicles not moving out of the way for runaway trucks or trucks decelerating faster than would be considered realistic. This is a fundamental drawback of the software. To overcome this a set of "pass/fail criteria were drawn up against which individual truck performance within the simulation was evaluated. The authors recognize these limitations and caution that results should be interpreted with sound judgement. Indeed, this is what led the team to rejection of the modeled ramp location with the higher pass rate in favor of that with the lower pass rate. Despite the pass rates, as alluded to earlier, there is subjectivity in regards TER location selection. In this case a sharp curve on the approach as well as a steeper downgrade and a shorter advanced warning distance were the determining factors in rejection of one location over the other.

Ramp Selection & ITS

An arrester bed type ramp was selected in favor of the gravity or dragnet type, which were rejected due to costly right-of-way requirements, damage to trucks and significant repair requirements. In this case it was decided to place the first advance warning sign 3.4 miles in advance of the escape ramp, which was determined by use of a VISSIM simulation. In terms of ITS, STANTEC recommended a permanent overhead variable message board across all lanes of traffic in the eastbound direction. This is an "Active Traffic Management (ATM)" approach. While other literature which was reviewed has described situation where entry onto a TER triggers an upstream warning to truck operators on variable messages signs that the ramp is occupied, this proposal describes a more advanced real-time solution which can provide additional pertinent changeable information such as lane closures, maintenance activities, advisory speed etc. As per other sources of literature consulted for this review, the design around the escape ramp length and bed width were based on the guidelines set out in the AASHTO 'Green Book.'

The study refers to another project being developed on the I-70 corridor which has specific emphasis on ITS and safety. The system which is described includes variable speed limit capabilities along the corridor. The study indicates that any devices employed in this effort might have the potential to be incorporated in truck safety measures, which are interpreted to mean safe speed advisory.

Brake Cooling Station

As part of their discussion on the selection of a brake cooling station for upgrading, STANTEC laid out several recommendations to increase the as-planned usage of one of the existing stations. These recommendations, need not necessarily be exclusive to this particular case and might have the potential to be implemented at other brake cooling stations throughout Colorado, as such they are worth noting:

- VMS in advance of brake cooling stations,
- Display of number of available spots at cooling stations,
- Increased education by way of fliers/notifications at Port of Entry,
- Education for out-of-state truck operators prior to state entry and
- Pavement markings leading to brake cooling stations.

While not concerned with developing a crash reduction factor (CRF) for implementation of TERs, this report does collect ramp usage data for the five TERs on eastbound I-70 between 2005-2017. The data seems to be primarily sourced from another report which is reviewed as part of this literature review, that is the 2018 CDOT report on Emergency Escape Ramps produced by Valdes Vasquez et al (Valdez Vasquez, Strong, & Shuler, 2018). The study highlights that the truck-related crash history on this section of I-70 is above average when compared to similar mountainous facilities in the U.S. As outlined in the report by Valdes Vasquez et al., between 2005 and 2017 truck usage (as opposed to non-commercial vehicles entering the ramps recreationally or otherwise), of the five ramps averaged 1.7 instances per month.

This report outlines in detail the review and selection process for determining and designing a new eastbound TER on I-70 in Colorado. While it is not specifically concerned with quantifying the potential safety benefits from the new ramp in terms of crash reduction, it does point to the importance of design characteristics as well as advance signage in the successful operation of a TER. It also serves to emphasize the potential applications ITS elements can have within any TER operation.

Hu X. et al., Intelligent Control and Parameter Calculation of Highway Truck Escape Ramps (2022)

This paper acknowledges at its outset what has been set forth in this literature review thus far, that is that most research on truck escape ramps has been focused on identifying correctly when the environment is suitable for implementing TERs, and the physical components of a ramp system such as materials or geometrics (Hu & et al., 2022).

Hu and colleagues are concerned with the secondary breaking-off of commercial vehicles from the TERs due to the large exterior force imposed by aggregate in the arrester bed which slows down the vehicle, and secondary crashes due to truck rollover of roll-back. The objective of their research is predicting and controlling the driving state of the runaway truck.

This research proposes an intelligent control model system which uses an ITS composed of lidar, radar, speedometer and radio frequency identification, to obtain information on an approaching truck. This technology combined with a breaking device and control module, would adapt to breaking accordingly. The research was supported by MATLAB simulation.

Reference is repeated in this paper to two of the most common reasons for cases of runaway trucks: inappropriate control of vehicle speed by the driver for downhill conditions, or brake failure.

Results of this research effort showed the proposed system stabilizes small vehicles and prevents them from deviating or overturning, while for high-speed heavy vehicles the system mainly exerts braking control to ensure maximum utilization of the braking ramp length of the TER to stabilize the vehicle, preventing overturning and secondary injuries by reducing external forces.

The paper concludes that under certain conditions the proposed ITS system will ensure full utilization of the braking ramp to achieve full braking by runaway trucks.

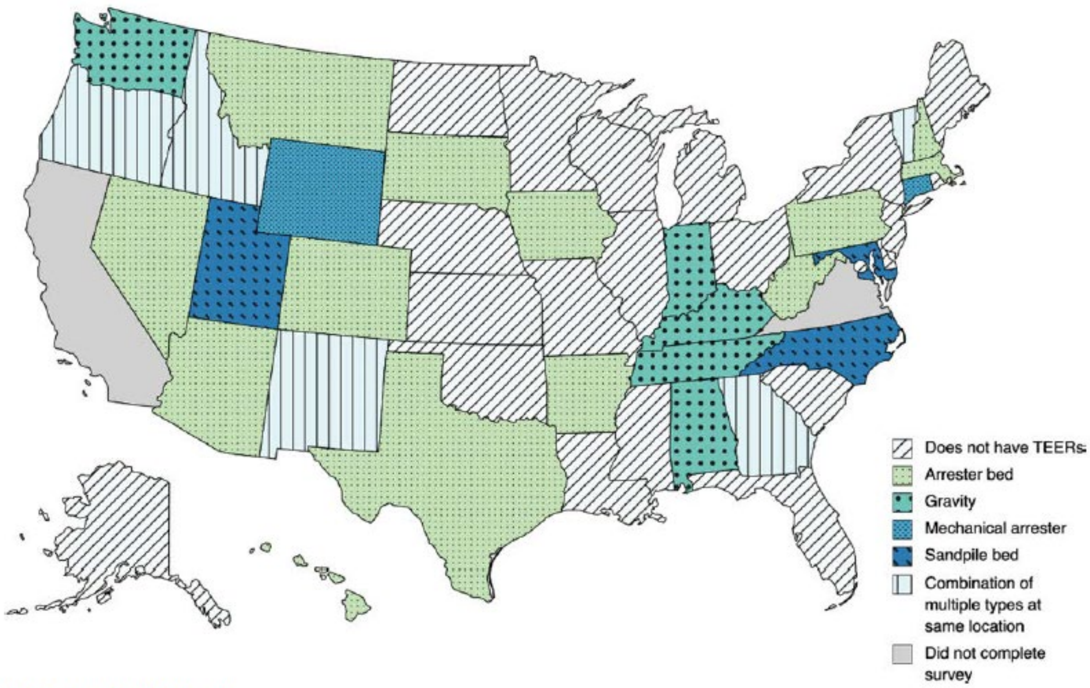
Transportation Research Board, Truck Emergency Escape Ramp Design and Operation (2024)

This report was published by the Transportation Research Board and puts forward the findings of an NCHRP report completed by the University of Missouri, whose objective was to gather, synthesize and ultimately document information at the national level regarding state DOT practices for the design and operation of truck escape ramps (Transportation Research Board, 2024). This was completed primarily by way of survey responses from 49 of the 50 states, as well as follow-up interviews regarding case studies. Additional information gathered in the process included education/outreach efforts undertaken by the states to increase awareness of TERs for the trucking industry, maintenance and operations, and improvements of refinement practices which were developed.

It was found that TERs nationally are used very infrequently, with 17 states indicating that all of their combined ramps statewide were used on average 0-5 times annually. Of interest to this research, the authors report that the most frequently used TER in the U.S. is the Straight Creek ramp on I-70 in Colorado and claim it is used once a week on average.

One main finding of the report was that generally states prefer to emphasize maintenance of the existing TERs ramps over the construction of new ramps.

Pennsylvania DOT was found to have the most TERs in its jurisdiction (26 to 50), while western states were found to have approximately 11 to 25 ramps in their jurisdictions. Arrester bed type ramps, as well as combination style ramps were determined to be the most common across the U.S. (**Figure 1-9**).



(Map created with mapchart.net)
Note: Hawaii is shown as arrester bed, but it has an equal number of arrester beds and of a combination of multiple types at the same location.

Figure 27. Map showing most prevalent TEER type by responding state DOT.

Figure 1-9: Map of Most Prevalent TER Type by State (TRB, 2024)

Design Guidance

As was found across other literature reviewed, there is a recognized lack of official design guidance on TERs. Of the states surveyed as part of this effort, four reported having developed their own guidelines for the TERs. The most notable aspects of effective design involved items such as adequate drainage, indications for occupied ramps, and improved clear zones, as well as improved signing and lighting.

Literature which the synthesis report recognized as offering some degree of design guidance (some of which was also identified across other sources in this literature review) includes:

- The ASSHTO ‘Green Book’ “A Policy on Geometric Design of Highways and Streets (AASHTO 2018),
- NCHRP Synthesis 178: Truck Escape Ramps (Witheford, 1992),
- The Institute of Transportation Engineers (ITE) publication, “Recommended Practice: Truck Escape Ramps,” (Washington, D.C., 1989), and
- The report produced by Vasquez et al (Valdez Vasquez, Strong, & Shuler, 2018) which has been reviewed earlier in this literature review, and
- The 2003 report by HDR (HDR Engineering, 2003), which has also been reviewed in this literature review, and
- State DOT manuals for eleven states (Arizona, Kentucky, New Hampshire, Nevada, New York, North Carolina, Oregon, Pennsylvania, South Dakota, Utah and Washington State).

As other reports found, this report indicates that smooth round gravel provides the best performance in terms of arrester bed material, with pebble shape influencing load bearing capacity.

Other design elements which were commonly found to be recommended across the sources reviewed were:

- Good sight visibility of the ramp for approaching truck operators,
- A departure angle of a maximum 5 degrees,
- Adequate drainage,
- An appropriate length, and
- Located on a tangent in advance of a horizontal curve.

Escape Ramp Features

Similar to other literature reviewed, this report found that crash history and engineering judgment were primary factors in the locational selection of TERs. Signage was found to be the most common feature of ramps employed by the states. This included both static signs and more detailed signs including visual locational information and information on steep grades. Other features did include lighting, striping, cameras and less frequently ITS components, and vehicle detection and warning systems.

In terms of new technology or improvements to ramps, Colorado was highlighted as a state piloting a system which would include in-cab notifications to truck operators and detection systems for excessive truck speeds combined with in-cab warnings, colored striping for ramp entry (this is allegedly planned by CDOT at the Mount Vernon Canyon ramp), and median entry ramps (Colorado and Texas). Only two states currently employ vehicle detection systems, one of which is Colorado, Nevada being the other. Wyoming reportedly uses ITS with its ramps, and North Carolina reportedly uses a vehicle warning system.

Findings from the data gathering performed for this report indicate that the preferred ramp type employed by state DOTs is strongly influenced by perception of safety, as well as cost and other local factors such as climate and material availability.

Maintenance Findings

As stated previously, maintenance and operations was one areas of focus in data collection. This aspect was cited most frequently by the states as a particular challenge regarding TERs. The literature review performed as part of the report generated a list of measures which are considered to be effective maintenance practices and include:

- A maintenance schedule with periodic inspections to include identification of frozen crusts where applicable,
- Reshaping of the arrester bed after recorded use but also at regular intervals without use,
- Scarifying aggregated and testing it for durability and hardness with a regular sampling plan, and
- Salt application as needed.

The survey, however, determined that only 23 of the 50 states performed maintenance following use and 13 maintained the ramps periodically or irregularly.

Ramp Performance

Of note for this research project, the authors report that regarding TER performance nationally, there is limited information. Indeed, one of the challenges reported by states regarding TERs was the difficulty in determining a method to quantify the expected ramp benefits (i.e. ramp performance). The picture painted by the report is that the trend nationally appears to be non-implementation of any specific performance measures for TERs. Furthermore, when performance measures are used, crash history/number of recorded uses and number of successful uses were found to be what might be considered the most reliable and data driven measures. Other performance indicators which were used might be considered more subjective, such as DOT personnel and trucking industry feedback, or measures which may not always have information reported or available for all cases, such as degree of vehicle damage and degree of driver injury. **Figure 1-10** provides the summary table of performance measure methods, as indicated by survey responses in the National Academies report.

Table 11. Survey results for use of performance measures for TEERs (Question 8).

Performance Measure	Response	Count
Crash history	39%	11
Feedback from agency personnel	25%	7
Feedback from the trucking industry	4%	1
Number of uses	32%	9
Rate of successful use	14%	4
Vehicle damage or driver injury after use	14%	4
Other (please describe)	4%	1
My agency does not use any specific performance measures for truck emergency escape ramps	57%	16
No answer provided	7%	2

Notes: Cell shading is based on increments of 25%; percentages are based on the number of responding state DOTs with TEERs (n_1 = 28). Participants could select multiple answers.

Figure 1-10: Performance Measure Methods Employed by Responding States, (TRB, 2024)

The report briefly discusses the performance of a selection of ramps in different states where unsuccessful uses were recorded, including fatal incidents. At one location in Massachusetts at which a fatal incident was recorded, it was later determined that improvements to ramp safety and performance could be made and included: increasing ramp visibility by clearing brush, inclusion of lighting, overhead signage, and realignment.

Case Studies

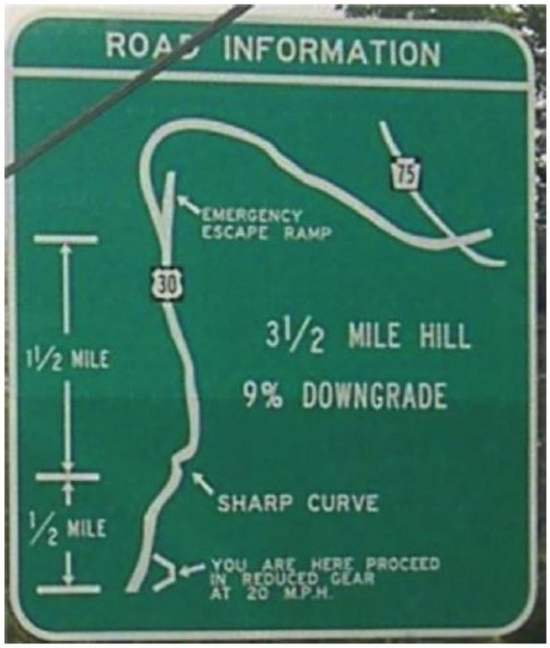
Colorado was one of the six states which participated in case study examples as part of the research effort. From the pool of six participant case studies, Colorado would appear to be the state which shows the most initiative and tangible plans for implementation of intelligent technology and responsive systems. The performance measures reported to be used by CDOT were rate of successful ramp use, number of ramp uses, crash history on the freeway, feedback from DOT personnel and damage to the truck and injury to the driver.

Nevada, like Colorado, was reported to use a vehicle detection system and cameras on one of its four ramps, which reports back to District Road Operations when a use has been triggered. This particular ramp also has license plate reader technology and pavement heating, as well as blank-out capabilities on its overhead entry sign. Unlike Colorado, Nevada's ramps include "Runaway Vehicles Only" painted on the ramp entry pavement, however in a climate which experiences frequent snow, this may not be as useful. Maintenance reported ramp usage gets logged into a online asset management database. Respondents from Nevada DIT indicated that the state seeks to increase use of technology on existing and newly planned ramps, including cameras and ITS.

While New Hampshire has only a single TER, it echoes the trend with others states in relying on reporting by maintenance personnel and emergency personnel regarding ramp use. Maintenance activities include brush clearing, slope mowing and snow ploughing of the approach pavement.

North Carolina DOT appears to employ a system on some of its ramps with similar capabilities to the planned piloted system by CDOT, that is some of the ramps in North Carolina have excessive speed warning feedback. The trend of reliance on agency personnel and emergency responders and law enforcement to alert the DOT to ramp usage was also reported by North Carolina DOT.

Pennsylvania DOT (PennDOT) employs diagrammatic warning signs in advance of their ramps to indicate to truck operators their locations relative to sharp curves and escape ramps (**Figure 1-11**). In addition to sources such as law enforcement, PennDOT also monitors ramp use through reports made by towing companies, as well as reports made through the PennDOT Customer Care Center. The case study ramp in Pennsylvania, at Pine Grove Mills, has a mandatory truck pull off bay 1 mile upstream of the TER for vehicles over 21,000 pounds. The ramp itself is on a corridor with an 8% downgrade and a series of 'S' curves just prior to a populated town.



(Pennsylvania DOT 2023)

Figure 59. Example signage in advance of the TEER on US-30 near Fort Loudon, Pennsylvania.

Figure 1-11: Pennsylvania DOT Advance Ramp Signage, (TRB, 2024)

Texas DOT monitors its escape ramps daily by way of maintenance crews, however the state has only 3 ramps and all are in the same geographic area on the same highway. Similar to the other warm-weather state, Nevada, Texas uses hatched striping on the approach to the ramp entry.

Other Aspects

Drivers who are inexperienced or unfamiliar with the area were noted to be a particular challenge across the states regarding TER use.

Public outreach informational material was only found to be implemented in Colorado, Nevada and Wyoming, by way of brochures, flyers, pamphlets or websites.

Survey responses indicated that monitoring of ramp use by states seems to rely upon reporting by law enforcement and DOT agency personnel, with only Nevada having sensors at one ramp. Other methods included inspection and video recording.

This synthesis report includes a list of recognized knowledge gaps related to TERs as well as areas of research which would help to fill those gaps. Included in this, and relevant to this research effort, are the recommendations for economic analysis in order to determine ramp safety benefits, and research which promotes supplementary warning systems for trucks, as well as research on the effects of drivers unfamiliar with the area as it impacts TER use. The authors of this report are also proponents of an online clearinghouse databank which would provide all states access to data regarding TER installations and their use, as a means of knowledge sharing.

This synthesis report provides a detailed overview of the current inventory and practices regarding TERs across the U.S. It also puts forward challenges faced by DOTs in their operation, as well as laying out knowledge gaps which hinder advancement of TERs. Pertinent to this research effort, the report identifies a lack of methodology for quantifying the expected benefits of a TER as one of the reasons some states are hesitant to implement them, and also no clear methodology for quantifying performance, as an indicated challenge by states where they are in operation.

Summary of Findings

Truck escape ramps (TERs) are typically found on routes which experience heavy truck traffic in mountainous downgrades to stop and contain runaway commercial vehicles. In the case of runaway trucks, a TER offers an opportunity for safe deceleration and arresting of the vehicle away from the mainline traffic.

This research project is focused on evaluating the feasibility of deploying a new detection and warning system on all Colorado TERs. This new system would offer real-time feedback and guidance to runaway commercial vehicles. The literature review surveyed extant literature with a focus on the effectiveness of truck escape ramps and the use of Intelligent Transportation Systems (ITS) on TERs.

It was found that most literature around truck escape ramps and runaway commercial vehicles is centered on details of geometric design, gradation of the aggregate in the arrester bed, design of the dragnet, drainage requirements, signing and striping, driver education, ramp types, provisions for the removal of vehicles and other issues.

It was found that the most popular escape ramp design tends to be the arrester-bed style ramp with ‘pea-gravel’ employed as the bed material. Our review also showed that while there is no national standard for the design of truck escape ramps, and while adopted standards vary between states, with some states having developed their own guidelines, the field in general appears to be informed by two publications: AASHTO “Green Book” and the NCHRP report, “Synthesis 178 Truck Escape Ramps: A Synthesis of Highway Practice” published by the Transportation Research Board.

Generally, the literature we encountered, when discussing the topic of ramp improvements or important factors for ramp design, tended to include the provision of enhanced and/or detailed advance warning signage as recommendations/important factors. Lighting was one such other feature which was encountered more than once as being considered an important factor in the successful operation of TERs. For those reports which outlined meetings with stakeholders, which included motor carriers’ associations and truck industry representatives, the details provided on the feedback they received from these stakeholders tended to indicate that there is some degree of hesitation on the part of some truck operators to use TERs due to a perceived danger and fear of overturning or jackknifing. In this regard, the outcomes of this research project may prove beneficial in supporting increased awareness and education on the operations of TERs for truck operators and DOTs.

In terms of ITS, we found that the literature refers to a limited number of tools in use currently, which includes loop detectors, cameras, communications equipment and, in some cases, dynamic signs which provide warning that a ramp is occupied. A 2024 synthesis report published by the Transportation Research Board (TRB) of the National Academies (Transportation Research Board, 2024) provides a summary of the most recently available data compiled on escape ramp usage across the 50 states. This report indicates that advance signage as well as lighting are the most frequently used measures in ramp identification, while it also suggests that Colorado seems to be ahead of other states in terms of intelligent technology adaptations and plans for escape ramps. Plans in Colorado include a pilot program for in-cab notifications and excessive speed warnings. Some locations, such as Nevada, are more advanced than others in terms of technology, employing detection sensors for ramp occupancy, CCTV and automatic license plate readers.

A report produced by Florida DOT in 2005 (Florida Department of Transportation, 2005) recognized the Before-and-After method as a widely accepted and broadly robust tool for the assessment of the performance of safety improvement projects. This report, and the FHWA CRF Desktop Reference Guide (U.S. Department of Transportation Federal Highway Administration, 2007) (which is based on the FDOT report) were the only sources where direct reference was made to Crash Reduction Factors (CRFs) specifically related to the provision of truck escape ramps. The CRFs vary depending on crash type and severity and are based on studies performed by Arizona and California DOTs. The numbers do not instill a large degree of confidence, as the CRFs from Arizona show counterintuitive results indicating a crash rate increase, while those from California do not appear to be statistically significant. The TRB synthesis report (Transportation Research Board, 2024) broadly indicates that state do not have formal means of performance measurement for escape ramps, with Colorado having the most detailed and widely ranging means of measuring ramp performance, although not in a formalized methodology. The report outlines that broadly speaking the tendency for states to rely on reports from DOT personnel, law enforcement or emergency responders in order to determine ramp usage and performance.

The aforementioned 2024 report by the TRB indicates that quantifying the safety benefits of escape ramps by way of economic analysis is an identified knowledge gap in the field, as well as research on performance evaluation methods. As such, it appears that this research effort is timely. To our knowledge no observational before and after studies with proper correction for the regression to the mean bias have been conducted to evaluate the effectiveness of truck escape ramps or assess the effectiveness of ITS. The importance of the evaluative research which this literature review supports is thus emphasized due to the apparent lack of prior research with a focus on quantifying the effectiveness of truck escape ramps on runaway truck crashes and on the effectiveness of ITS which support the operation of those escape ramps in guiding runaway vehicles. Therefore, this literature has led to the expectation that the findings of the research effort will result in a valuable set of data and information which can support not only the Colorado DOT in their efforts to improve road safety as related to runaway commercial vehicle crashes, but also other transportation officials nationally.

Chapter 2 – Development Of Application Of Directional SPF Analysis

Since truck escape ramps prevent crashes in one direction only it is critically important to develop methodology for evaluating safety performance in one direction. As part of the research effort, DiExSys has developed an analytical framework for conducting Safety Performance Function Analysis by direction with correction for the regression to the mean.

Directional Analysis Using Safety Performance Functions

In some cases, road safety improvements affect crashes predominantly in one direction. Examples include construction of the new truck escape ramp, improvements to the existing ramp, ramp metering or directional curve warning signage. Under these circumstances it is necessary to adjust the Safety Performance Function (SPF) to predict the expected mean frequency and severity of crashes in one direction. This chapter of the report provides the analytical framework of how this adjustment can be made.

The frequency and severity of crashes predicted by the Safety Performance Function (SPF) represents an expected number of crashes at a specific level of Annual Average Daily Traffic (ADT). Based on substantial empirical evidence derived from observing safety performance of various segments as well as work of other researchers (Hauer, Harwood, Griffith, & Council, 2002), Sigmoidal and Hoerl functions are used to represent the underlying relationships between safety and exposure. Sigmoidal and Hoerl functions are both very flexible nonlinear models (Kononov, Lyon, & Allery, 2011); they lend themselves well to capturing the overall shape of observed data for roadway segments. The general model forms of Sigmoidal and Hoerl functions used in SPF development are provided below:

$E(y) = l\left(\beta_0 + \frac{\beta_1}{1 + \beta_2(x^{-\beta_3})}\right)$, Sigmoidal Function for Segment SPFs

$E(y) = l\beta_0(x)^{\beta_1}\exp(\beta_2 x)$, Hoerl Function for Segment SPFs

Where:

- $E(y)$ – Number of crashes expected to occur annually on a segment of road
- x – Segment AADT
- l – Segment Length
- β – Model Parameters

The mean of the number of crashes occurring annually on a segment may be estimated naively by observing the number of crashes in a given number of years and dividing the total count by the number of years. However, when the magnitude of the problem on the segment or at the intersection is assessed, it is important to correct observed crash frequency for the regression to the mean (RTM) bias using the Empirical Bayes (EB) procedure. The Empirical Bayes (EB) method for the estimation of safety increases the precision of estimation; it is based on combining the information contained in accident counts for a facility (known crash history) with the information contained in knowing the safety of similar facilities. The information about safety of similar facilities is brought into the EB procedure by the mean (μ) of the Safety Performance Function (SPF) (Hauer, Harwood, Griffith, & Council, 2002). To illustrate the application of the EB method we will examine safety performance of a segment of SH 160 A MP 158.70-166.60 over a period of 4 years (1/1/2014-12/31/2017). This segment has experienced 129 crashes over the study period which translates into 4.12 acc/mile per year.

Observed 4 years average accident frequency (η) is 4.12 acc/mile per year

Expected frequency (μ) is 1.48 acc/mile per year predicted by the SPF

Over-dispersion parameter α = 0.262 estimated from the SPF

Number of years of crash history n = 4

Weight (W) = $\frac{1}{1+(\mu \times n)\alpha}$ = 1/(1 + 1.48 x 4 x 0.262) = 0.392

EB Corrected Estimate = W x μ + (1-W) x η =

= 0.392 x 1.48 + (1.00-0.392) x 4.12 = 3.09 acc/mile per year

Figure 2-1 below shows safety performance of this segment in both directions without EB correction for the RTM and **Figure 2-2** shows it with EB correction.

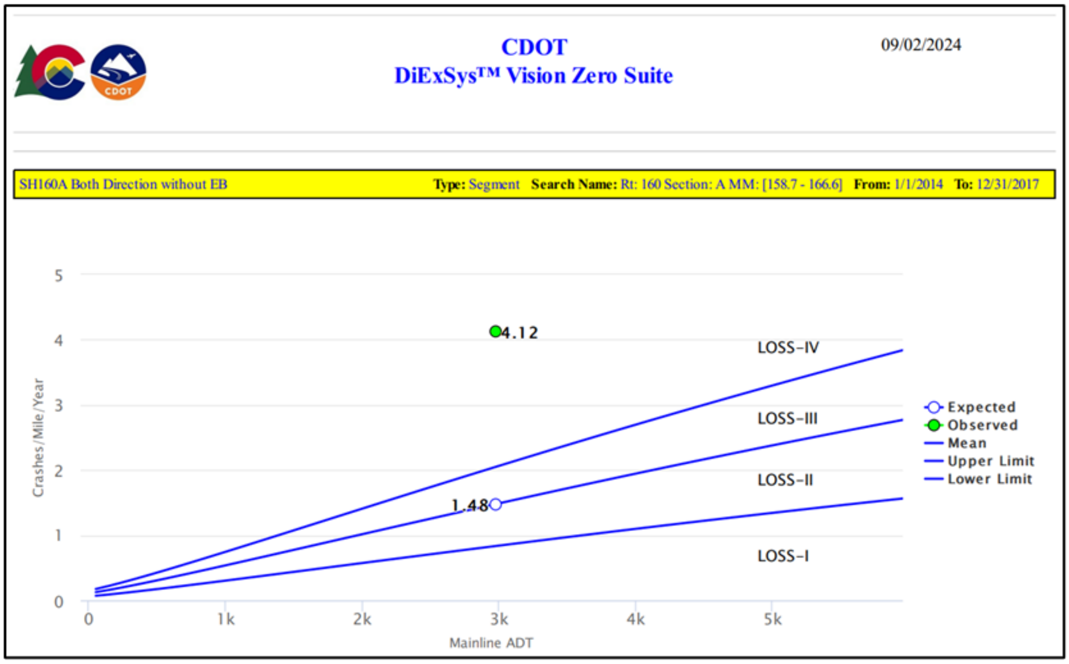


Figure 2-1: Frequency SPF Both Directions without EB Correction

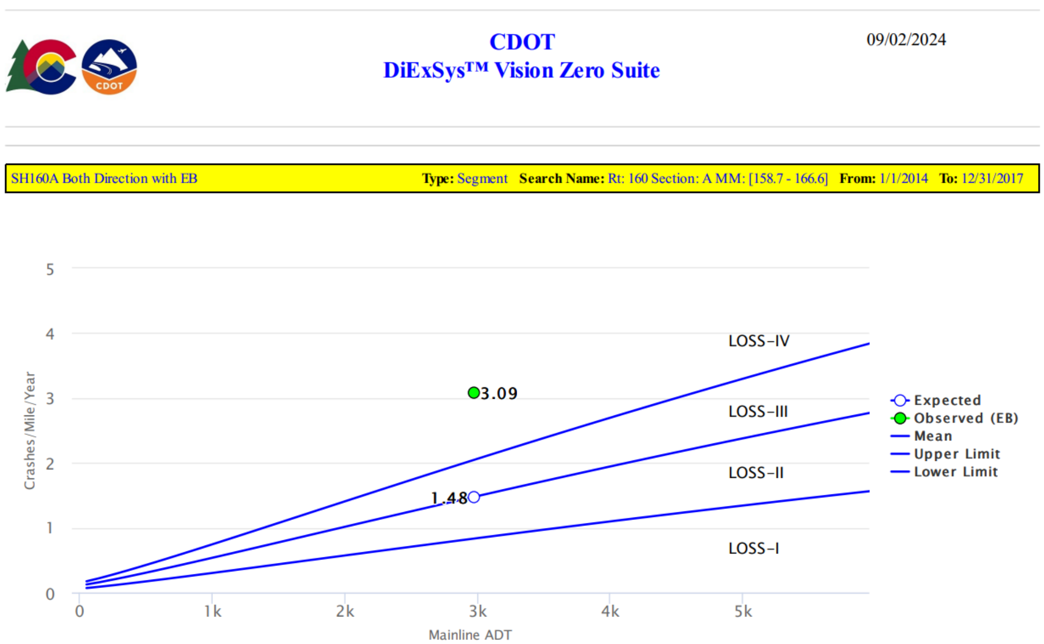


Figure 2-2: Frequency SPF Both Directions with EB Correction

Nearly 80% of crashes occurred in the westbound direction. This uneven distribution of crashes by direction suggests that using a directional SPF would provide a better assessment of the magnitude of the safety problem in the westbound direction. It is reasonable to assume that the expected mean of the SPF in one direction should be half of the mean in both directions. It is also reasonable to expect that the overdispersion parameter (α) should remain the same, at 0.262. The safety performance of this segment in the westbound direction only with the EB correction for RTM can be evaluated as follows:

Observed 4 years average accident frequency (η) is 3.29 acc/mile per year in westbound direction

The expected frequency (μ) is 0.74 acc/mile per year in one direction predicted by the SPF

Over-dispersion parameter α = 0.262 estimated from the SPF

Number of years of crash history n = 4

Weight (W) = $\dfrac{1}{1+(\mu \times n)\alpha}$ = 1/ (1 + 0.74 x 4 x 0.262) = 0.563

EB Corrected Estimate = W x μ + (1-W) x η =

= 0.563 x 0.74 + (1.00-0.563) x 3.29 = 1.85 acc/mile per year

Figure 2-3 shows safety performance of this segment in the westbound direction corrected for RTM. It provides a more accurate indication of how the segment is performing in the westbound direction and will be used in the observational before and after study in the next chapter.

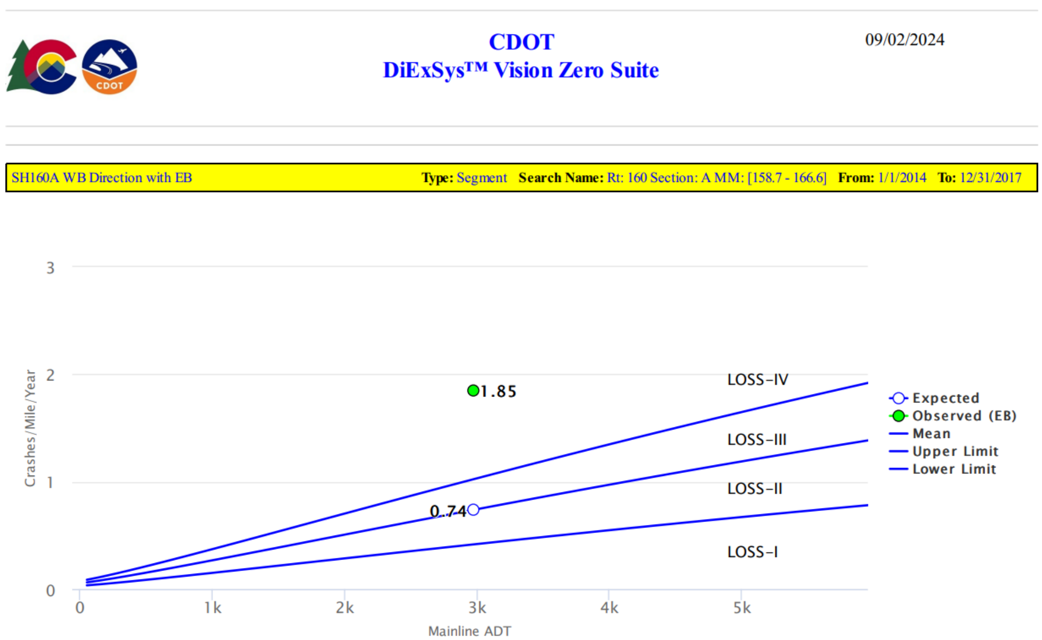


Figure 2-3: Frequency SPF Westbound Direction with EB Correction

Chapter 3 – Observational Before And After Study Of Effectiveness Of The Experimental Truck Signing, Detection And Warning System At Wolf Creek Pass

A preliminary analysis of commercial vehicle crashes on SH-160 (Wolf Creek Pass) suggested that the recently introduced (2018) experimental truck signing, detection and warning system may be effective in preventing commercial vehicle crashes. In order to evaluate its effectiveness, an observational before and after study using the Empirical Bayes method with correction for regression to the mean was conducted.

Background

Figure 3-1 shows the extents of the study limits for the observational before and after study on Wolf Creek Pass, covering a distance of approximately 7.90 miles. Work was started on the project on 6/4/2018 and was completed in late 2018.

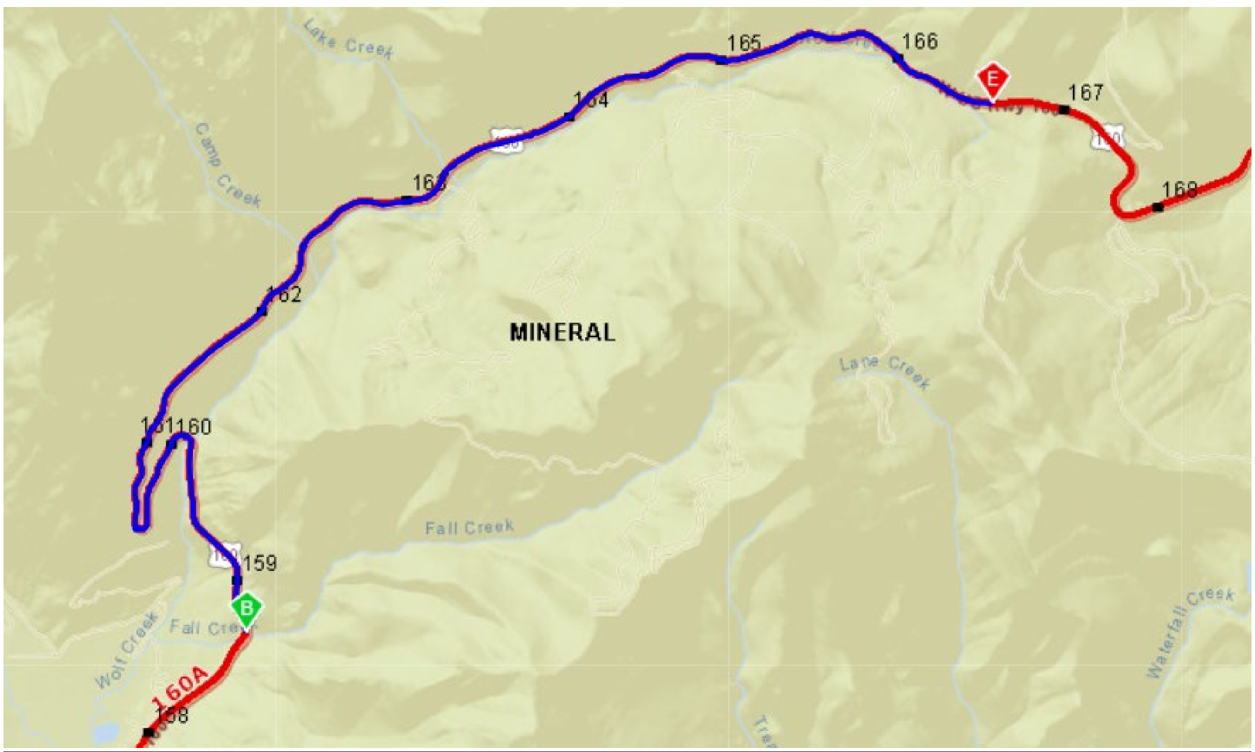


Figure 3-1: SH160 MP 158.70-166.60 (Wolf Creek Pass) Study Limits

An identified problem of high rates of westbound downhill off road and overturning crashes involving commercial vehicles (trucks) led to the implementation of the experimental treatment system. This project enhanced the existing RUNAWAY TRUCK RAMP signage at MP 160.80 and MP 161.15 with flashing beacons and blank outs, as well as the erection of advance warning diagrammatic signage for a hairpin curve, including truck ramp locations and commercial vehicle speed advisory, at MP 166.60 and MP 162.97 on westbound SH 160A. Combined, these measures offer a guidance system providing real time feedback to runaway trucks with guidance onto escape ramps. The hairpin curve depicted on the signage occurs at approximately MP 160.50 and the first diagrammatic warning sign appears at approximately MP 166.60 westbound. Although not as severe, there is a second hairpin curve in very close proximity at approximately MP 159.90, from which a lane or roadway departure could also take place, and in the vicinity of which there are existing crash records, therefore our zone of influence and study area was approximately 8.0 miles, from MP 166.60 to MP 158.70. The before period for SH 160 in this report comprised the 4 years prior to the construction (2014 - 2017), and the after period comprised the 4 years following construction (2019 - 2022).

It was estimated that the project cost for this location was approximately $1,200,000.

For almost all of the study area, there are two lanes in either direction and centerline rumble strips. Four lane undivided mountainous highways are quite rare in Colorado and at present we do not have an SPF model developed for this facility type. As such, where necessary we have employed a 2-lane proxy model as the best fitting alternative.

Figure 3-2 to **Figure 3-13** following show the improvements that were made to the truck escape ramp guidance and warning system.

Figure 3-2: 1st WB Diagrammatic Warning Sign, Approx. MP 166.60 (OTIS 2022)

Figure 3-3: Enhanced Grade & Curve Warning Sign with Blank-Outs, Approx. MP 163.39 (OTIS 2022)

Figure 3-4: 2nd WB Diagrammatic Warning Sign, Approx. MP 163 (OTIS 2022)

Figure 3-5: 1st Escape Ramp Warning Sign, Approx. MP 162.61 (OTIS 2022)

Figure 3-6: 1st WB Escape Ramp (OTIS 2022)

Figure 3-7: Enhanced Overturning Warning Sign with Blank-Outs, Approx. MP 161.82 (OTIS 2022)

Figure 3-8: 2nd WB Escape Ramp Warning Sign, Approx. MP 161.49 (OTIS 2022)

Figure 3-9: 2nd WB Escape Ramp Warning Sign Enhanced with Blank-Outs, Approx. MP 161.18 (OTIS 2022)

Figure 3-10: 2nd WB Escape Ramp with Enhanced Guidance, Approx. MP 160.87 (OTIS 2022)

Figure 3-11: View of 2nd WB Escape Ramp (OTIS 2022)

Figure 3-12: Overturning Warning Sign, Approx. MP 160.59 (OTIS 2022)

Figure 3-13: Hairpin Curve WB, Approx. MP 160.53 (OTIS 2022)

Traffic counts indicate that the average ADT on this portion of SH-160 increased slightly by approximately 9% between the before (2014-2017) and after (2019-2022) periods. The ADT in the before period was 2,975 vehicles per day on average and was 3,250 vehicles per day on average in the after period (2019-2022).

Safety Analysis

The analysis of safety before and after the improvements were made on this portion of the corridor shows a reduction in both the total number of crashes and the number of severe crashes. There were 129 total crashes on the segment during the four-year period before the improvements were made (2014 – 2017). Among the 129 crashes, 36 resulted in injuries and 2 resulted in fatalities. A total of 39 people were injured and 2 were killed. The remaining 91 crashes involved property damage only. Remarkably, 103 of the 129 crashes involved westbound vehicles (over 79%), furthermore, westbound crashes represented all but one of the injury crashes recorded and all of the fatal crashes recorded. In addition, crashes involving commercial vehicles represented over 45% of all westbound crashes (47 crashes) and almost 64% (23 crashes) of all injury crashes on the corridor, which as established previously were almost exclusively westbound except for one crash, while westbound commercial vehicle crashes accounted for all of the fatalities recorded on the study corridor. There were 51 commercial vehicle involved crashes in the before period and 47 of those occurred in the westbound direction.

Although the westbound direction of the study segment is characterized by a downhill grade, almost 90% of westbound commercial vehicle involved crashes occurred when roads were dry (**Figure 3-14**), indicating that adverse weather was not a major contributing factor.

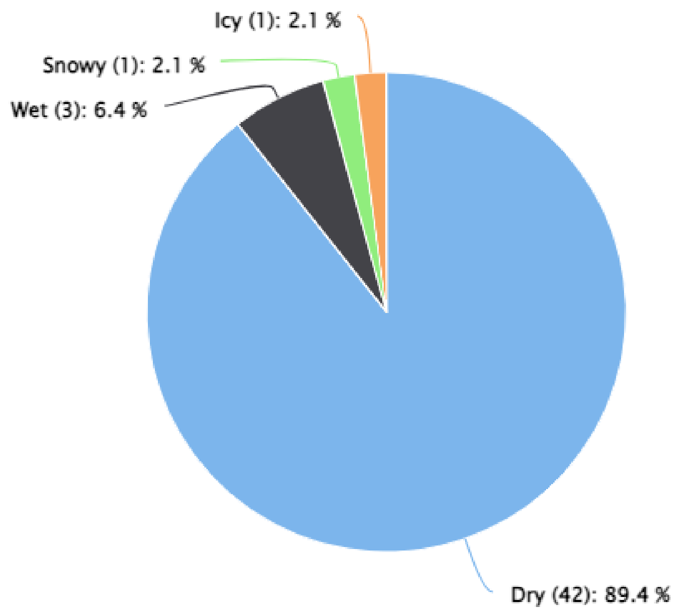


Figure 3-14: Road Conditions for WB Commercial Vehicle Involved Crashes (2014-2017)

Approximately 92% of westbound commercial vehicle involved crashes in the before period were Fixed Object or Overturning crashes (**Figure 3-15**).

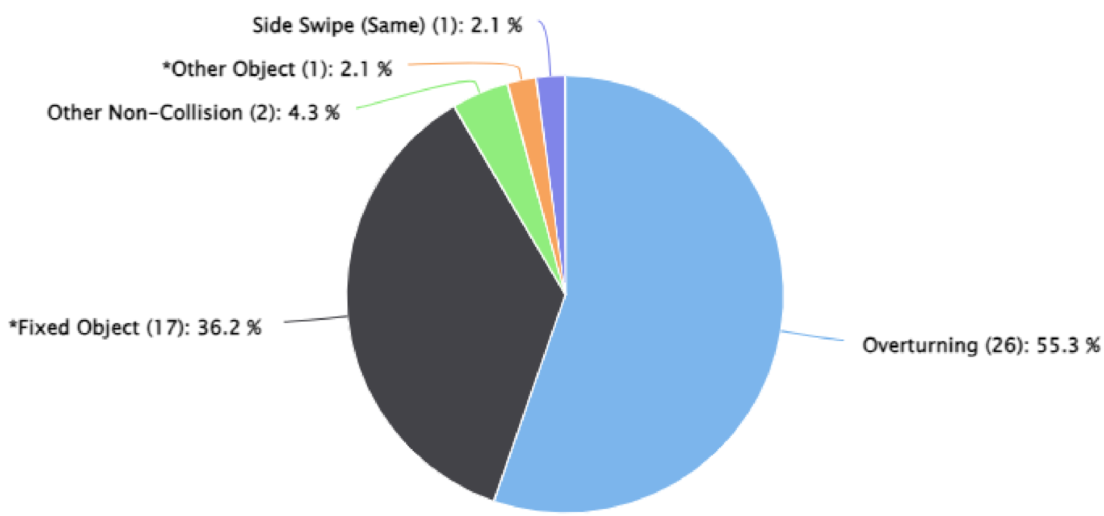


Figure 3-15: Distribution of WB Commercial Vehicle Crashes (2014-2017)

A breakdown of fixed object crashes (**Figure 3-16**) for westbound commercial vehicle involved crashes shows that they were much more likely to involve terrain or concrete barriers rather than other objects.

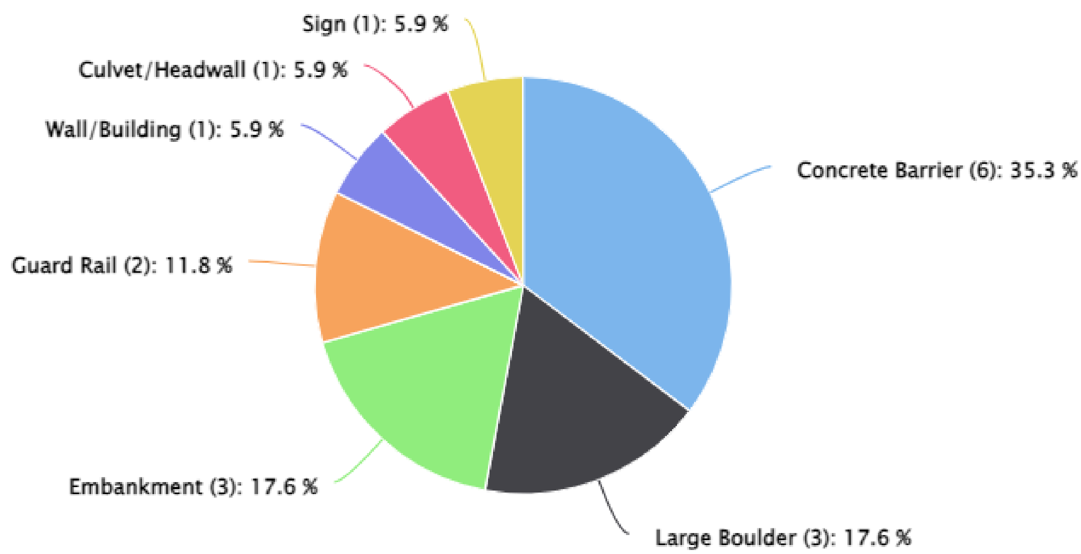


Figure 3-16: Breakdown of WB Commercial Vehicle Fixed Object Crashes (2014-2017)

All westbound commercial vehicle involved severe (injury and fatal) crashes were overturning or fixed object crashes, (19 crashes and 6 crashes, respectively) and most happened at or near the hairpin curves (approximately MP 159.90 and MP 160.5) (**Figure 3-17**). Also note, the truck escape ramps are located at approximately MP 160.90 and MP 162.40.

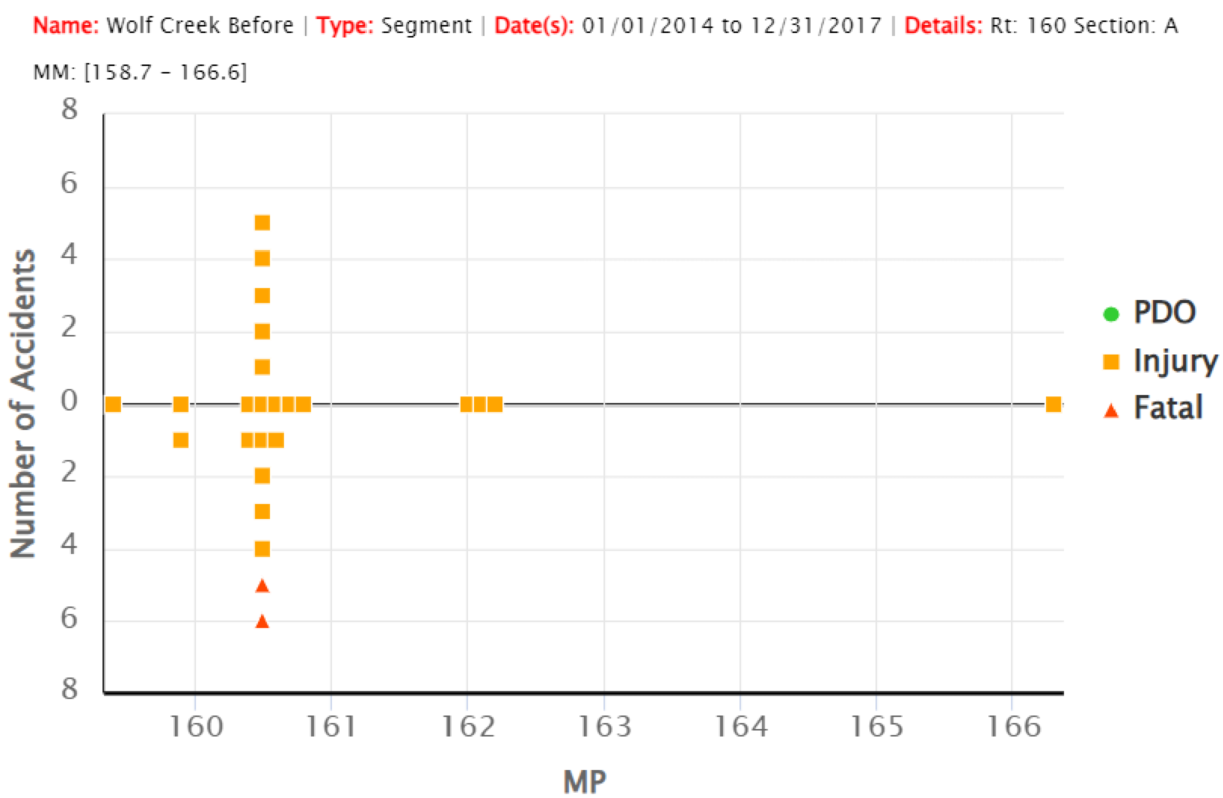


Figure 3-17: Straight Line Diagram for INJ+FAT WB Commercial Vehicle Crashes (2014-2017)

Figure 3-15, **Figure 3-16** and **Figure 3-17**, suggest that where commercial vehicles were involved in off-road crashes, they failed to use the escape ramps.

Comparatively, there were only 4 eastbound commercial vehicle involved crashes in the before period, and only 1 involved a Fixed Object crash. While we do not have normative baseline percentages for 4-lane undivided mountainous highways in Colorado, the crash records indicate that westbound direction crashes were dominant on the corridor, with all severe crashes, except for one, occurring in the westbound direction. In combination with this, commercial vehicle crashes make up the vast majority (almost 68%) of severe crashes in the westbound direction, and as a subset are predominantly represented by fixed object and overturning crashes. It is highly likely that both overturning and fixed object crashes, as well as crashes involving commercial vehicles are overrepresented.

For the four-year period after improvements were made to the runaway truck guidance system (2019 – 2022), the total number of crashes on the segment decreased to 76, a reduction of 41%. The number of injury related crashes decreased from 36 to 19 (about 47%), meanwhile the number of fatal crashes increased from 2 to 3 in the after period. The number of injured people decreased from 39 to 28, about 28% (records show 32 people injured but 4 of these resulted from a fatal collision), while the number of persons killed increased by 50% from 2 to 3. It should be noted that one of the fatal crashes included 4 injuries, which contributes to the high number of overall injuries in the after period. The remaining 54 crashes involved property damage only.

Although most crashes in the after period continued to occur in the westbound direction, the disparity was not as severe, with 64.5% (49 crashes) occurring westbound. In the before period the balance of westbound to eastbound crashes was 79% to 21%, or about 4 to 1, while in the after period the balance of westbound to eastbound crashes is closer to 2 to 1. Similarly, for severe crashes about 68% (15) occurred in the westbound direction in the after period, as compared to all but one crash in the before period. All 3 fatal crashes in the after period occurred in the westbound direction, all occurring near the hairpin curves at approximately MP 160.50 and MP 159.70.

Furthermore, crash history shows that 23 crashes (about 30%) in the after period involved commercial vehicles. Of those 23, 19 involved westbound commercial vehicles. This represents a reduction in commercial vehicle involved crashes of about 55% (from 51 to 23) generally, and in the westbound direction in particular, it shows a reduction from 47 to 19, or of about 60%.

In addition, when only injury level crashes are considered, commercial vehicle involved crashes comprised about 47% of injury crashes in the after period, compared to about 64% of injury crashes in the before period. Furthermore, when only westbound injury crashes are considered, commercial vehicles comprised about 63% of these crashes in the after period, compared to all but one crash, i.e. almost 100% of these crashes in the before period. This represents a significant reduction in the frequency of injury level crashes involving westbound commercial vehicles on the study segment.

When fatal crashes are considered, it appears there was an increase of 50% in fatal crashes, from 2 crashes in the before period to 3 in the after period. However, a review of crash records shows that for 1 of those crashes in the after period "illegal drugs" are cited as a contributing factor and the crash also involved a passenger vehicle, not a commercial vehicle. The crash in question, which occurred on 9/9/2022, occurred near mile point 159.70, which is the final, less severe hairpin curve and is located beyond the more severe hairpin curve (near MP 160.50). This fatal crash unfortunately also involved multiple occupants, so as outlined previously, in addition to the fatality, it also resulted in 4 injuries.

Of the 19 westbound commercial vehicle crashes, 17 (about 90%) occurred under dry road conditions in the after period.

Figure 3-18 shows that in the after period, westbound commercial vehicle involved crashes continued to display predominantly Fixed Object and Overturning patterns.

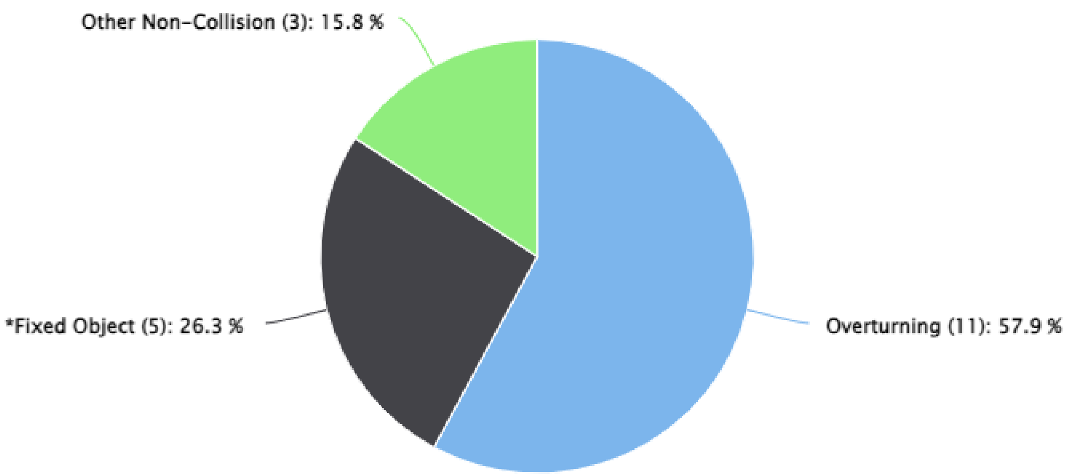


Figure 3-18: Distribution of WB Commercial Vehicle Crashes (2019-2022)

Figure 3-19 shows that for the westbound commercial vehicle crashes which were Fixed Object crashes, the crashes still show a likelihood for vehicles to collide with terrain or concrete barriers.

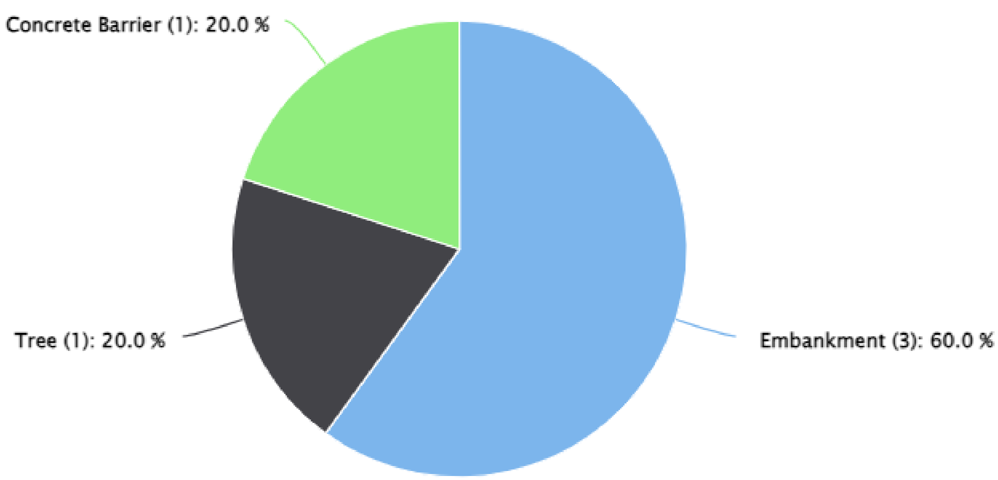


Figure 3-19: WB Commercial Vehicle Fixed Object Crashes by Type (2019-2022)

In the four-year after period, all westbound commercial vehicle involved severe (injury and fatal) crashes were Overturning or Fixed Object crashes (8 and 2, respectively), and most happened at or near the hairpin curves (**Figure 3-20** and **Figure 3-21)**.

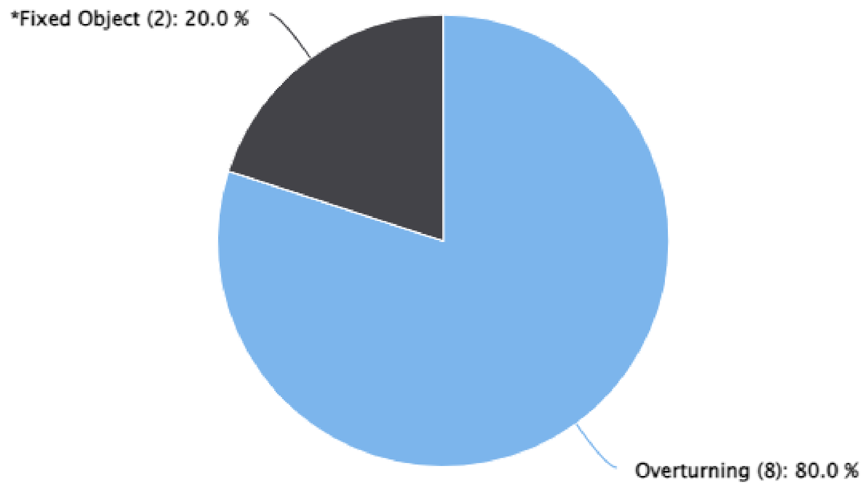


Figure 3-20: Distribution of WB Commercial Vehicle Severe Crashes (2019-2022)

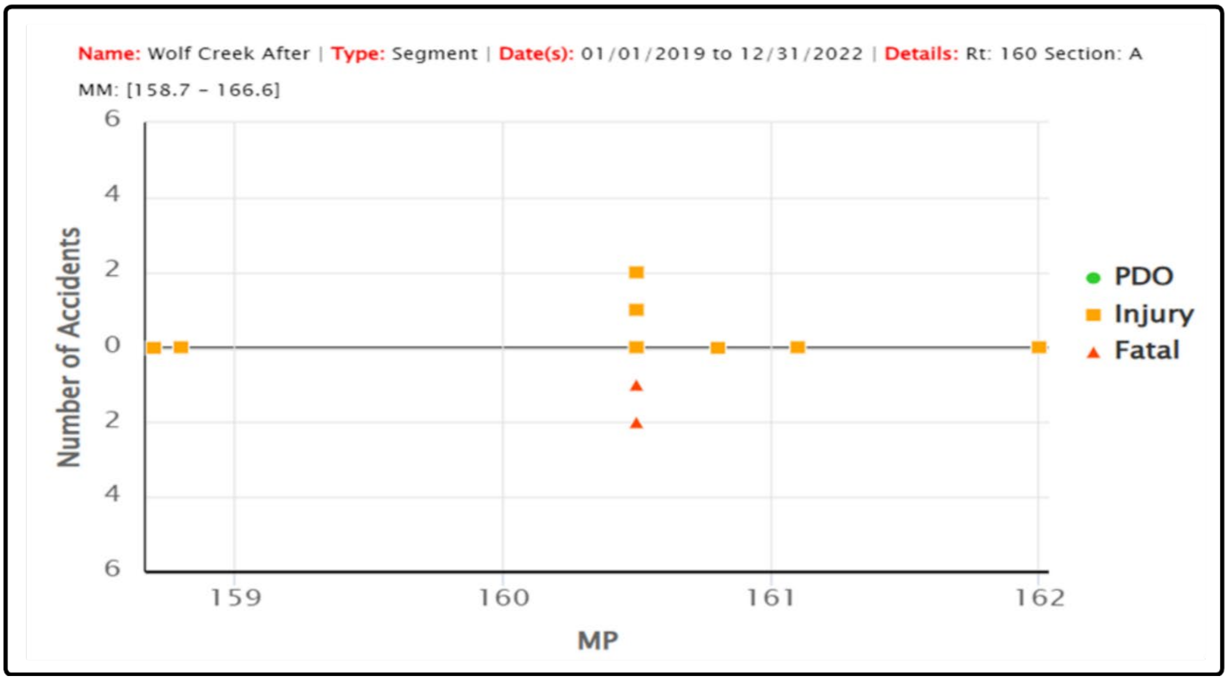


Figure 3-21: Straight Line Diagram for INJ+FAT WB Commercial Vehicle Crashes (2019-2022)

Figure 3-21 suggests that for commercial vehicle involved crashes in the westbound direction, the warning and detection system has been effective but hasn't resulted in 100% of vehicles which should be using the escape ramps doing so. If we further consider the available crash records, overall, the number of severe (injury and fatal) crashes involving westbound commercial vehicles decreased by over 61% between the before and the after period. In the before period 26 severe westbound commercial vehicle involved crashes were recorded, while in the after period this fell to 10 crashes. When the fatal crashes are considered, the number remains unchanged, at 2 involving westbound commercial vehicles.

It is very likely that the effects of the signing, detection and warning system played a role in the reduction of the frequency of severe westbound commercial vehicle involved crashes between the before and after period.

Results of Safety Analyses

Using Vision Zero Suite the review of before and after crash records in the westbound direction from MP 166.60 to 158.70 shows a decrease in the total number of crashes from 129 during the four-year period (2014 to 2017) before the improvements to 76 during the four-year after period (2019 to 2022) (see **Table 3-1**). The number of injury crashes showed a decrease in the after period, while the number of fatal crashes shows an increase:

- Before (2014 – 2017) – two fatal crashes with 2 killed and 36 injury crashes with 39 injuries
- After (2019 – 2022) – three fatal crashes with 3 killed and 4 injured, and 19 injury crashes with 28 injuries

There was an increase of approximately 9% in traffic volume on the corridor from the before period to the after period that we could determine from available sources. This increasing trend in the volume of traffic, suggests the conclusions that follow show a somewhat more pronounced degree of safety improvement.

- Before (2014 - 2017): 3.76 crashes per million vehicle miles (cpmvm)
- After (2019 - 2022): 2.03 cpmvm

Table 3-1: SH-160, Wolf Creek Pass West Side, West Bound (MP 158.70 – 166.60) - Results of Overall Crash Analyses

	Before	After
Time Period:	1/1/2014 to 12/31/2017 (4 yr.)	1/1/2019 to 12/31/2022 (4 yr.)
AADT	2,975 vpd	3,250 vpd
Filters:	All Non-Intersection Related Mainline Crashes	All Non-Intersection Related Mainline Crashes
Total Crashes	**129**	**76**
Fatal Crashes (Fatalities) [% Westbound]	2 (2) [100%]	3 (3) [100%]
Injury Crashes (Injuries) [% Westbound]	36 (39) [97.3%]	19 (28) [63.2%]
Property Damage Only [% Westbound]	91 [72.5%]	54 [64.8%]
Crash Type: # (%)		
Fixed Object [WB Com. Veh.]	75 (58.1%) [17 (22.7%)]	40 (52.6%) [5 (12.5%]
Overturning [WB Com. Veh.]	32 (24.8%) [26 (81.3%)]	20 (26.3%) [11 (55%)]
Westbound Commercial Vehicle Involved (% of total crashes)	47 (36.4%)	19 (25%)

The magnitude of safety problems on select highway sections and intersections can be assessed through the use of Safety Performance Function (SPF) methodology. An SPF reflects the complex relationship between exposure (measured in ADT) and the crash count for a section of roadway measured in crashes per mile per year (CPMPY) or for an intersection, measured in crashes per year. The SPF models provide an estimate for the expected crash frequency and severity for a range of ADT among similar facilities. This allows for an assessment of the magnitude of the safety problem from a frequency standpoint.

Development of the SPF lends itself well to the conceptual formulation of the Levels of Service of Safety (LOSS). The concept of level of service of safety quantitatively assesses and qualitatively describes the degree of safety of a roadway segment or intersection in reference to its expected frequency and severity. If the level of safety predicted by the SPF represents a normal or expected number of crashes at a specific level of ADT, then the degree of deviation from the normal can be stratified to represent specific levels of safety.

- LOSS-I – Indicates low potential for crash reduction
- LOSS-II – Indicates low to moderate potential for crash reduction
- LOSS-III – Indicates moderate to high potential for crash reduction
- LOSS-IV – Indicates high potential for crash reduction

LOSS boundaries are calibrated by computing the 20th and the 80th percentiles using the Gamma Distribution Probability Density Function. Gradual change in the degree of deviation of the LOSS boundary line from the fitted model mean reflects the observed increase of variability in crashes as ADT increases. LOSS reflects how a segment of roadway or intersection is performing in regard to its expected crash frequency at a specific level of ADT.

Although SPF models have not yet been developed for rural 4-lane undivided highways in mountainous terrain in the State of Colorado, we can provide a naïve comparison with the model for a rural 2-lane undivided highway in mountainous terrain.

Vision Zero Suite also contains the capacity to evaluate SPFs for a single direction only. In this case SPF models were generated for the westbound only direction on the study segment. SPF plots for both westbound total crashes (**Figure 3-22**) and for westbound severe crashes (**Figure 3-23**) reflect an improvement in the crash record in terms of both total crashes and severe crashes. LOSS moved from the high LOSS IV range for total crashes into the low LOSS IV range. LOSS moved from the LOSS IV range to the LOSS III range for severe crashes.

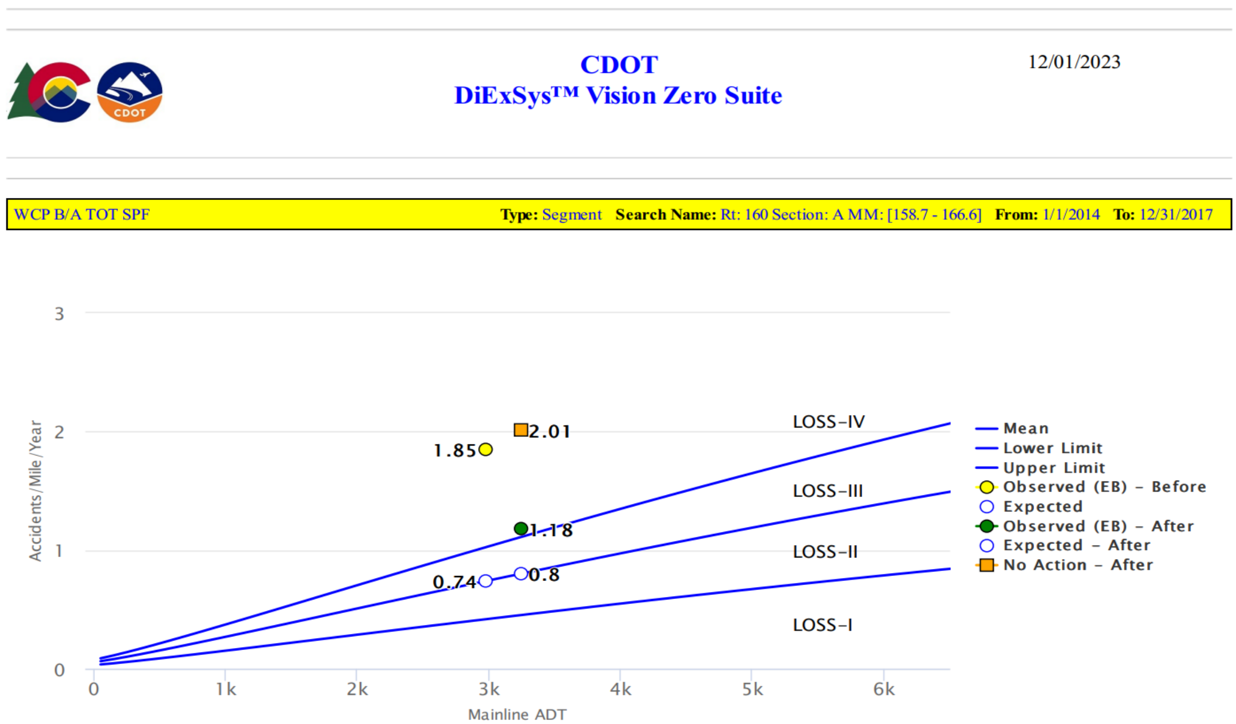


Figure 3-22: SPF for Total Crashes Westbound Compared to Mountainous 2-ln Undivided Hwy
SH-160A, MP 158.70 to 166.60
Before: 2014 to 2017 After: 2019 to 2022

WCP B/A SEV SPF **Type:** Segment **Search Name:** Rt: 160 Section: A MM: [158.7 - 166.6] **From:** 1/1/2014 **To:** 12/31/2017

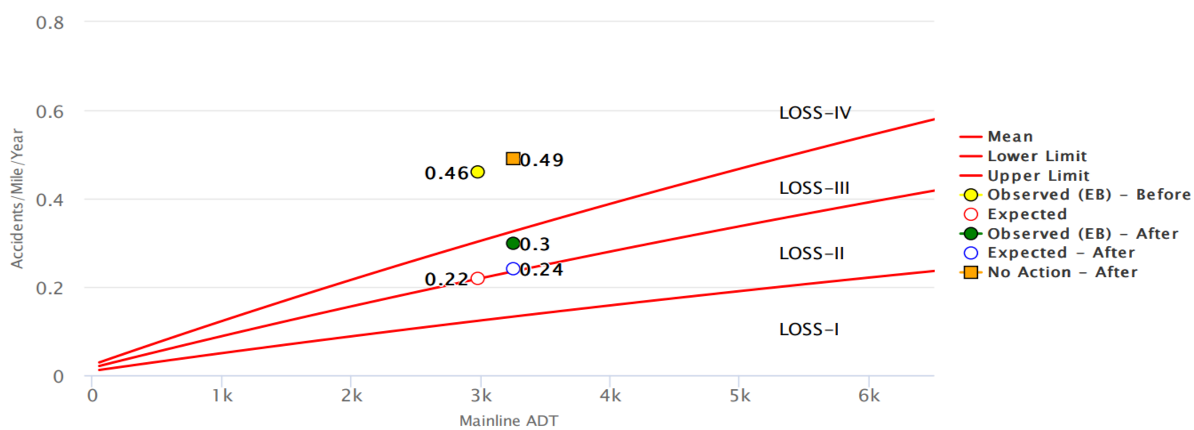


Figure 3-23: SPF for INJ+FAT Crashes Westbound Compared to Mountainous 2-ln Undivided Hwy
SH-160A, MP 158.70 to 166.60
Before: 2014 to 2017 After: 2019 to 2022

The EB-corrected before-after comparison indicates that 1.18 total crashes/mile/year were observed in the after period compared to 2 total crashes/mile/year expected under the increased volume without any modifications (no action), a reduction of 41 percent. For severe (injury and fatal) crashes, 0.30 severe crashes/mile/year were observed in the after period compared to 0.49 crashes/mile/year expected for no action, a reduction of 38.8 percent. For the purposes of assessing the economic benefit, a crash reduction factor (CRF), of 41 percent for total crash frequency, and 39 percent for severe crashes, will be utilized.

Vision Zero Suite includes benefit/cost (B/C) analyses within its procedures. The results of the B/C analysis are shown in **Figure 3-24** for all westbound crashes in the segment. The evaluation of the signing, detection and warning system has been made post system construction and installation, and an estimated improvement cost of $1.2 million, over a 20-year service life, with a $2,500 annual maintenance cost, has been employed. The result of the Benefit/Cost calculation is a B/C ratio of **20.57.** This highly positive result strongly suggests that the project was justified from both the cost-effectiveness and safety improvement standpoints.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/04/2025

WCP Truck Warning/Guidance System — **Loc:** 160 A **Begin:** 158.7 **End:** 166.6 **From:** 1/1/2014 **To:** 12/31/2017

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 66	17 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 17	15 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 12	6 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 6	2 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 2		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost: $1,200,000
Years in Crash Search: 4
CRF 1 Type: Runaway Truck Signing, Detection & Warning System for Hairpin Curves & Escape Ramps
Notes: Mainline westbound crashes only.
Benefit/Cost Ratio: 20.57
CRF 2 Type:
CRF 3 Type:
CRF 4 Type:

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Figure 3-24: SH-160, Wolf Creek Pass West Side, West Bound (MP 158.70 – 166.60) – Benefit Cost Analysis

Conclusions

The observational before and after study on the signing, detection and warning system which was implemented on Wolf Creek Pass strongly suggests that the system has very likely been effective in reducing the frequency and severity of directional commercial vehicle involved crashes but has not resulted in 100% of vehicles which should be utilizing the ramp in doing so. When only westbound commercial vehicle crashes are considered, the data shows that there was (approximately) a 59% reduction in PDO crashes, a 48% reduction in injury level crashes, and no change in fatal crashes. The directional SPF analysis shows that total crash frequency was reduced by 41 percent, while severe crash frequency was reduced by a magnitude of 39 percent.

These findings have permitted the quantification of the effectiveness of the signing, detection and warning system on Wolf Creek Pass (WCP) to be approximated. Findings will be applied in the section which follows later in this report regarding the feasibility of the implementation of a similar signing, detection and warning system at other escape ramp locations across the state of Colorado.

Chapter 4 - Safety Assessment Of All Truck Escape Ramps In Colorado Using Directional SPF Analysis

A primary feature of this research was the evaluation of the application of a runaway truck signing, detection and warning system which is similar to that implemented on Wolf Creek Pass, to other escape ramp locations across the state of Colorado. A precursor to that evaluation was the completion of safety assessments for all existing Colorado TERs, including the application of directional SPF analysis which was developed for Vision Zero Suite (VZS). This included predictive and diagnostics analysis using Colorado-specific SPFs and Diagnostic norms.

Apart from WCP, the other TER locations which were assessed for safety and TER effectiveness were:

1. US 6 Westbound MP 219 Loveland Pass
2. US 40 Westbound MP 142 Rabbit Ears Pass
3. US 50 Eastbound MP 204 Monarch Pass
4. I-70 Westbound MP 182 Lower Vail Pass, and MP 186 Upper Vail Pass
5. I-70 Westbound MP 209 Lower Straight Creek, and MP 212 Upper Straight Creek
6. I-70 Eastbound MP 257 Mount Vernon Canyon
7. US 141 Northbound MP 18 Slick Rock Hill
8. US 550 West(south)bound MP 53, Coal Bank Hill

The primary intent of the safety assessment reports was to provide a safety assessment report of the truck escape ramps. Additionally, directional safety analysis using Colorado-specific predictive and diagnostic tools was introduced. The reports were prepared in the context of a potential roll out of an enhanced signing, detection and warning system for runaway trucks on Colorado mountainous highways and identifies opportunities for safety improvements justified by crash history, to improve safety around the truck escape ramps listed above. The safety assessment reports will:

- Assess the magnitude and nature of the safety problem within the project limits by direction.
- Relate crash causality to roadway geometrics, roadside features, traffic control devices, traffic operations, driver behavior, road conditions, maintenance and vehicle type.

The safety assessments are based on the comprehensive analysis of 10 years of crash history, and traffic volume available from CDOT website and databases. The Region is advised to verify through field survey the information included in the assessments regarding physical features and roadside characteristics in the study areas.

Detailed safety assessment reports for each location are provided in the Appendix for this report, which has been published as a separate document, "*Appendices for the Evaluation of Feasibility of Deployment of Runaway Truck Detection and Warning Systems at Truck Escape Ramps*," and are also available to access via embedded links for each location on the GIS map which was developed as part of this research project (CDOT Runaway Truck Escape Ramps). As such, abbreviated versions of those reports, which focus only on directional commercial vehicle involved crashes and TER performance are provided in the main body of this report. Additionally, to avoid repetition, when recommendations are made in the safety assessments which follow to implement a TER signing, detection and warning system similar to that in use on WCP, references to blank-outs on existing signs, activated Overturning warning signs, and diagrammatic ‘story map’ signs, can be illustrated by examples seen in **Figure 4-1**, **Figure 4-2** and **Figure 4-3**.

Figure 4-1: Dynamic Warning Sign with Blank-Outs, MP 163.39 US160

Figure 4-2: Dynamic Overturning Warning Sign, MP 161.82 US160

Figure 4-3: Diagrammatic Warning Sign, MP 166.60 US160

The safety assessments for each of the 8 TER locations listed above now follow.

Location 1 – Loveland Pass: U.S. 6 Westbound, MP 221.25-216.75

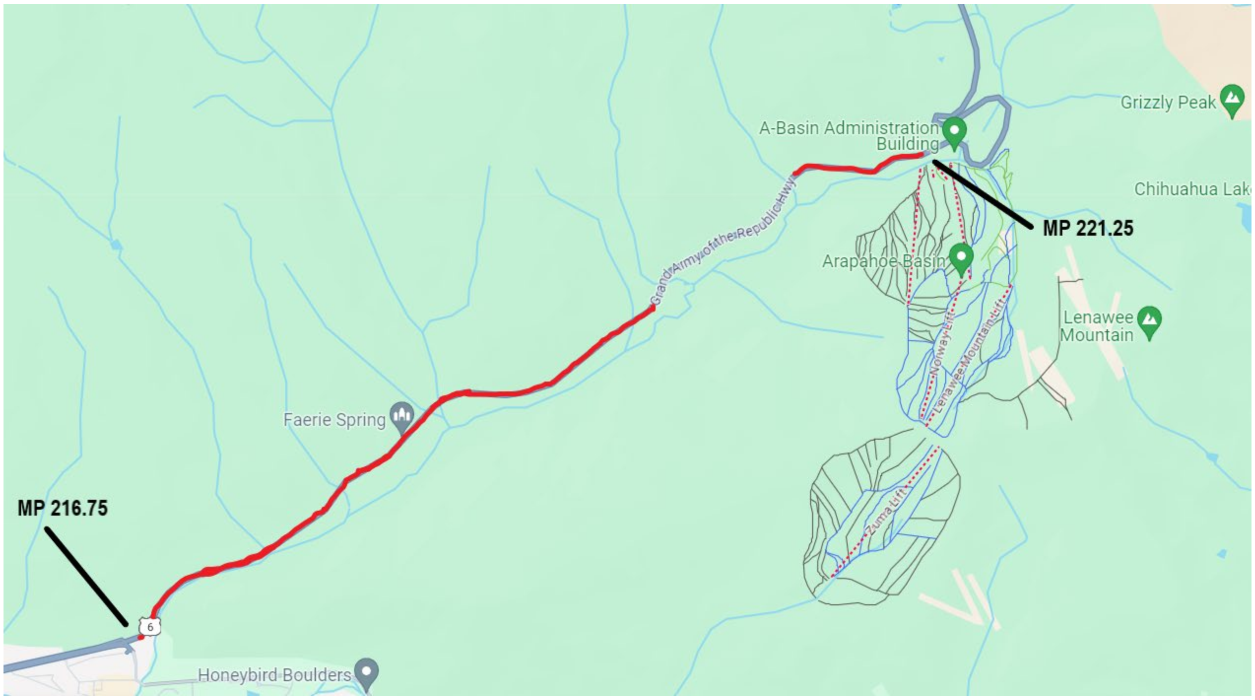


Figure 4-4: Loveland Pass Study Limits

Site Location

The Loveland Pass truck escape ramp is located on U.S. 6 near mile point 218.80 westbound. To capture a zone of influence, this study considers the corridor between MP 216.75 just beyond the escape ramp to MP 221.25 near where the initial truck warning signs are seen in advance of the escape ramp. The included distance is approximately 4.50 miles.

Site Conditions

US-6 is classified as a rural regional highway on mountainous terrain. US-6 is a 2-lane, undivided highway with 12' lanes. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 1,700 and the percentage of truck traffic is 20.7%.

The speed limits eastbound are 50 mph east of MP 216.75 to MP 219.40, then 40 mph to MP 221.25. Westbound, the speed limit is 50 mph from MP 221.25 to MP 219.59, and west of MP 219.59 the speed limit is 45 mph. There are lower advisory speed limits in both directions throughout the study corridor.

Outside shoulder width along the study segment varies considerably, from 0 ft at MP 220.92 to 55 ft at MP 218.25, while there is no information for the inside secondary shoulder width. The corridor is characterized by frequent changes in horizontal curvature. There is a climbing lane eastbound between MP 217.43 and MP 217.56, MP 218.29 to MP 218.65, MP 219.66 to MP

219.97, and MP 220.59 to MP 220.80. **Figure 4-5** shows a typical section of the corridor westbound.

Figure 4-5: Typical Section of US-6, Westbound, July 2023

Westbound Commercial Vehicle Crashes

There were 3 recorded commercial vehicle crashes on westbound US-6 between MP 216.75 and MP 221.25 in the 10-year study period. This included 2 Injury level crashes, with 4 people injured and 1 Property Damage Only (PDO) crash.

Both injury level crashes were Overturning crashes, while the PDO crash was a Rear End collision. Upon examination of the crash records, it is clear that the Rear End collision was mis-coded to the westbound direction, as law enforcement records clearly indicate the incident involved eastbound traffic slowing. As such, there were effectively only 2 commercial vehicle crashes on the westbound corridor in the study period.

Surprisingly, given the patterns involving other vehicle types on the westbound corridor which tended to occur under adverse winter weather and road conditions, all commercial vehicle involved crashes occurred on dry road conditions. In the case of both Overturning incidents, "Driver Unfamiliar with Area" was cited as a contributing factor. One of the crash narratives refers to the truck losing control rounding a corner. However, neither report refers to use of the truck escape ramp.

The commercial vehicle crashes occurred at MP 216.90 and MP 218.80 (**Figure 4-6**). Both of these locations are characterized by being preceded by curves (**Figure 4-7** and **Figure 4-8)**. For truck operators unfamiliar with the area, the combination of horizontal curvature changes and a steep downgrade on a mountainous road with narrow shoulders can lead to ambiguity around decisions, a loss of vehicle speed and control and ultimately run-off-the-road crashes. Although crashes under adverse weather and road conditions were a pattern on this corridor, this is not reflected by these commercial vehicle crashes. It is more common that truck crashes occur in favorable road and weather conditions, as drivers are more likely to be traveling at reduced speeds in unfavorable conditions.

Figure 4-6: WB Commercial Vehicle Crashes, US6 MP 216.75-221.25, 2013-2022

Figure 4-7: Approach to MP 218.80 WB US6, Oct. 2023

Figure 4-8: Approach to MP 216.90 WB US6, Oct. 2023

There are no discernable patterns to the two recorded commercial vehicle crashes on the study corridor. Given that the truck escape ramp is located at MP 218.80, it could be reasonably concluded that at least one of these crashes could have utilized the escape ramp. Although it is impossible to identify a pattern with only one crash, given that the driver was unfamiliar with the area, the failure to utilize the runaway truck ramp might point to inadequacies in the advance notice given to truck operators in the westbound direction of the presence and location of the ramp.

With only 2 crashes in the 10-year period on a corridor which does not appear to have an electricity supply or fiber network, a system similar to that at the Wolf Creek Pass ramp is likely to be unjustified in terms of cost efficiency, although it would carry a safety benefit.

As such, there are no material recommendations regarding commercial vehicle crashes at this time. However, CDOT is advised to keep the corridor clear of large Boulders/Rocks which would cause a truck to have to make sudden evasive maneuvers, to maintain the advance RUNAWAY TRUCK RAMP warning signs so that text remains legible, and to upkeep ramp maintenance such that the arrester bed is fluffed and free of shrubs or other growth.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the US-6 corridor surrounding the Loveland Pass truck escape ramp located near MP 218.80, and to provide an evaluation of the performance of the truck escape ramp. The analysis was focused on the westbound US-6 corridor between MP 216.75 and MP 221.25 to capture the effects of the ramp. Both directions were evaluated together to provide a general safety overview before the westbound direction was independently analyzed for directional SPF assessment.

Westbound

Westbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-IV for the corridor in terms of total crashes, and LOSS-III in terms of crash severity. This represents high potential for crash reduction, and moderate to high potential for crash reduction, respectively.

CDOT
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11/23/2023

SPF TOT WB **Type:** Segment **Search Name:** Rt: 6 Section: F MM: [216.25 - 221.75] **From:** 1/1/2013 **To:** 12/31/2022

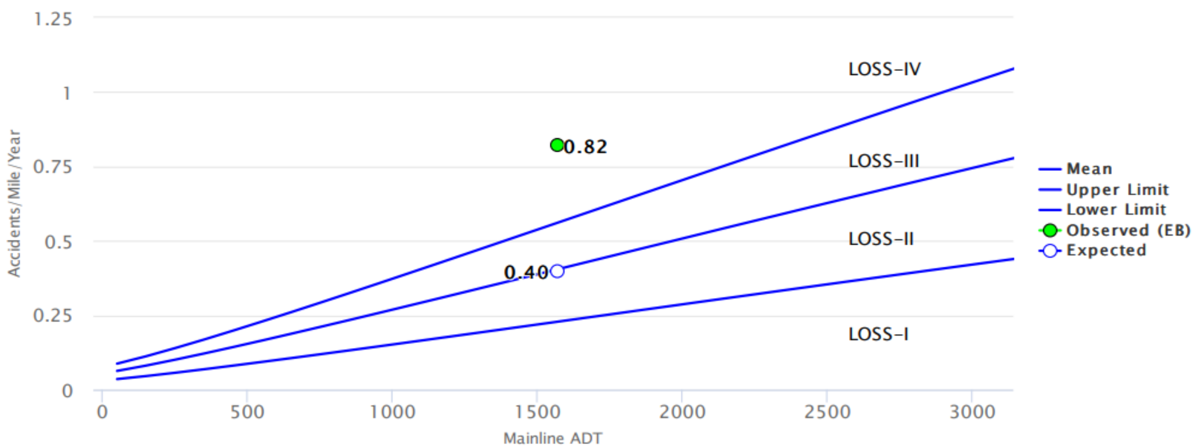

Figure 4-9: SPF Total Crashes US-6 Westbound

CDOT
DiExSys™ Vision Zero Suite

11/23/2023

SPF SEV WB **Type:** Segment **Search Name:** Rt: 6 Section: F MM: [216.25 - 221.75] **From:** 1/1/2013 **To:** 12/31/2022

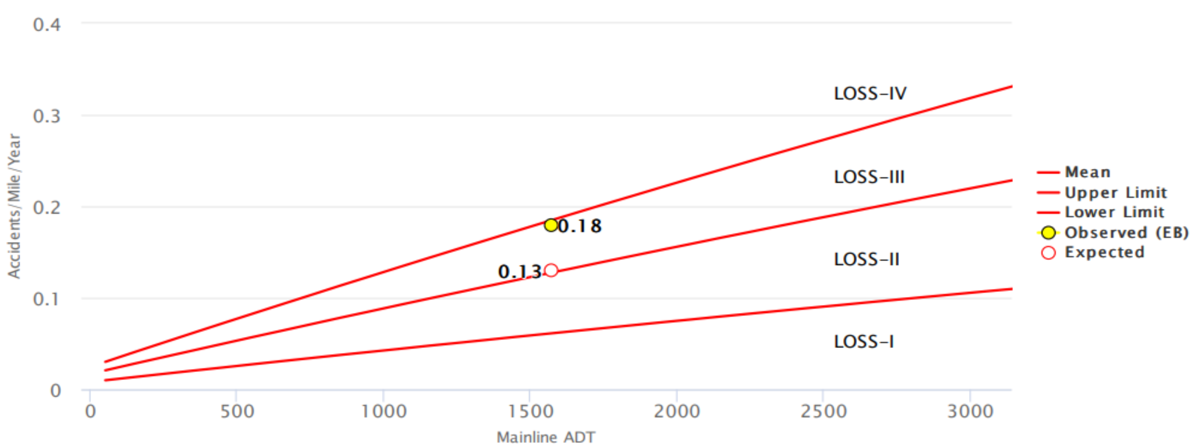

Figure 4-10: SPF INJ+FAT Crashes US-6 Westbound

Most patterns identified on the westbound corridor were correlated with roadway geometrics, and moreover with weather and road conditions, as well as driver familiarity with the area. Embankment crashes and crashes into the terrain were a pattern on the corridor. Rear-End collisions were also a pattern, as were crashes involving unfamiliar drivers.

There is a large overlap between other identified crash patterns and crashes under adverse winter weather and road conditions. General recommendations for the westbound corridor are summarized as follows:

- Repair the northside concrete barrier in the vicinity of MP 219.30-219.60 to maintain integrity in mitigating future roadway departure collisions,
- Ensure speedy removal of fallen rocks from the roadway between MP 218.60 and MP 219.40,
- Install FALLEN ROCKS warning sign (MUTCD W8-14) with supplementary “NEXT MILE” plaque (MUTCD W16-4P) near MP 219.50,
- Install gated SLIPPERY CONDITIONS signs (MUTCD W8-5) with supplementary “ICE” plaques on the corridor, and
- Consider installing edge line and centerline rumble strips on the study corridor in both directions.

In terms of the performance of the truck escape ramp, there were only 2 identified commercial vehicle crashes on the westbound corridor in the 10-year study period, which is not indicative of a pattern. Furthermore, only 1 of these crashes appears to have been one which might have potentially used the escape ramp. It cannot be stated conclusively that the current ramp warnings are ineffective based on a history of one crash.

Furthermore, while a signing, detection and warning system like that on Wolf Creek Pass would provide a safety benefit, it is unlikely to prove cost effective on this corridor given the commercial vehicle crash history and the apparent lack of power and fiber network.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the westbound direction. Crash distribution is predominantly in the westbound direction, the direction of the escape ramp, with 61% of crashes occurring in that direction. It is in the westbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 2 – Rabbit Ears Pass: U.S. 40 Westbound, MP 145.00-141.00

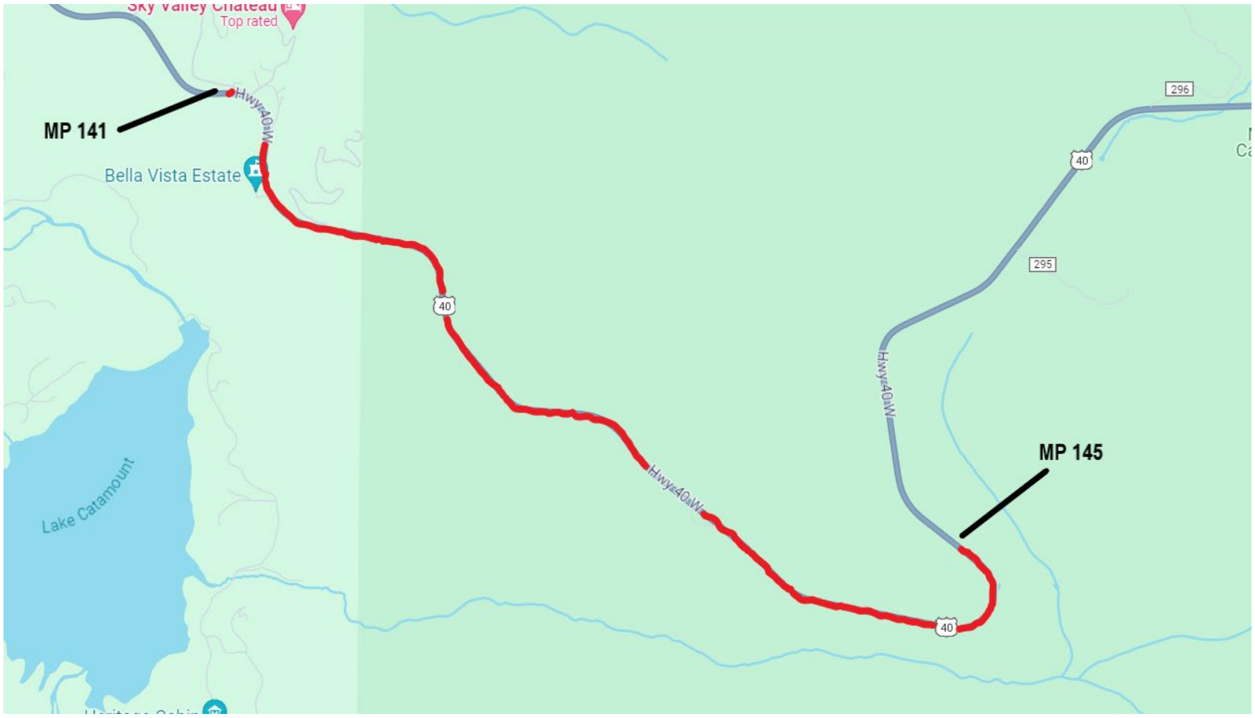

Figure 4-11: Rabbit Ears Pass Study Limits

Site Location

The Rabbit Ears Pass truck escape ramp is located on U.S. 40 westbound near mile point 142. To capture a zone of influence, this study considers the corridor between MP 141.00 just to the west beyond the escape ramp, to MP 145.00 approximately 1.25 miles upstream of the initial truck warning sign in advance of the escape ramp. The included distance is approximately 4.00 miles.

Site Conditions

US-40 is classified as a rural regional highway on mountainous terrain. US-40 is a 3-lane, undivided highway with 12' lanes. There are 2 lanes eastbound and 1 lane westbound through the study corridor. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 5,200 and the percentage of truck traffic is 8.7%.

The speed limit is 50 mph in both directions. There are lower advisory speed limits in both directions throughout the study corridor.

Shoulder width along the study segment varies considerably, from 4 ft at MP 143.40 to 19 ft at MP 143.80, for example. The corridor is characterized by frequent changes in horizontal curvature and a steep downgrade. **Figure 4-12** below shows a typical section of the corridor westbound.

Figure 4-12: Typical Section of US-40, Westbound, July 2023

Westbound Commercial Vehicle Crashes

There were 16 recorded commercial vehicle crashes on westbound US-40 between MP 145 and MP 141 in the 10-year study period. This included 1 Fatal crash, with 1 fatality, 3 Injury level crashes, with 3 people injured and 12 Property Damage Only (PDO) crashes. **Figure 4-13** shows the location of crashes involving commercial vehicles (trucks) on the westbound study corridor.

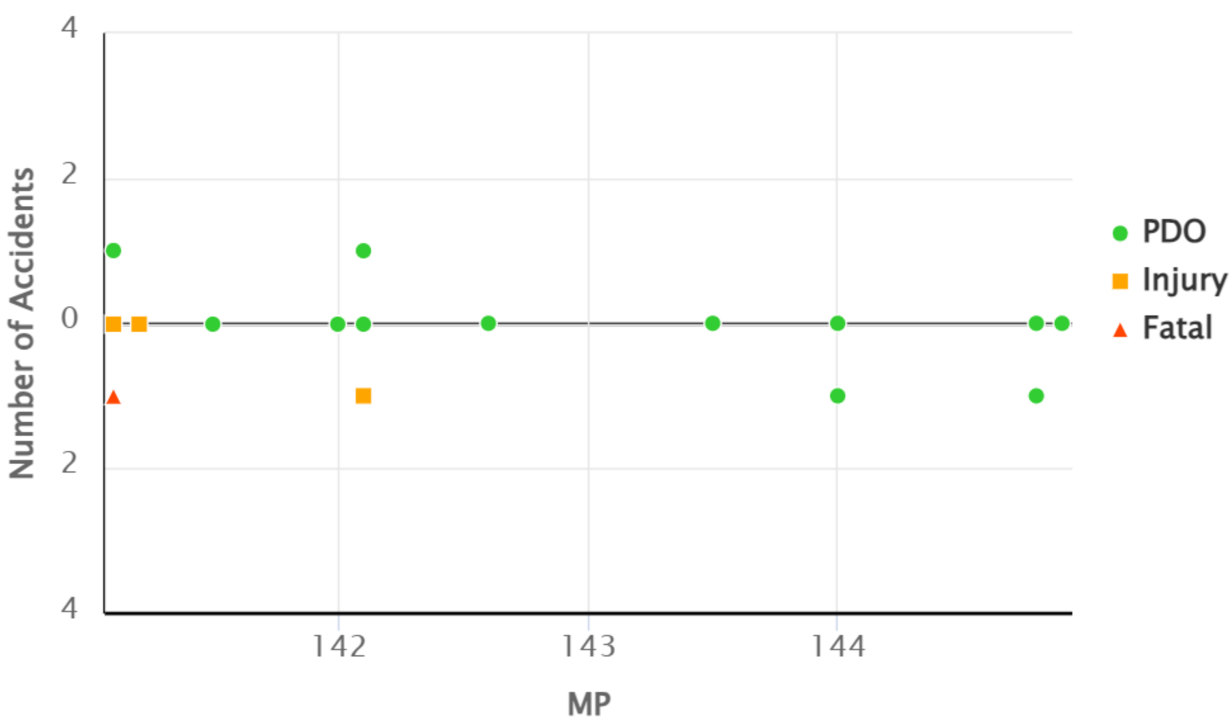

Figure 4-13: Truck Crash Locations, WB US40 MP 145-141

Figure 4-13 shows that most crashes occurred prior to or at the truck escape ramp (MP 142). However, it also indicates that there were severe (injury+fatal), crashes recorded beyond the escape ramp near or at MP 141. **Figure 4-14** shows that there are two curves immediately following the one at MP 142. The first that drivers would encounter is less severe (MP 141.5), while the second is another sharp curve (MP 141.25) (see **Figure 4-15**). Both curves are also on a downgrade.

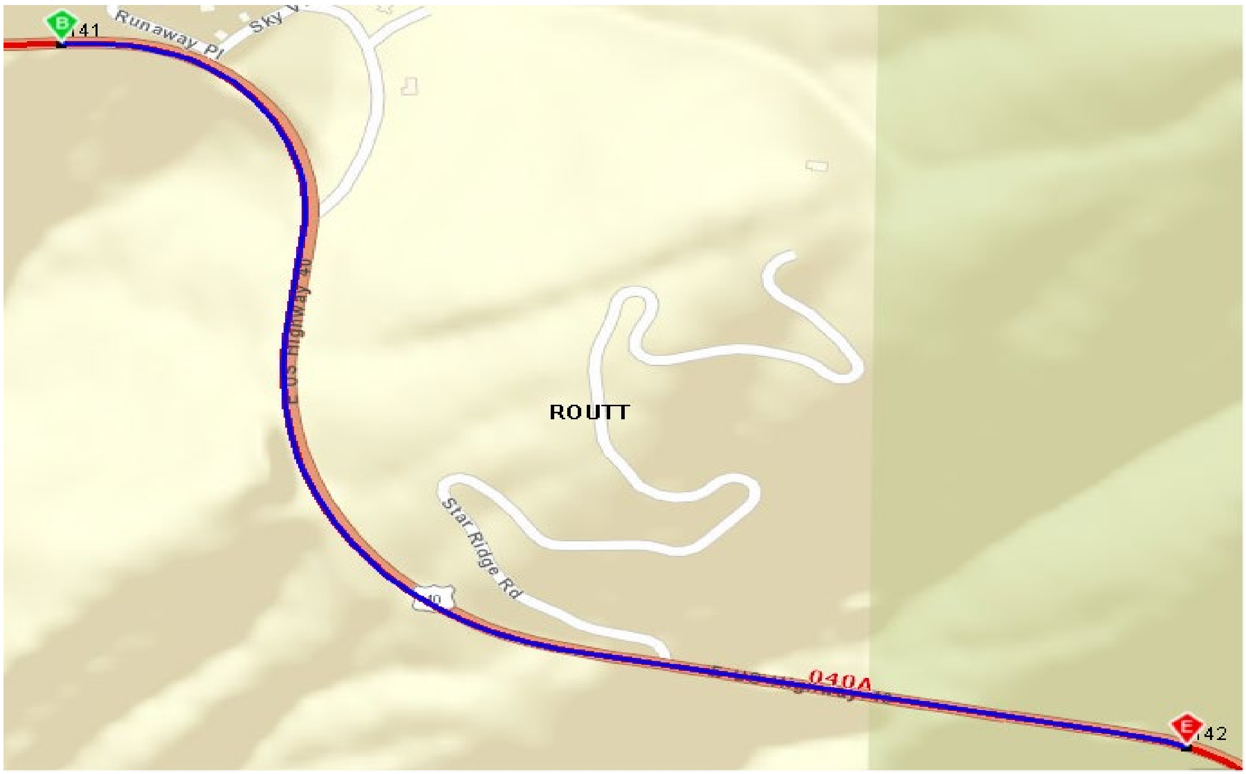

Figure 4-14: Curves Beyond MP 142 Truck Escape Ramp, WB US40

Figure 4-15: Sharp Curve near WB US40 MP 141.25

Figure 4-16 shows that truck crashes on the study segment were predominantly run-off-the-road crashes (Fixed Object, Overturning), while **Figure 4-17** shows that Fixed Object crashes tended to be with terrain rather than other objects.

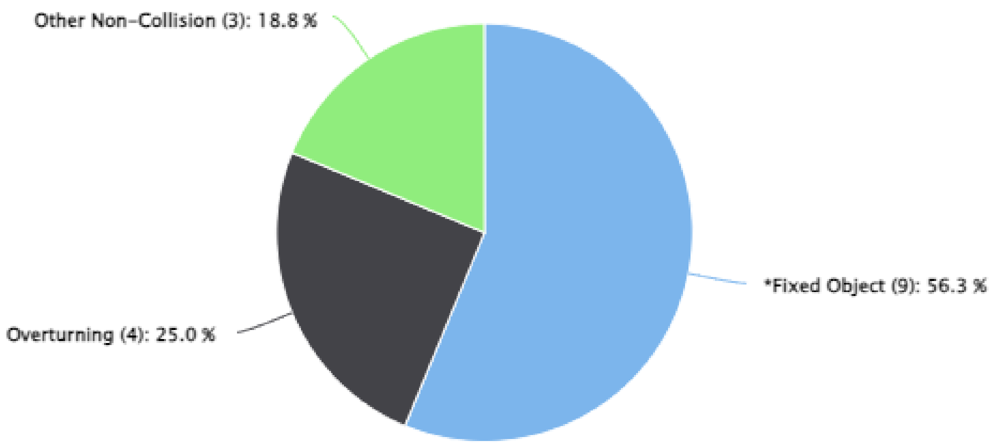

Figure 4-16: Truck Crashes, Crash Type Distribution, WB US40 MP 141-145

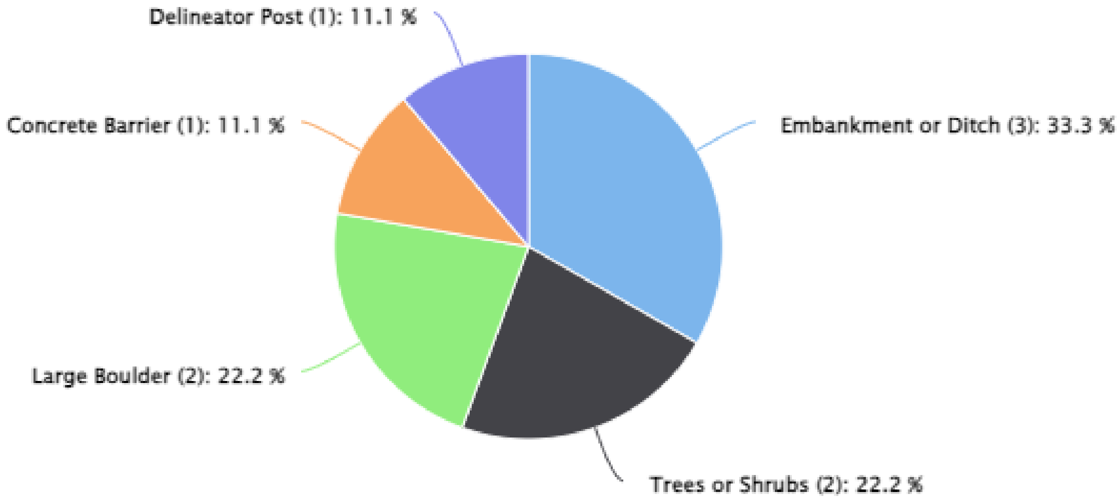

Figure 4-17: Truck Fixed Object Crashes Distribution

Figure 4-18 shows that driver inexperience and unfamiliarity with the area were significant contributing factors to truck crashes on the study segment, having an influence on at least 50% of all crashes.

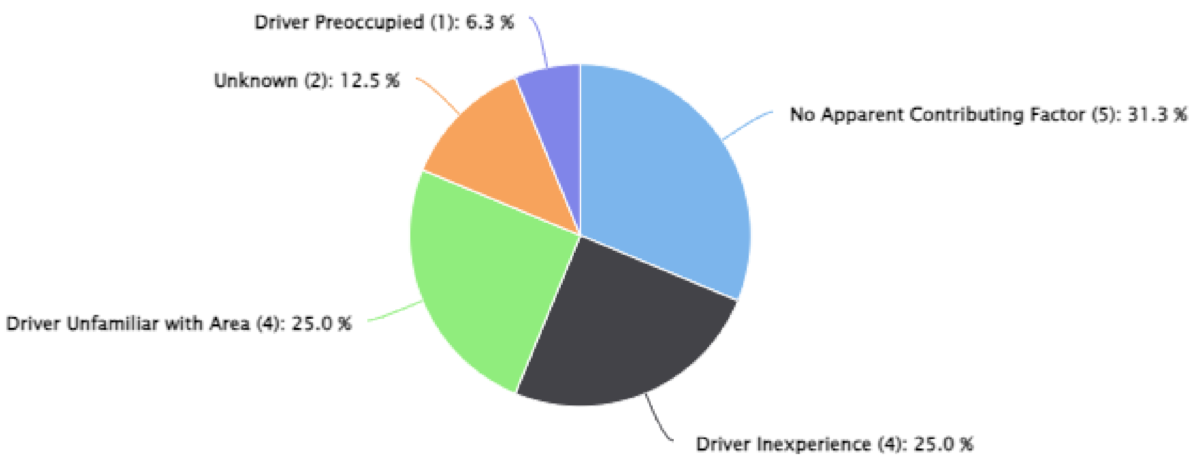

Figure 4-18: Truck Crashes, Human Contributing Factors

As outlined previously, the more severe truck crashes seem to occur after the escape ramp near MP 141 (1 Fatal, 2 Injury). A review of crash history records shows that 1 of the 3 recorded Injury level crashes on the study segment occurred at the escape ramp (MP 142.09). This was an Overturning crash, lighting and road conditions were not a factor in the crash. In this case the truck driver did not use the escape ramp.

There were 3 other instances recorded in which the driver did use the escape ramp. All 3 crashes were at the PDO level. In 2 cases there is a record of the truck hitting a snowbank, present due to ploughing, upon accessing the escape ramp. A situation like this creates a bump on the path of the truck utilizing the escape ramp which is undesirable as trucks using escape ramps tend to be traveling at speed and a bump can cause the vehicle to deviate from the path or jackknife and makes injuries more likely. Additionally, for these reasons, the presence of a snowbank may deter truck drivers from utilizing an escape ramp. These 2 cases, however, did demonstrate successful use of the ramp. Notwithstanding, the details of the crashes suggest that a review of maintenance procedures may be warranted to avoid the development of snowbanks across/on truck escape ramps posing hazardous conditions.

In the 3rd case, brake failure was the precipitating factor in the use of the truck escape ramp. The crash narrative shows that after entering the escape ramp the truck traveled beyond the end of the ramp, into the trees, rolled back and jackknifed. Driver inexperience was a factor in this crash. Compounding this, the crash also occurred under dark conditions. In this case, it cannot be said conclusively that the escape ramp functioned successfully. While the truck was eventually arrested, it suffered a jackknife and was not arrested before reaching the end of the ramp. However, it must also be considered that the driver was inexperienced.

When the severe crashes which occurred beyond the escape ramp are considered, the Fatal crash involved a driver unfamiliar with the area traveling at speed, with dark conditions, resulting in an Overturning crash. One of the injury level crashes was a Concrete Barrier crash and occurred under dawn/dusk conditions. In the case of the latter, driver inexperience was a contributing factor. The final injury level crash was an Overturning crash due to brake failure and driver unfamiliarity with the area was a contributing factor, which may partly explain why the escape ramp 1-mile upstream was not utilized by the driver.

When all of these crashes are considered as a whole, it is clear that driver inexperience and unfamiliarity with the area, which can be exacerbated by poorly lit conditions, are contributing to the run-off-the-road truck crashes on the study corridor. The geometry and alignment of the corridor appears to be a major contributing factor also. Furthermore, it must be considered why run-off-the-road crashes occur beyond the escape ramp, when several of the crashes which occurred could have potentially utilized the ramp. Particularly, as there is an advance warning sign that curves and grades are sharper beyond the ramp (**Figure 4-23**).

In consideration of the aforementioned combined factors, imagery shows that there are several advance warning signs regarding curvature, grade, and the escape ramp, on the approach to the escape ramp, some of which already have solar powered flashing beacons. **Figure 4-19** through **Figure 4-25** provide an overview of the progression of the advance warnings and devices already in place.

Advance warning for the truck escape ramp begins approximately 1.5 miles in advance of the ramp with a sign located near MP 143.77, which has solar powered flashing beacons (**Figure 4-19**).

4-18).

Figure 4-19: 1st Escape Ramp Advance Warning Sign, MP 143.77

This is followed by another warning sign for the escape ramp about ¾ of a mile before the ramp, at approximately MP 143.08 (**Figure 4-20**). This sign also has solar powered flashing beacons.

Figure 4-20: 2nd Escape Ramp Advance Warning Sign, MP 143.08

Trucks are warned of a steep 7% grade from MP 143.02, approximately, for 4 miles (**Figure 4-21**).

Figure 4-21: Steep Grade Warning, MP 143.02

An advisory speed limit of 45 mph is issued at approximately MP 142.93 (**Figure 4-22**) in advance of the curve preceding the escape ramp.

Figure 4-22: Advisory Speed Limit, MP 142.93

As outlined earlier, there is a warning sign aimed at truck drivers in advance of the escape ramp, at approximately MP 142.80, which indicates that alignment and grade become even less favorable beyond the ramp (**Figure 4-23**).

Figure 4-23: Curve & Grade Warning, MP 142.80

The final sign for the escape ramp is seen 1500 ft in advance of the ramp, at approximately MP 142.55 (**Figure 4-24**), it also has solar powered flashing beacons.

Figure 4-24: Final Escape Ramp Warning, MP 142.55

The entrance sign for the truck escape ramp does not itself have flashing beacons (**Figure 4-25**).

Figure 4-25: Truck Escape Ramp Entrance Sign, MP 142.25

Imagery indicates that these signs may be prone to becoming obstructed by foliage seasonally (**Figure 4-21** and **Figure 4-26**). As such, CDOT is advised to perform regular maintenance to ensure adequate visibility of signage, particularly to benefit the out-of-town and nighttime truck operator.

Figure 4-26: Advance Warning MP 143.08, Partial Foliage Obstruction, Jul. 2023

Regarding the curves occurring immediately beyond the truck escape ramp, at MP 141.50 and MP 141.25 approximately, there is a grade warning sign at MP 141.71 (**Figure 4-27**) and an advisory speed limit and curve warning sign at MP 141.33 (**Figure 4-28**), both of which have solar powered flashing beacons. However, as has been established, crashes have none-the-less been recorded following these curves, indicating that the warning signs may not be performing as intended. Furthermore, because commercial vehicle crashes, particularly severe crashes, have been recorded near the MP 141 location, this also suggests that the combination of steep grade and changes in horizontal alignment may exacerbate instances of any brake failure, on this study segment. As such, improved signing, warning and guidance would be beneficial, especially in the case of inexperienced drivers and drivers who are unfamiliar with the area.

Figure 4-27: Grade Warning Sign, MP 141.71 US40

Figure 4-28: Curve & Advisory Speed Warning, MP 141.33 US40

As outlined, the crash history on the study segment both near MP 142 near the truck escape ramp, and beyond MP 142, near MP 141, might point to inadequacies in the advance notice given to truck operators in the westbound direction of the presence and location of the ramp, as well as the dangers posed by the changing alignment on steep downgrades. This location may benefit from a system similar to the enhanced signing, warning and guidance system which has been employed at the Wolf Creek Pass ramp.

As described previously, the current signage system does have solar powered flashing beacons. This system could be upgraded to reflect that on the Wolf Creek Pass by employing Blank-Outs on the existing signs (**Figure 4-1**) to provide real-time feedback to truck drivers. Furthermore, the crash history indicates that the study segment would also benefit from the inclusion of activated Overturning warning signs, similar to those on Wolf Creek Pass (**Figure 4-2**). Additionally, a diagrammatic "story map" sign (**Figure 4-3**), would help give a clearer picture to truck drivers of both the location of the escape ramp, but also of the sharp curves along the corridor, enabling them to make better informed decisions and adjust driving style appropriately.

A system such as this would require an electricity supply and fiber cable network access.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the US-40 corridor surrounding the Rabbit Ears Pass truck escape ramp located near MP 142.00, and to provide an evaluation of the performance of the truck escape ramp. The analysis was focused on the westbound US-40 corridor between MP 141.00 and MP 145.00 to capture the effects of the ramp.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area. Both directions were evaluated together to provide a general safety overview before the westbound direction was independently analyzed for directional SPF assessment.

Westbound

Westbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-IV for corridor in terms of total crashes, and LOSS-II/III in terms of crash severity. This represents high potential for crash reduction, and low to moderate potential for crash reduction, respectively.

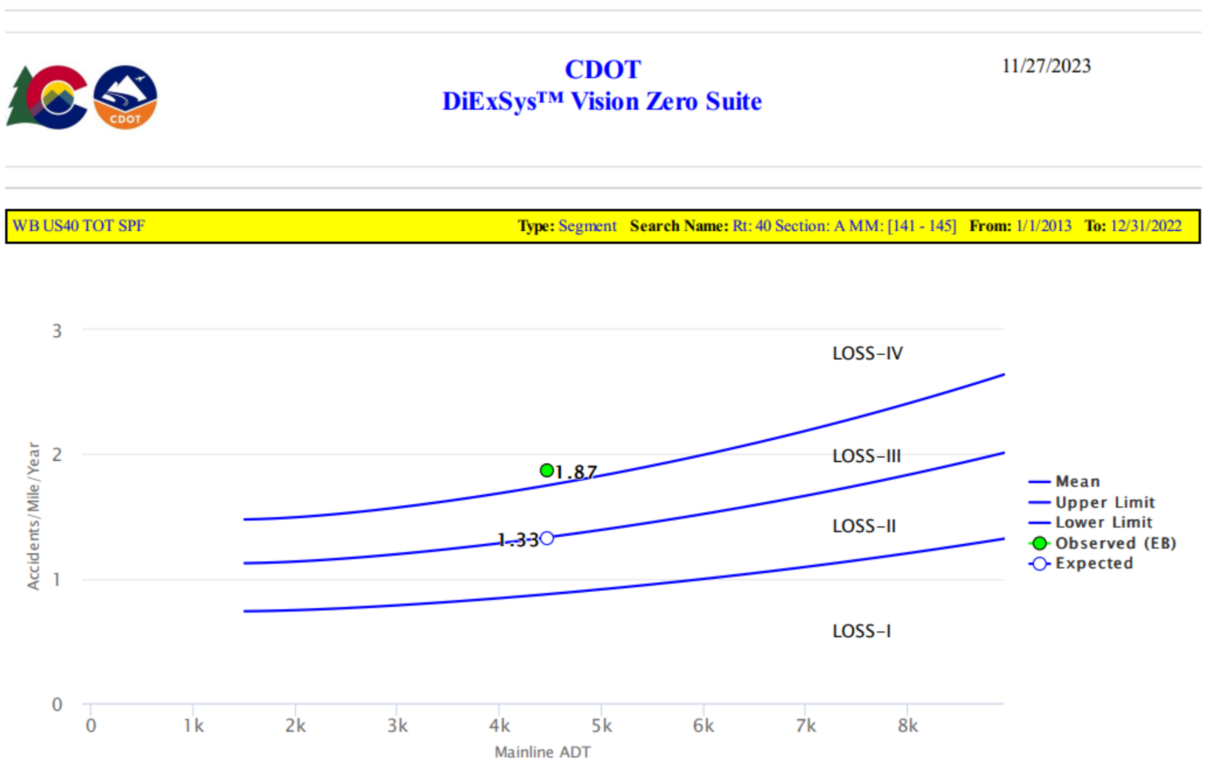

Figure 4-29: SPF Total Crashes US-40 Westbound

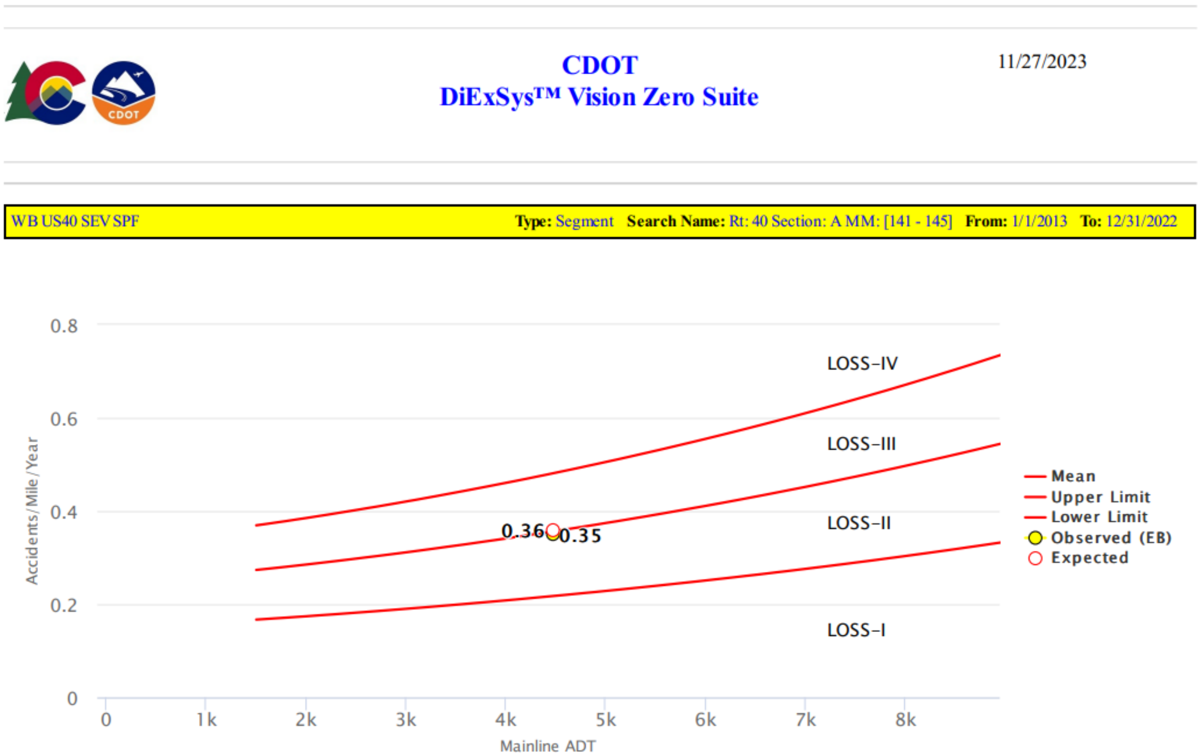

Figure 4-30: SPF INJ+FAT Crashes US-40 Westbound

Most patterns identified on the westbound corridor were correlated with roadway geometrics, weather and road conditions, and driver familiarity with the area. Identified patterns were representative of run-off-the-road crashes, commonly seen as overturning crashes and crashes with Embankment, for example. It is apparent that there is an overlap between run-off-the-road crashes and crashes under adverse winter weather and road conditions.

A summary of recommendations for the westbound direction in general can be summarized as follows:

- Install a SLIPPERY CONDITIONS warning sign (*MUTCD W8-5*) at the beginning of the corridor with supplementary "ICE" plaques (*MUTCD W8-5aP*),
- Install a CURVE WARNING signs (*MUTCD W1-2*) in advance of the curve near MP 143.30 with an advisory reduced speed limit plaque (*MUTCD W13-1P*), and
- Consider westbound edge line rumble strips as well as centerline rumble strips on the corridor.

Truck crashes were found to be predominantly Fixed Object crashes. Driver inexperience and unfamiliarity with the area were significant contributing factors to truck crashes.

A number of crashes, including injury and fatal, were found to have occurred near two curves following the escape ramp, near MP 141.50 and MP 141.25. There are several advance warning signs prior to these curves indicating the presence of curves and grades and providing advisory speed limits, but the presence of crashes indicates that the warning signs could be made more effective.

There were 3 identified uses of the escape ramp in the study period (all PDO), with 1 additional crash occurring at the ramp location. In 2 cases the truck hit a snowbank formed from ploughing upon accessing the ramp. These 2 cases demonstrate successful use of the ramp. In the 3rd case, brake failure was the precipitating factor. The outcome was less successful as the truck traveled beyond the end of the ramp and jackknifed.

For crashes recorded beyond the ramp, driver unfamiliarity with the area, inexperience, dark conditions and brake failure, were contributing factors. It must be considered why run-off-the-road crashes occur beyond the escape ramp, when many of the crashes which occurred could have potentially utilized the ramp.

The combination of steep grade and changes in horizontal alignment appears to be a significant contributory factor to truck run-off-the-road crashes.

A summary of recommendations in relation to westbound commercial vehicle crashes can be made as follows:

- Review winter maintenance protocols to ensure snowbanks are not deposited across the arrester bed/ramp access,
- Ensure advance warning signs for the escape ramp, grades and curves are kept clear of foliage and obstructions, and
- Implement enhanced runaway truck signing, warning and guidance system to include blank-outs and flashing beacons on advance warning signs, as well as vehicle detection and guidance, overhead diagrammatic warning signs with pertinent locational information. Sufficient solar paneling and battery supply to be provided.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the westbound direction. Crash distribution is predominantly in the westbound direction, the direction of the escape ramp, with 66.9% of crashes occurring in that direction. It is in the westbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 3 – Monarch Pass: U.S. 50 Eastbound, MP 201.00-204.75

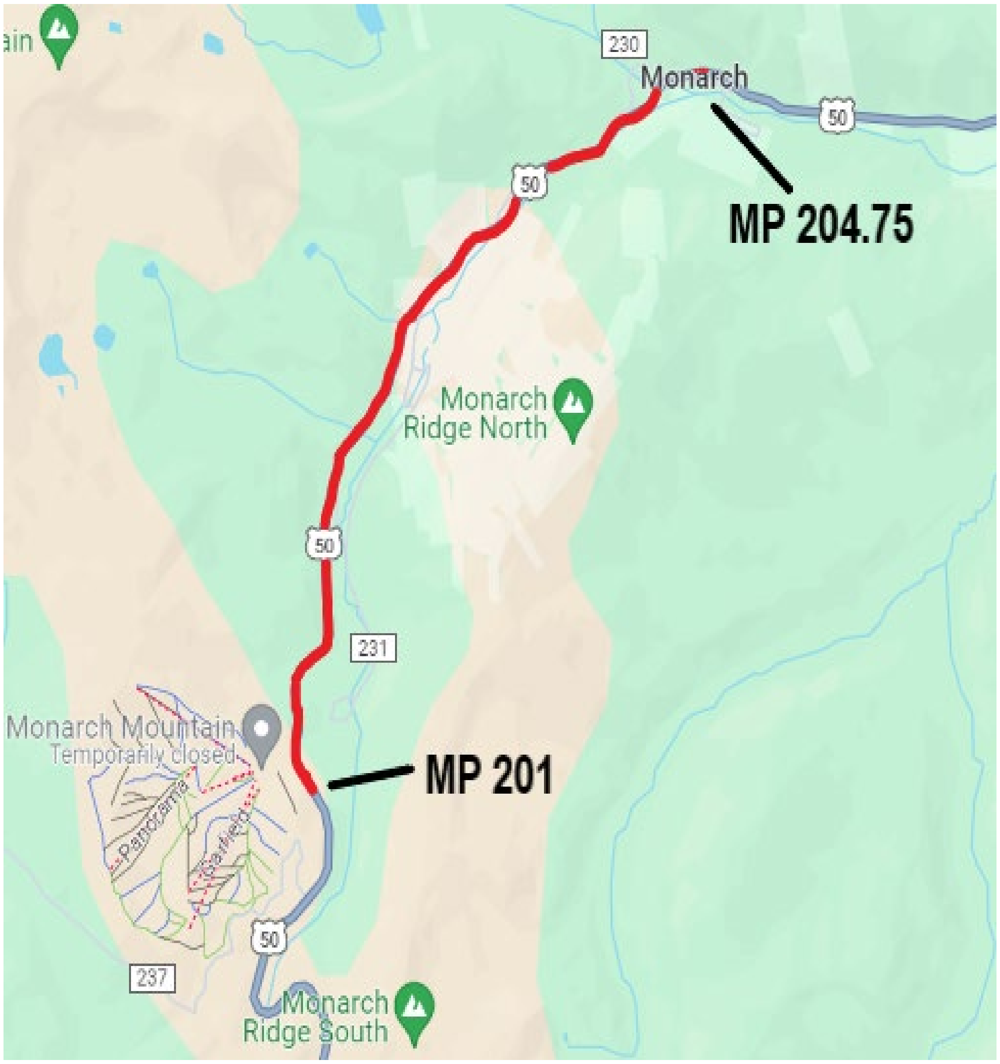

Figure 4-31: Monarch Pass Study Limits

Site Location

The Monarch Pass truck escape ramp is located on U.S. 50 eastbound near mile point 204.00. To capture a zone of influence, this study considers the corridor between MP 201.00, near to where the initial truck warning signs are seen in advance of the escape ramp, to MP 204.75, just beyond the escape ramp. The included distance is approximately 3.75 miles.

Site Conditions

US-50 is classified as a rural regional highway on mountainous terrain. US-50 is predominantly a 3-lane, undivided highway with 12' lanes, with 1 lane in the eastbound direction and 2 lanes in the westbound direction, with some departures to a single lane westbound. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 2,400 and the percentage of truck traffic is 13%.

The speed limits eastbound and westbound are 45 mph between MP 201.00 – MP 202.00 and MP 204.09 – MP 204.75, and 55 mph between MP 202.00 and MP 204.09. There are lower advisory speed limits in both directions throughout the study corridor.

Outside shoulder width along the study segment varies considerably, from 3 ft at MP 201.33 to 41 ft at MP 203.24, while there is no information for the inside secondary shoulder width. The corridor is characterized by frequent changes in horizontal curvature and downgrades. **Figure 4-32** below shows a typical section of the corridor eastbound.

Figure 4-32: Typical Section of US-50, Eastbound MP 203.37 July 2022

Eastbound Commercial Vehicle Crashes

This safety assessment is primarily concerned with the history of commercial vehicle crashes along the study corridor. There were 13 recorded commercial vehicle crashes on eastbound US-50 between MP 201.00 and MP 204.75 in the 10-year study period. This included 3 Injury level crashes, with 4 people injured and 9 Property Damage Only (PDO) crashes, and 1 Fatal crash, with 1 fatality.

Figure 4-33 shows the location of commercial vehicle crashes within the study segment. Apart from 1 injury crash which occurred at MP 201.80, most severe (injury+fatal) commercial vehicle crashes occurred within ½ mile either side of the truck escape ramp.

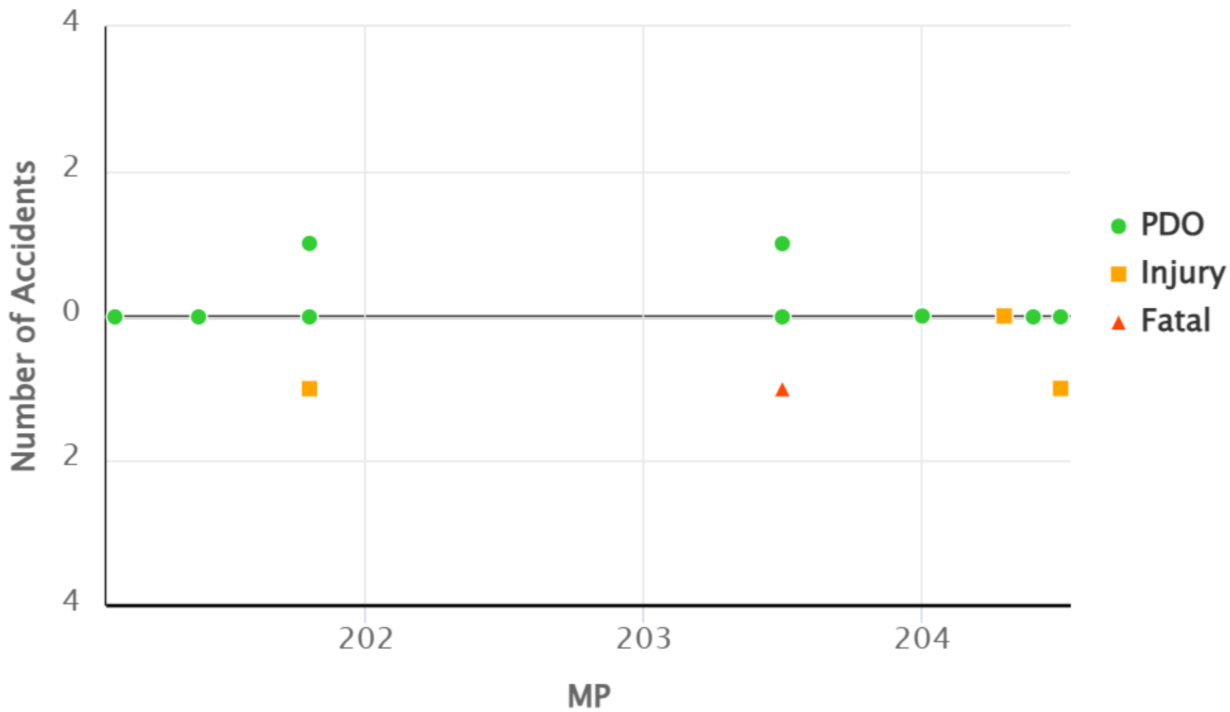

Figure 4-33: EB Commercial Vehicle Crash Locations, US 50

- The fatal crash occurred on 9/19/2020 at MP 203.50 and was an Overturning crash. The crash records show that the crash resulted from brake failure combined with the driver's inability to negotiate a curve. The crash occurred under dark conditions. Records show that the driver was also unfamiliar with the area. The crash records also indicate that the driver struck the guardrail before overturning, which is reflective of the Guardrail pattern seen on the study corridor. In this case the driver ran off the road before the truck could reach the escape ramp, approximately ½ mile further down the corridor.
- The injury level crash at MP 204.30 was an Overturning crash which occurred on adverse road conditions during winter weather, the driver was preoccupied, and records indicate the driver lost control on a curve.
- The injury crash at MP 204.50 was a run-off-the-road collision with a sign, occurring in wet and dark conditions, the driver was unfamiliar with the area, and crash records indicate that the driver failed to manipulate the curve.
- The third injury crash, at MP 201.80 is somewhat of an outlier in that the records show the precipitating factor was that the vehicle "accelerated without explanation into the opposing lane," and it was not related to an overtaking maneuver. This portion of the study corridor is on a clear downgrade, and so one possible explanation for the sudden acceleration might be brake failure. Furthermore, the eastbound side of the road is unprotected by guardrail in this location and the maneuver into the westbound lane may have been to avoid rollover down the steep embankment (**Figure 4-34**).

Figure 4-34: View of MP 201.80 Commercial Vehicle Crash Location, Jul. 2022

As alluded to above by the crash records, all 4 of the severe commercial vehicle crashes occurred on curves. Additionally, 7 out of the 9 PDO truck crashes occurred on curves. This indicates that the alignment of the study corridor is a likely contributing factor to truck crashes, with drivers unable to successfully negotiate the changing horizontal curvature. Compounding this, **Figure 4-35** shows that adverse winter weather and road conditions were significant factors to truck crashes, with crash records also having frequent references to losing traction on ice and sliding on ice and snow. Furthermore, **Figure 4-36** shows that the majority of truck crashes (over 61%), involved drivers who were unfamiliar with the area or inexperienced.

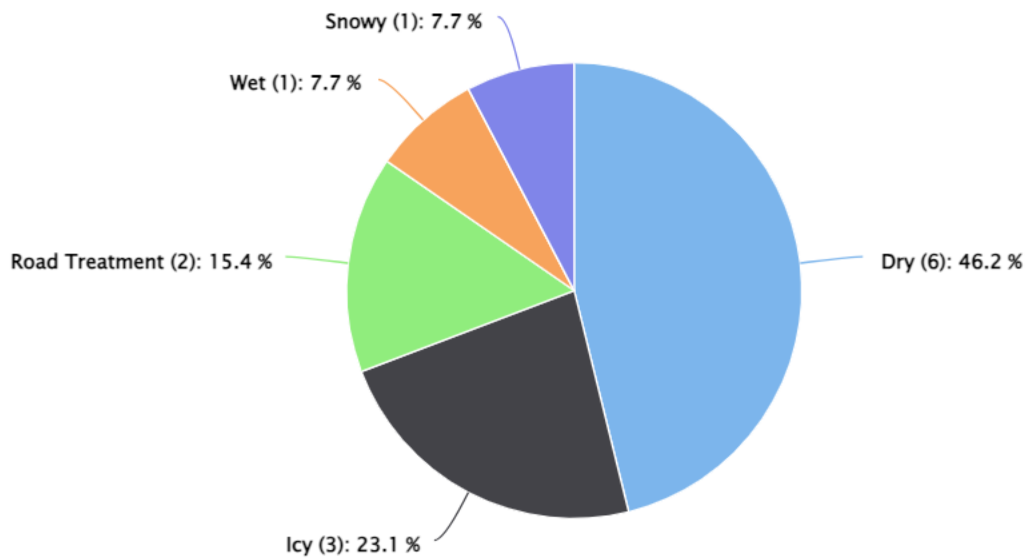

Figure 4-35: EB Commercial Vehicle Crashes, Road Conditions

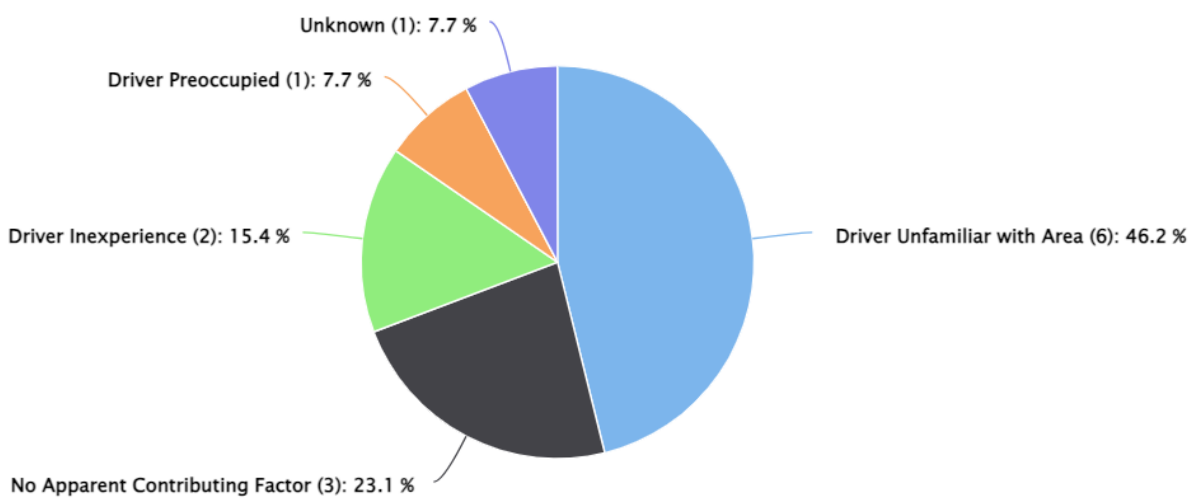

Figure 4-36: EB Commercial Vehicle Crashes, Human Contributing Factors

When changing alignment on a downgrade, adverse driving conditions and unfamiliarity/inexperience are considered together, it presents a scenario in which additional advance warning of the geometry ahead, advisory speeds, and location of the truck escape ramp, would allow truck operators to make appropriate adjustments to driving style or prepare for a safe roadway departure by utilizing the escape ramp. A truck signing, detection and warning system similar to that which is in place on Wolf Creek Pass would support this. Diagrammatic "story" signs like that seen in **Figure 4-3**, would assist truck operators to more readily identify upcoming hazardous curves and to be better prepared to negotiate them. Real-time vehicle detection would allow display of a warning to use the escape ramp upon detection of the speed threshold being exceeded for commercial vehicles via dynamic message signs.

Figure 4-37 shows the distribution of crashes by crash type for commercial vehicle crashes on the eastbound study segment.

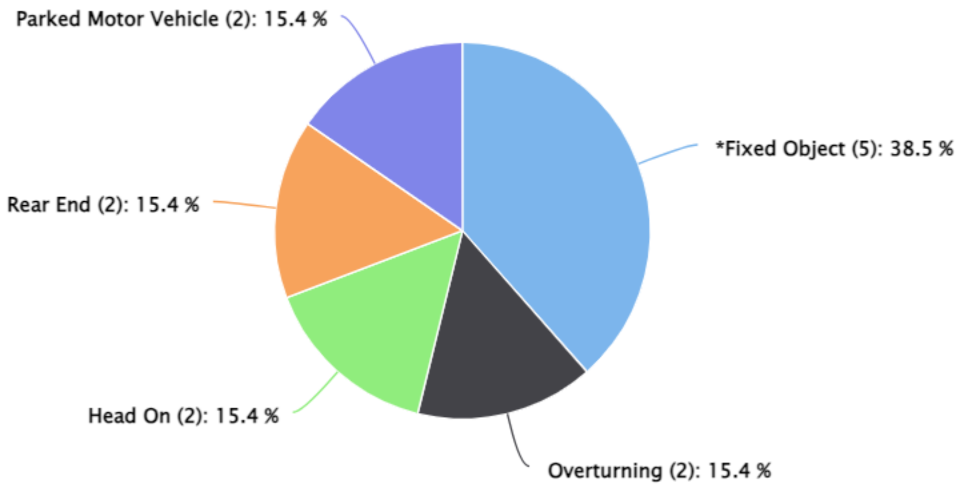

Figure 4-37: EB Commercial Vehicle Crash Type Distribution

Records show that just under half of truck crashes were off-road crashes (6 of 13). **Figure 4-38** shows that off-road crashes did not occur at the location of the truck escape ramp but rather appear to show a cluster beyond it at the curve near the town of Monarch at MP 204.50.

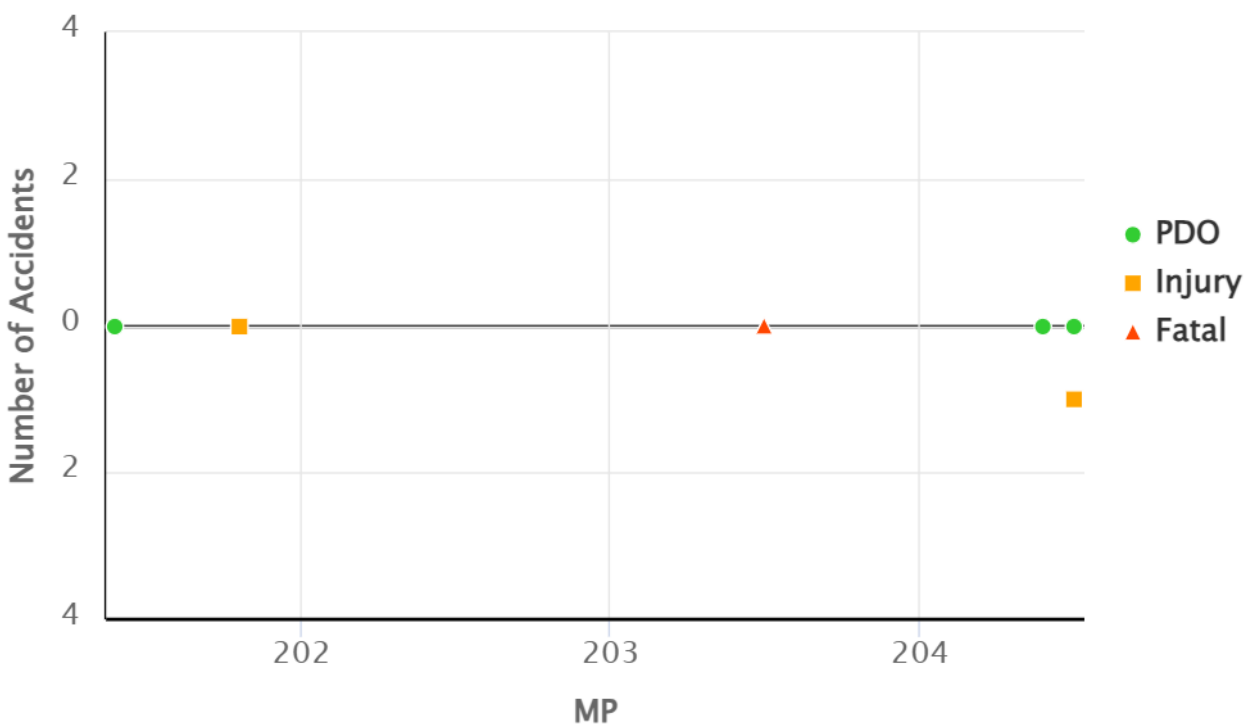

Figure 4-38: EB Off-Road Commercial Vehicle Crash Locations

The crash records for the study period do not make any reference to the truck escape ramp having been used in the 10-yr period. For this reason and because there were no off-road commercial vehicle crashes recorded at MP 204.00, it is difficult to conclusively say the ramp has been successful.

When we consider those truck crashes which resulted in run-off-the-road collisions, and in particular those severe level truck crashes described earlier, it might be considered if the truck ramp would have been better placed in advance of MP 204.00, closer to MP 203.50, or further downstream closer to MP 204.50 where crash clusters are seen. However, in the case of the latter location, there are narrow shoulders, a river and a hotel on the east side (**Figure 4-39**).

Figure 4-39: Aerial View of Curve near EB US50 MP 204.50

The use of truck escape ramps typically results from the failure of brakes. In this analysis we found one example of brake failure which occurred ½ mile in advance of the ramp, and one potential case of brake failure which occurred at MP 201.80 and was described earlier. In both cases, it is difficult to say if use of the escape ramp would have benefitted the outcome, as it is located too far from where the crashes occurred, and in addition there are curves in between the crash locations and the ramp which would have needed to be negotiated.

Regarding curve negotiation, it appears based on the crash history for the eastbound study corridor, that this rather than brake failure, has been an over-arching factor in almost all commercial vehicle crashes. As stated above, this location may benefit from an enhanced signing and warning system similar to that which has been employed for the Wolf Creek Pass escape ramp. In particular, in addition to the diagrammatic signs providing curve locations, which were recommended earlier in the report, curve series and grade warning signs, or

SLIPPERY CONDITIONS warning signs with flashing beacons or dynamic feedback, similar to that seen in **Figure 4-1**, would benefit truck operators in navigating the changing curvature of the corridor under adverse conditions, especially if they are unfamiliar with the area and inexperienced with mountainous driving.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the US-50 corridor surrounding the Monarch Pass truck escape ramp located near MP 204.00, and to provide an evaluation of the performance of the truck escape ramp. The analysis was focused on the eastbound US-50 corridor between MP 201.00 and MP 204.75 to capture the effects of the ramp.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area. Both directions were evaluated together to provide a general safety overview before the eastbound direction was independently analyzed for a directional SPF assessment.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the eastbound direction. Although crash distribution is almost evenly split in both directions, the eastbound direction, on which the escape ramp is located has been the focus of this assessment.

Eastbound

Eastbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-III for corridor in terms of total crashes, and LOSS-II in terms of crash severity. This represents moderate to high potential for crash reduction, and low to moderate potential for crash reduction, respectively.

CDOT
DiExSys™ Vision Zero Suite

12/05/2023

EB US50 TOT SPF **Type:** Segment **Search Name:** Rt: 50 Section: A MM: [201 - 204.75] **From:** 1/1/2013 **To:** 12/31/2022

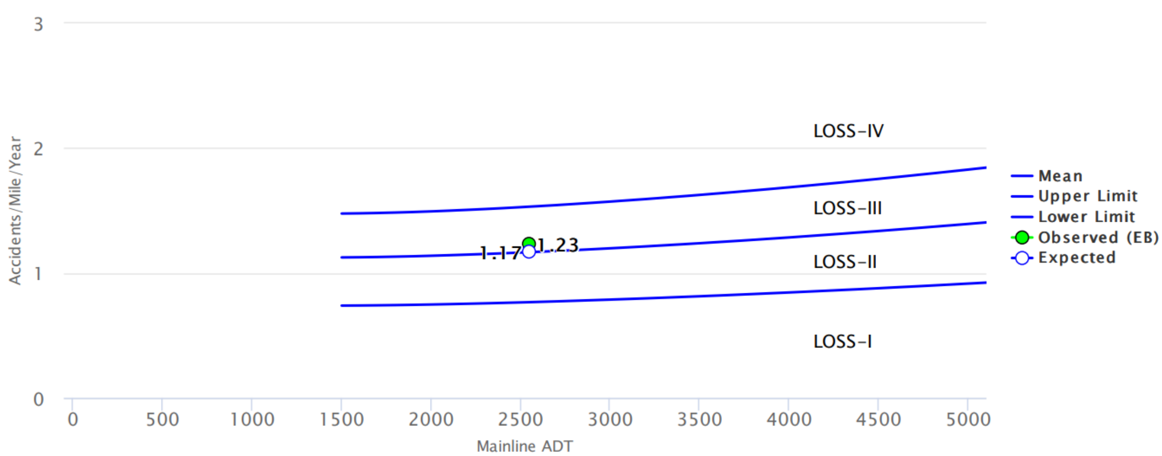

Figure 4-40: SPF Total Crashes US-50 Eastbound

CDOT
DiExSys™ Vision Zero Suite

12/05/2023

EB US50 SEV SPF **Type:** Segment **Search Name:** Rt: 50 Section: A MM: [201 - 204.75] **From:** 1/1/2013 **To:** 12/31/2022

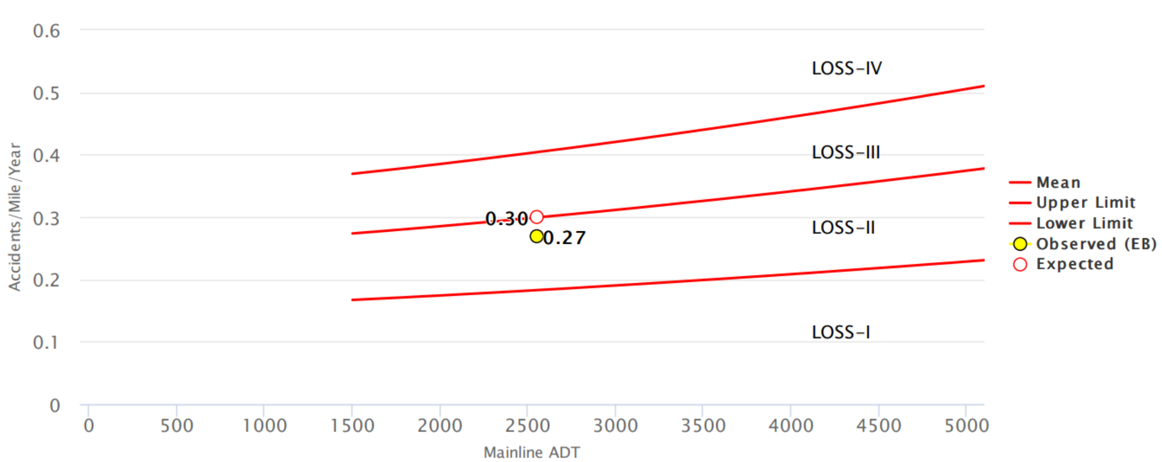

Figure 4-41: SPF INJ+FAT Crashes US-50 Eastbound

Most patterns identified on the eastbound corridor were correlated with roadway geometrics, weather and road conditions, and driver familiarity with the area. Rear End, Guardrail, and Tree crashes are overrepresented, as well as crashes involving drivers unfamiliar with the area, and crashes under adverse winter weather and road conditions. Crashes under adverse winter weather and road conditions are a persistent pattern for almost the entire study segment. An overlap was identified between Fixed Object crashes and crashes involving drivers unfamiliar with the area.

The primary contributing factor to Rear-End collisions appears to have been adverse winter weather and road conditions, with driver inexperience and unfamiliarity with the area also contributing. Most of the severe Fixed Object crashes occurred just prior to or just following the truck escape ramp, and chiefly in adverse winter weather and road conditions. Over 51% involved drivers who were unfamiliar with the area or inexperienced. The corridor is characterized by a series of curves.

General recommendations for the eastbound corridor can be made as follows:

- Install a SLIPPERY CONDITIONS warning sign (*MUTCD W8-5*) with supplemental "ICE" plaque (*MUTCD W8-5aP*) on the corridor, and
- Consider installation of eastbound edge line rumble strips and centerline rumble strips on the study corridor.

There were 13 commercial vehicle crashes eastbound in the 10-year study period. This included 3 Injury level crashes, 9 PDO crashes, and 1 Fatal crash. The most severe truck crashes occurred within ½ mile either side of the truck escape ramp. At least 1 crash was confirmed as due to brake failure. Records show that most truck crashes occurred on curves. It was also determined that adverse road/weather conditions, as well as driver unfamiliarity with the area were significant contributory factors to truck crashes.

Records show that off-road truck crashes did not occur at the location of the truck escape ramp but rather appear to show a cluster beyond it at the curve near the town of Monarch at MP 204.50. There is no reference to the escape ramp having been used in the 10-yr period.

The recommendation for eastbound commercial vehicle crashes can be summarized as follows:

- Additional curve series/grade/SLIPPERY CONDITIONS warning signs with flashing beacons or blank-outs providing dynamic feedback.
- Implement enhanced runaway truck signing, warning and guidance system to include blank-outs and flashing beacons on advance warning signs, as well as vehicle detection and guidance, overhead diagrammatic warning signs with pertinent locational information. Sufficient solar paneling and battery supply to be provided.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the westbound direction. Crash distribution is predominantly in the westbound direction, the direction of the escape ramp, with 68.5% of crashes occurring in that direction. It is in the westbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 4 – Upper and Lower Vail Pass: I-70 Westbound, MP 189.60-181.30

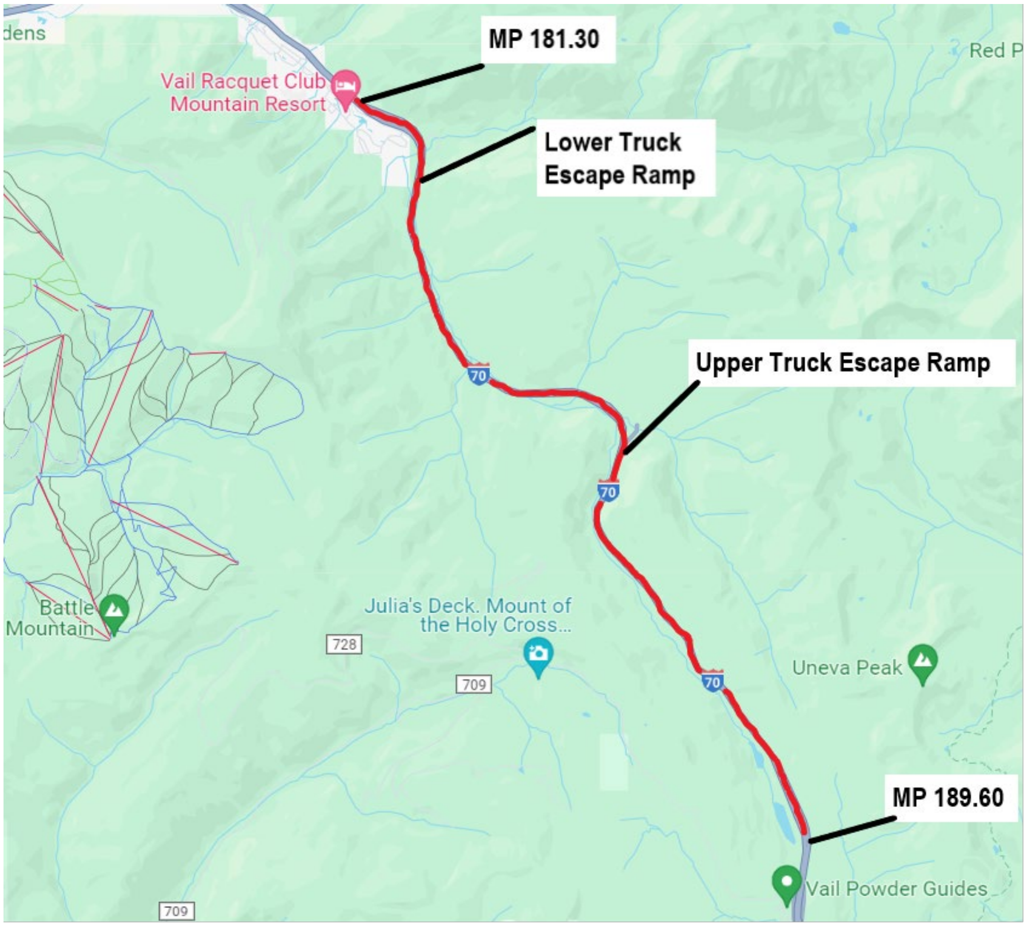

Figure 4-42: Upper and Lower Vail Pass Study Limits

Site Location

The Upper and Lower Vail Pass truck escape ramps are located on I-70 near mile point 182.36 and mile point 185.72 westbound, respectively. To capture a zone of influence, this study considers the corridor between MP 181.30 where the initial truck warning sign is seen in advance of the escape ramp westbound, and MP 189.60, approximately 1 mile beyond the lower escape ramp. The included distance is approximately 8.30 miles.

Site Conditions

I-70 is classified as a rural interstate on mountainous terrain for most of the study corridor, except between MP 182 and MP 181.30, where it is classified briefly as part of the urban Vail environment. I-70 is a 4-lane highway with two 12' lanes in each direction, and a concrete barrier dividing eastbound and westbound traffic. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 23,000 and the percentage of truck traffic is 13.8%.

The speed limit eastbound and westbound is 65 mph. There is a lower posted speed limit of 45 mph westbound (the direction of our primary focus), for heavier vehicles at MP 188.99, MP 186.98, MP 184.29, and MP 181.56. There are also lower advisory speed limits in both directions throughout the study corridor.

Outside shoulder width along the study segment varies considerably, from 3 ft at MP 181.87 to 19 ft at other locations, for example at MP 185.36. There is no information for the inside secondary shoulder width. The corridor is characterized by frequent changes in horizontal curvature. **Figure 4-43** below shows a typical section of the corridor westbound.

Figure 4-43: Typical Section of I-70, Westbound, Oct. 2023

Westbound Commercial Vehicle Crashes

There were 131 recorded commercial vehicle crashes on westbound I-70 between MP 181.30 and MP 189.60 in the 10-year study period. This included 98 Property Damage Only crashes, 32 Injury level crashes, with 54 people injured, and 2 fatal crashes, with 2 fatalities.

Figure 4-44 shows the distribution of crash types for truck involved crashes. When compared to the same distribution for all westbound crashes, truck involved crashes are also dominated by Fixed Object crashes, Rear-End collisions and Sideswipe same direction crashes. However, in the case of truck crashes it is notable that 26% were Sideswipe same direction crashes, compared to 12.4% for westbound crashes in general. This suggests that trucks are more prone than other vehicles to be involved in Sideswipe same direction crashes on the study corridor.

Sideswipe same direction crashes involving trucks were most typically seen to occur in adverse winter road conditions, with truck trailers sliding, or when a previous crash caused a driver to merge to another lane. Inappropriate merging from the right lane into the left lane across the path of a vehicle already occupying the left lane was also a frequent occurrence in Sideswipe same direction truck crashes, according to crash narratives.

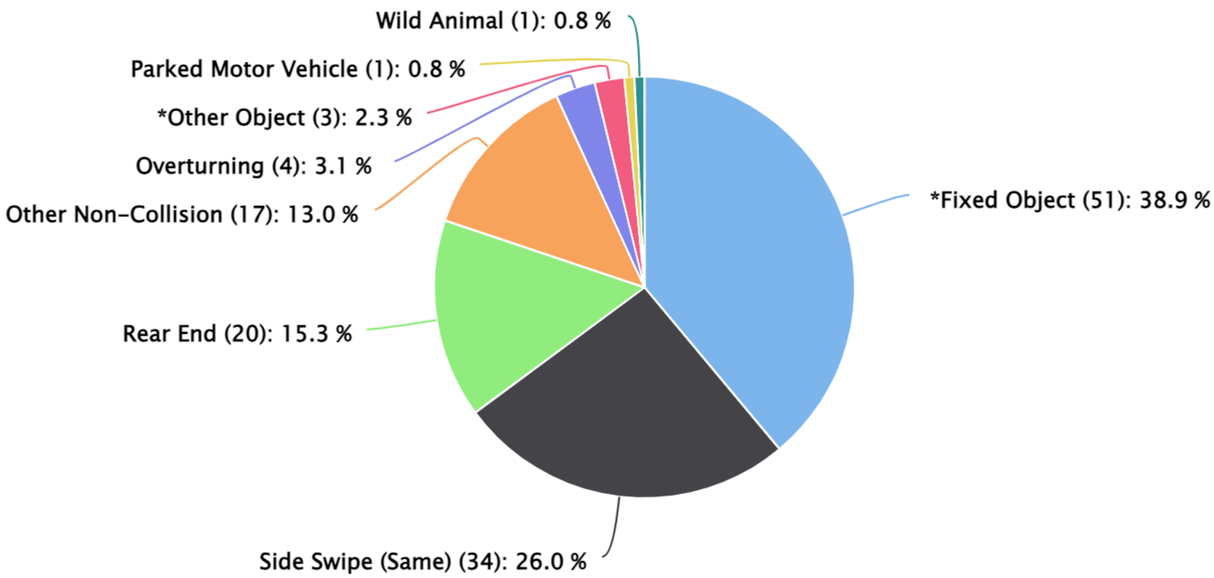

Figure 4-44: Crash Type Distribution for Commercial Vehicle Crashes

A sizeable 76.5% of all truck crashes occurred in adverse winter road conditions (**Figure 4-45**), indicating that adverse weather and road conditions are significant contributory factors to truck crashes on the corridor. This is further supported by **Figure 4-46**, showing truck crashes were more likely to be recorded in the winter and spring months when adverse weather can be expected, rather than in the summer months when crashes might be due to brake failure or overheating, for example. With steep downgrades and frequent changes in curvature, adverse winter road conditions can exacerbate these already challenging driving conditions for truck operators.

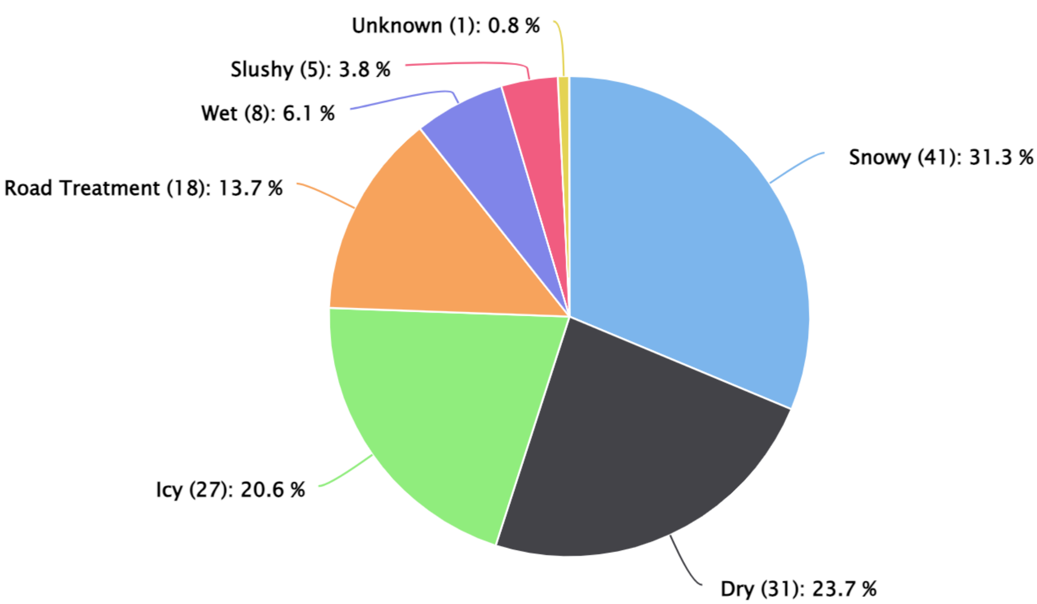

Figure 4-45: Commercial Vehicle Crashes, Road Conditions

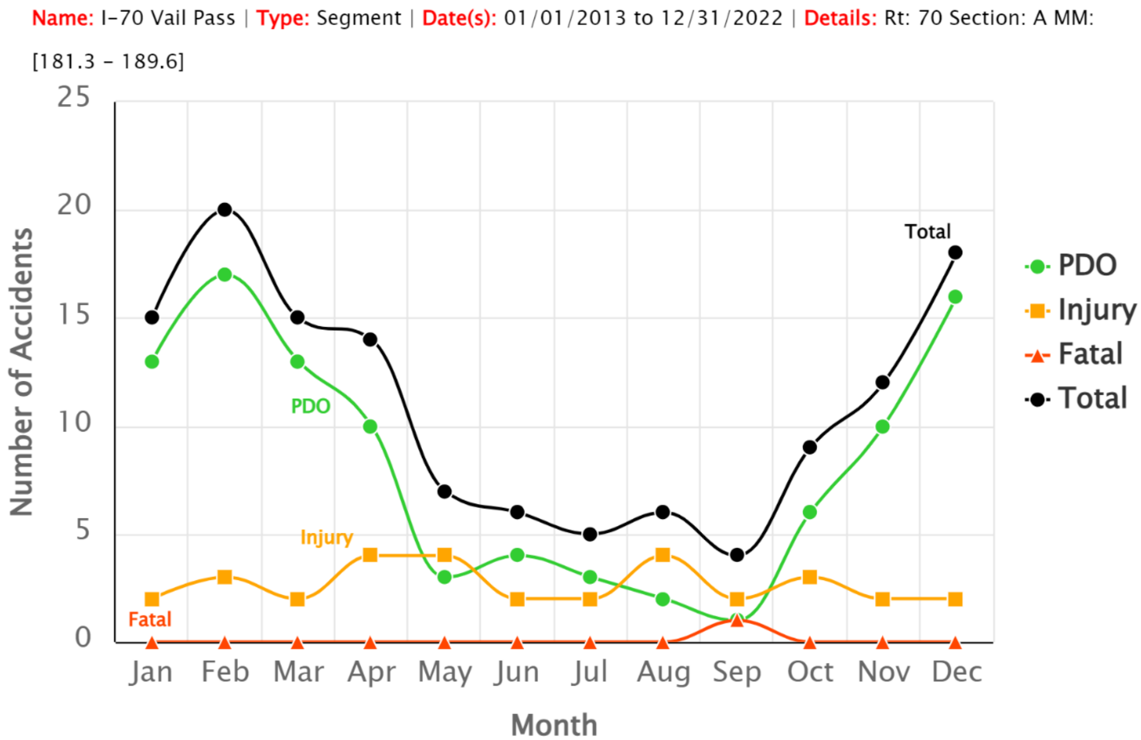

Figure 4-46: Commercial Vehicle Crashes, Month of Year

Analysis of human contributing factors shows that more than one in three truck crashes involved inexperienced drivers or drivers unfamiliar with the area (**Figure 4-47**). The corridor is characterized by steep downgrades and frequent changes to curvature which can prove challenging to navigate for drivers inexperienced in the mountainous environment or unfamiliar with the area and what to expect on the path ahead. All of this can be exacerbated by adverse road conditions making navigation with a commercial vehicle much more demanding and difficult.

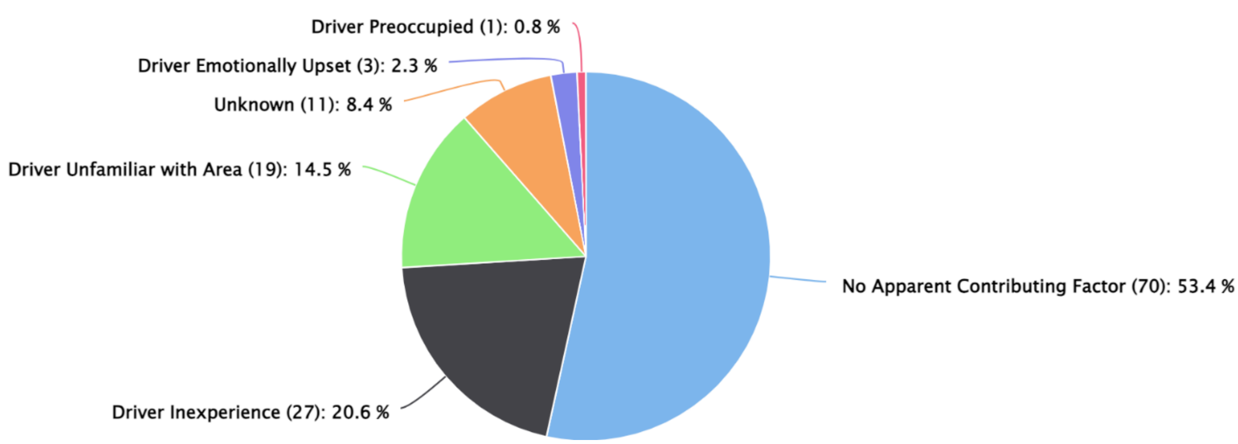

Figure 4-47: Commercial Vehicle Crashes, Human Contributing Factors

Figure 4-48 shows the location of truck crashes along the study corridor. Evidently the majority of crashes were recorded prior to MP 185 where downgrades are steeper. It seems the majority of crashes were recorded near MP 186, just following a sharp right curve on grade (**Figure 4-49**). The upper escape ramp is located near MP 185.72. Most of the injury level truck crashes occurred around the upper truck escape ramp. This might be reflective of the more pronounced curve in advance of the upper ramp, compared to the less severe curve prior to the lower ramp (see **Figure 4-42**).

A review of crash record narratives for truck crashes reflects the statistics shown above in **Figure 4-45**, that is that most crashes took place in adverse winter road conditions. Narratives were found to frequently cite a loss of control over the vehicle, as well as sliding or jackknifing in snowy or icy conditions. There were also frequent references made to attempts to avoid the scene of an earlier crash up ahead or adjacent to the path of the truck. It was found that crashes coded as "Other Non-Collision" were frequently collisions with snowbanks, embankments, or medians due to the truck having slid or lost control on ice or snow. Because most crashes involving trucks took place in winter and spring months and in adverse winter road and weather conditions, they typically do not present conditions of brake overheating or brake failure where drivers may need to use an escape ramp, because they are likely already traveling more slowly due to adverse conditions.

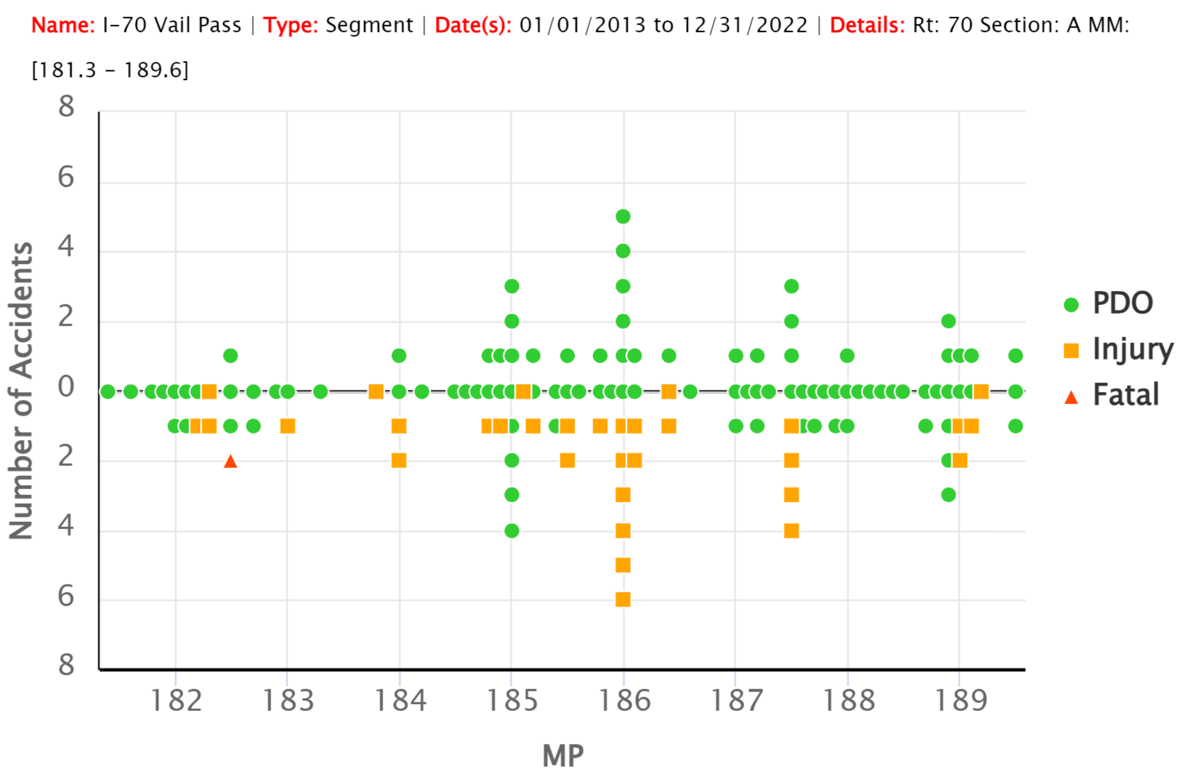

Figure 4-48: Commercial Vehicle Crashes, Straight Line Diagram

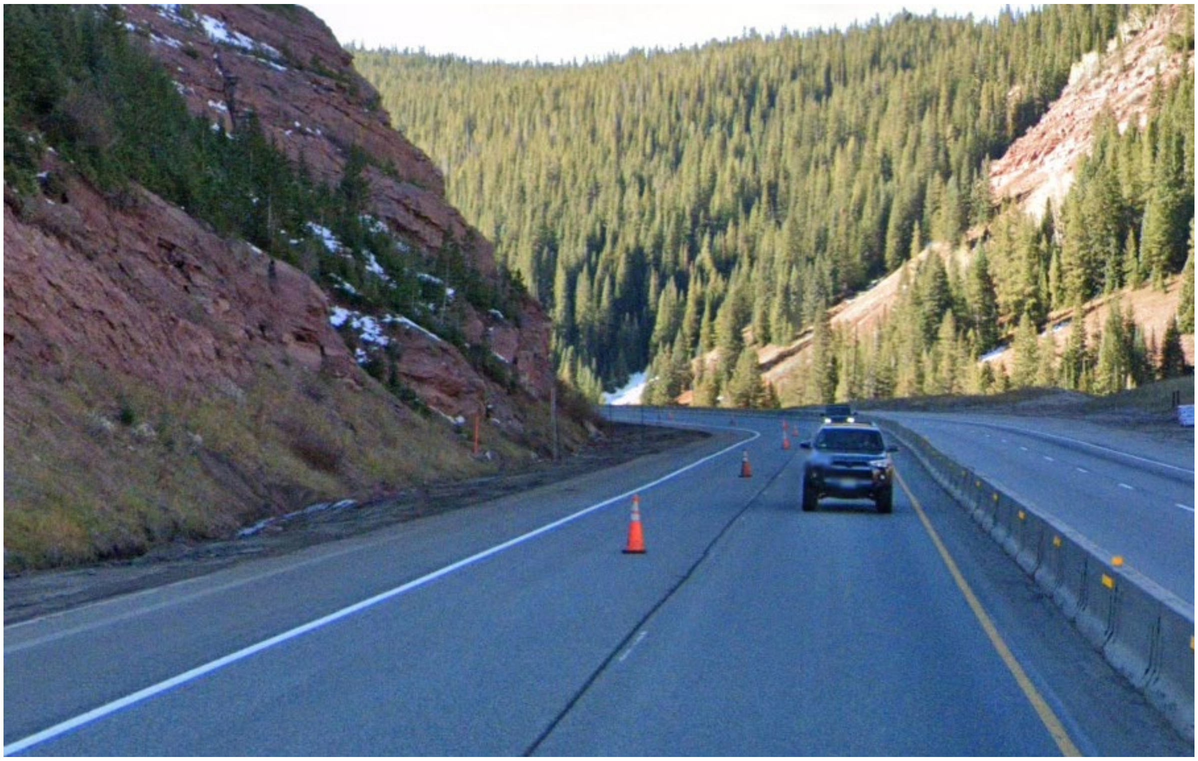

Figure 4-49: WB I-70 near MP 186 (facing East), Sharp Curve on Grade, Oct. 2023

There were, however, 5 recorded uses of the truck escape ramps over the 10-year period we assessed. This included one use of the Upper escape ramp (near MP 185.72) and 4 uses of the Lower escape ramp (near MP 182.36). There were also 2 cases in which an escape ramp might have been used but was not, and 1 case in which there is no narrative description of the crash, but it is suspected the Lower escape ramp might have been used.

1. On 4/11/13 use of the Upper escape ramp was recorded when a driver lost control of the truck. The vehicle collided with a snowbank at the entrance to the ramp and hit a sign while progressing down the arrester bed. Driver inexperience was a factor. This was a PDO crash.
2. On 3/17/21 near MP 183.80 a truck suffered brake failure and continued for approximately 1,000 feet before driving off the right side of the road due to slow moving traffic in front. It continued on the right shoulder for 575 feet before overturning down an embankment. Driver inexperience was a factor. This was an Injury level crash occurring on a wet road at a curve-on-grade. There is an advance warning sign for the Lower truck escape ramp near MP 183.72, however, as stated in the narrative the driver was inexperienced and may not have known how best to navigate the traffic ahead to access the escape ramp a mere 1.5 miles downstream. At the same time, a review of Google Streetview imagery shows that the text on the advance warning sign near MP 183.72 appears to have become faded between June 2018 and December 2018 and is currently faded (see **Figure 4-50**, **Figure 4-51** and **Figure 4-52**). This makes it difficult for drivers to determine exactly the distance to the ramp. This crash having occurred in 2021 was in the time frame when the sign was faded. This is an incidence in which the Lower escape

ramp could have potentially been used but a combination of driver inexperience and inadequate signing may have contributed to it not having been.

Figure 4-50: WB I-70 MP 183.72 Escape Ramp Advance Warning (Bold), Jun. 2018

Figure 4-51: WB I-70 MP 183.72 Escape Ramp Advance Warning (Faded), Dec. 2018

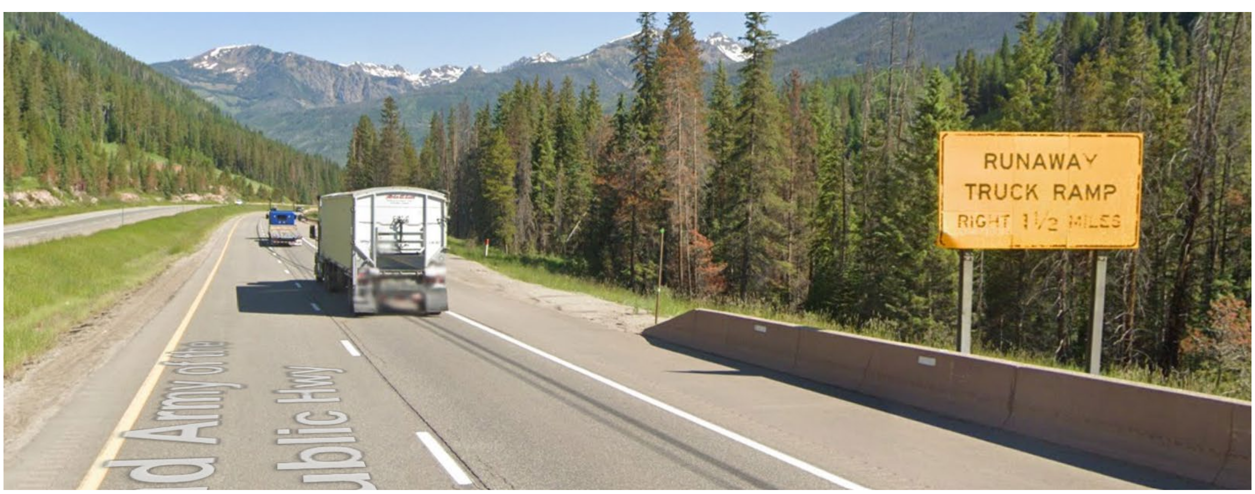

Figure 4-52: WB I-70 MP 183.72 Escape Ramp Advance Warning (Faded), Jul. 2023

3. On 5/24/19 near MP 182.30 a truck crash due to brake failure was recorded. This was an Injury level crash occurring on-grade. The truck went off the road to the right for 237 feet before colliding with a tree. The driver was unfamiliar with the area. The date of the crash puts it in the timeframe when the advance warning sign 1.5 miles in advance of the Lower ramp would have been faded. Additionally, imagery indicates that for the '1 Mile' advance warning sign near MP 183.24, it appears to be faded (**Figure 4-53**). It may be that it was very unlucky that the truck's brakes failed just at the escape ramp, not allowing the driver enough time to use the ramp. It might also have been that the brakes failed prior to the ramp and the driver attempted to use the ramp but was unsuccessful, and the crash was recorded at the location of the ramp. Inadequate signing regarding the exact distance to the ramp would not have served to assist a driver unfamiliar with the area.

Figure 4-53: WB I-70 MP 183.24 Escape Ramp Advance Warning (Faded), Sept. 2023

4. On 7/27/19 there was a recorded use of the Lower escape ramp. This was an injury level crash on grade in dry conditions. Driver inexperience was a factor. The driver initially used the right shoulder to aim for the escape ramp, then re-entered the right lane rear-ending another truck in the process, before entering the left lane, crossing back into the right lane and finally entering the escape ramp, where the truck was successfully arrested. This crash would have occurred in the period after which the 1.5-mile advance warning sign for the escape ramp was faded. Inadequate signage would not have been beneficial for the inexperienced truck driver in this situation where advance warning and guidance would have been crucial.
5. On 5/31/15 there was a recorded use of the Lower escape ramp. This was a PDO crash on grade in dry conditions. Driver inexperience was a factor. The crash record narrative states the truck traveled 167 feet along the ramp before hitting a sign on the right side

prior to being successfully arrested. This crash would have occurred prior to the fading of the advance warning signs.

6. On 6/6/13 there was a recorded use of the Lower escape ramp. This was a PDO crash on grade in dry conditions. The driver was unfamiliar with the area. The crash narrative states that the truck collided with a sign on the ramp on both the right and left sides, then collided with an embankment and overturned. This crash would have occurred prior to the fading of the advance warning signs.
7. On 6/23/21 there was a recorded use of the Lower escape ramp. This was a PDO crash on grade in dry conditions. Driver inexperience was a factor. The crash record narrative states that after traveling 1,000 feet along the ramp the truck exited the right side of the ramp and collided with a sign, then used the emergency side road, colliding with trees, before driving off a cliff. This is the 3rd recorded use of the Lower escape ramp where drivers were noted to have collided with signs while using the ramp and deviated in some way along or from the arrester bed. Cases like this may make truck operators hesitant to utilize escape ramps for fear of overshooting or overturning. **Figure 4-54** shows the Lower escape ramp in August of 2019. It is clear the ramp curves away to the right, out of the field of view of an approaching driver, this configuration could be off-putting for truck operators, particularly the inexperienced operator who may be less confident in their ability to successfully guide the vehicle along a curved ramp. While gravel arrester beds are intended to have the wheels of a truck sink in order to arrest the moment of the vehicle, this also creates a situation where steering becomes more difficult. While this may have more minimal effects during the use of ramp which is in a straight alignment, on a curved ramp such as this, it could cause deviations from the arrester bed, as has been seen in a several cases.

Figure 4-54: Lower Truck Escape Ramp (MP 182.36), Aug. 2019

Figure 4-55 shows that in late 2021 reconstruction and reconfiguration of the Lower escape ramp took place, perhaps due to the occasions of trucks departing the arrester beds when utilizing the ramp.

Figure 4-55: Lower Truck Escape Ramp, Reconstruction Oct. 2021

Comparison with **Figure 4-56** and **Figure 4-57** show the Lower escape ramp is now straightened so that drivers do not need to navigate a curve, and also impact attenuator barrels are present at the end of the ramp.

Figure 4-56: Lower Truck Escape Ramp, Aug. 2022

Figure 4-57: Lower Truck Escape Ramp, Aug. 2024

8. As outlined previously in the report, one of the fatal crashes on the study corridor was a truck crash. This occurred on 9/21/17 and was recorded at MP 182.46, which is generally in the vicinity of the Lower escape ramp, (approximately located at MP 182.36). The crash was recorded as occurring on a curve-on-grade. There is no crash narrative available for this crash, however the available details suggest that this may have involved an unsuccessful use of the escape ramp. The crash is recorded as "off-left" with the precipitating factors being collision with trees/shrubs and then overturning, while the crash in general is classified as "other non-collision." When looking at the location of the Lower escape ramp from June 2018, there are no trees/shrubs to the left of the highway, just a grass median. However, a closer look at the escape ramp itself shows that prior to reconstruction in 2021, if a vehicle accessed the ramp and did not round the right curve, it may have departed the ramp to the left into trees and potentially overturn (**Figure 4-58**). Additionally, the recorded speed of the truck was 75 mph, higher than the 45-mph limit for commercial vehicles through this section, and higher than the 65-mph general speed limit. It is possible this was a case of brake failure.

Figure 4-58: Trees and Shrubs to Left of Curved Lower Escape Ramp, Jun. 2018

Considering the above history of uses of the Upper and Lower escape ramps, it is clear that the Lower ramp has many more recorded uses than the Upper ramp. Also, the presence of snowbanks may be off-putting for truck operators who may necessitate use of the truck escape ramps in the winter or spring months, due to the fear of overturning. An alternative approach to winter ploughing and maintenance might be considered by CDOT. It also appears that the right curve on the Lower escape ramp which may have been off-putting for truck operators and possibly led to difficult navigation, collisions with signs and departure from the arrester bed, has been addressed in recent years with ramp reconfiguration.

It is difficult to make a judgement on the performance of the Upper ramp with only recorded use, however that use was successful. Regarding the Lower escape ramp, there were two recorded instances of brake failure in which drivers failed to utilize the escape ramp. Driver inexperience was a factor, but so too may have been inadequate advance warning and informational signage due to fading. Of the 4 confirmed uses and 1 suspected use of the Lower escape ramp, 2 of the 5 were successful uses of the ramp, while in the other 3 cases the trucks hit signs and/or left the arrester bed/ramp and overturned. The reconfiguration of the Lower ramp in recent years is likely to have mitigated the shortcomings of the ramp which may have caused departure from the ramp during use, as such successful use of the ramp should be more readily achievable.

What is also obvious from the crash narratives for those cases of recorded ramp use, is that driver inexperience and drivers being unfamiliar with the area were factors in all crashes. In this regard, given the mountainous environment with steep downgrade and frequent changes in curvature, it would be most beneficial to truck operators falling into either of these categories to have sufficient advance warning, signing and guidance.

The first advance warning sign for the presence of the Upper and Lower truck escape ramps is at MP 189.58 (**Figure 4-59**), indicating they are 4- and 7-miles ahead, respectively. There are also frequent gated warnings for truck operators as to the steep grades present on the corridor, as seen for example in **Figure 4-60**.

Figure 4-59: Initial Advance Warning for Truck Escape Ramps

Figure 4-60: Gated Grade Warning for Trucks, MP 189.49

In addition, there appear to be two overhead Variable Message Signs (VMS) present on the corridor, at MP 189.13 and MP 187.31, approximately. The example in **Figure 4-61** appears to warn of a lane closure ahead.

Figure 4-61: VMS Sign MP 187.31, Aug. 2023

Imagery indicates that the advance warning sign for the Upper ramp near MP 187.11 has had the mileage faded since sometime after July 2015 (**Figure 4-62**, **Figure 4-63** and **Figure 4-64**). This would not be of assistance to the inexperienced or unfamiliar truck operator.

Figure 4-62: Upper Escape Ramp Advance Warning MP 187.11 (Bold), Jul. 2015

Figure 4-63: Upper Escape Ramp Advance Warning MP 187.11 (Faded), Jun. 2018

Figure 4-64: Upper Escape Ramp Advance Warning MP 187.11 (Faded), Aug. 2023

Near MP 188.99, MP 186.98 and MP 184.29, there are gated lower truck speed limits of 45 mph. However, at MP 188.00 and MP 186.60 there are curve warning signs with an advisory 60 mph speed limit which may be conflicting and confusing especially for inexperienced or out of town truck operators (**Figure 4-65** and **Figure 4-66** for example).

Figure 4-65: Gated Truck Speed Limit, MP 186.98

Figure 4-66: Gated Curve Warning Advisory Speed MP 186.60

A second advance warning sign for the Upper ramp, indicating a 1-mile distance is located near MP 186.65. A third, indicating it is 1,500 feet downstream, is located near MP 185.95, while the entrance is located at approximately MP 185.72.

As outlined previously there are several grade warnings for trucks on the study corridor. However, imagery shows that the one located near MP 184.15, following the Upper ramp and in advance of the Lower ramp, has a supplemental "Next 4 Miles" plaque which appears to be twisted away from the oncoming driver since sometime between October 2021 and August 2022 (**Figure 4-67**, **Figure 4-68** and **Figure 4-69**).

Figure 4-67: Grade Warning with Supplementary Plaque, MP 184.15, Oct. 2021

Figure 4-68: Grade Warning with Supplementary Plaque, MP 184.15, Aug. 2022

Figure 4-69: Grade Warning with Supplementary Plaque, MP 184.15, Jul. 2023

There is an advance warning sign for the Lower escape ramp near MP 183.72 indicating it is located 1.5 miles downstream, but the text indicating the distance has been faded since sometime between June 2018 (**Figure 4-50**) and December 2018 (**Figure 4-51**). There is a 1-mile advance warning near MP 183.24 and another warning near MP 182.66 indicating the ramp is 2,000 feet downstream. The Lower ramp is located at approximately MP 182.36.

The failure to utilize the runaway truck ramp in a couple of instances listed above might point to inadequacies in the advance notice given to truck operators in the westbound direction of the presence and location of the ramps. It is recommended that CDOT replace the text on the advance warning signs related to the distance to the truck escape ramps on the westbound corridor to ensure it is bold and clearly legible. Additionally, CDOT should repair the supplementary distance plaque on the grade warning sign near MP 184.15 so that it faces drivers straight on.

Furthermore, this location may benefit from a system similar to the enhanced signing, warning and guidance system which has been employed at the Wolf Creek Pass ramp. This would involve enhancement of existing RUNAWAY TRUCK RAMP advance warning signage and other truck warning signage to include flashing beacons and blank outs, as well as the erection of advance warning diagrammatic signage depicting significant curves, upper and lower truck ramp locations and commercial vehicle speed advisory (see examples from Wolf Creek, **Figure 4-3** and **Figure 4-1**). Combined these measures would offer a guidance system providing real-time feedback to runaway trucks with guidance onto escape ramps. The system would also benefit the inexperienced and out-of-town truck operator to be better prepared for changes in roadway geometry and to adopt a more appropriate driving style, as well as to be better prepared for entry onto the escape ramps if required.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the I-70 corridor surrounding the Upper and Lower Vail Pass truck escape ramps located near MP 185.72 and MP 182.36, respectively, and to provide an evaluation of the performance of the escape ramps. The analysis was focused on the westbound I-70 corridor between MP 181.30 and MP 189.60 to capture the effects of the ramps.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area.

Westbound

Westbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-IV for the corridor in terms of both total crashes and crash severity. This represents high potential for crash reduction.

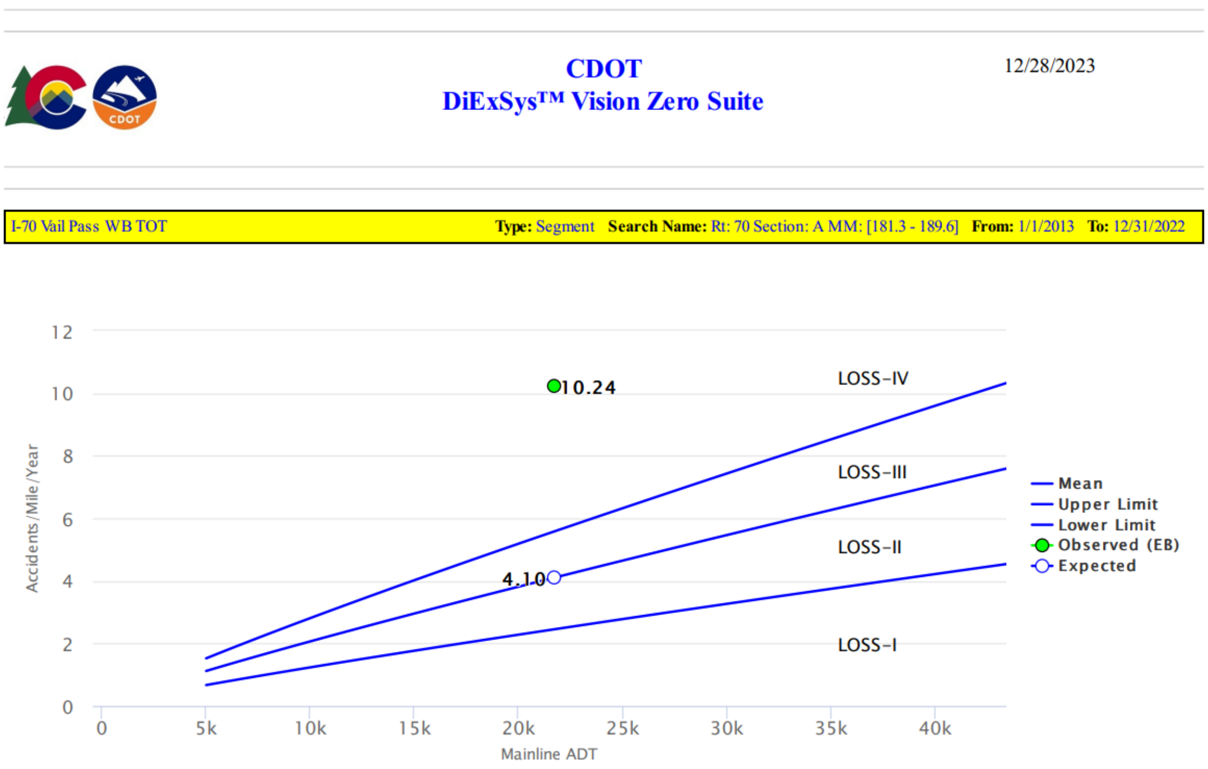

Figure 4-70: SPF Total Crashes I-70 Westbound

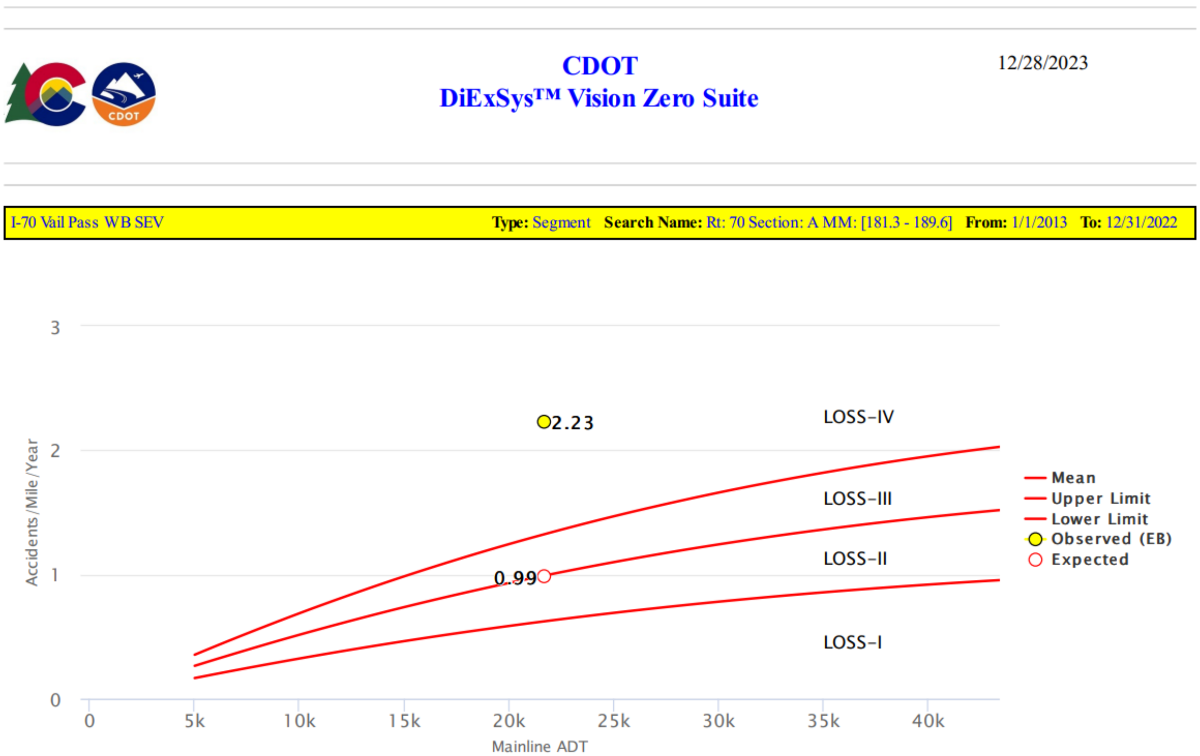

Figure 4-71: SPF INJ+FAT Crashes I-70 Westbound

Most patterns identified on the westbound corridor were substantially correlated with adverse winter weather and road conditions, which seem to compound challenges already posed by difficult mountainous roadway geometrics. There was also some correlation with driver familiarity with the area and driver inexperience. Crash patterns typically representative of run-off-the-road crashes were a pattern, as were sideswipe same direction crashes. There is an apparent overlap between all crash patterns and crashes in adverse winter weather and road conditions.

A summary of general recommendations can be made as follows:

- Install SLIPPERY CONDITIONS (W8-5) signs with supplementary "ICE" plaques (W8-5aP) along the westbound corridor, and
- Implement a weather-based VSL system along the westbound corridor including VMS signs to display information regarding road conditions and crashes ahead, as well as dual VSL speed limit displays.

Truck crashes, including severe crashes, were found to be more dominant in the section preceding MP 186 westbound, this is likely due to a more severe curve in advance of the Upper escape ramp rather than the Lower ramp. Also, truck crashes were far more likely to occur in adverse winter conditions than in the summer months, therefore were more likely to be due to loss of control on icy or snowy roads rather than due to brake failure for example.

In terms of the performance of the truck escape ramps, there were 5 confirmed uses of the ramps, (1 Upper and 4 Lower) on the westbound corridor in the 10-year study period, with 2 instances in which the Lower ramp could have been utilized but due to driver inexperience or inadequate advance warning, was not used. There is also 1 suspected instance of ramp use involving a fatality. Analysis of crash history narratives indicates that the Lower ramp was used much more than the Upper ramp, but prior to reconfiguration to straighten it out in late 2021, there were a number of recorded instances of trucks hitting signs or embankments, deviating from or leaving the arrester bed or overturning.

The current ramp warnings may have diminished efficacy due to fading of the text which displays their distance ahead.

A summary of recommendations related to commercial vehicle crashes can be made as follows:

- Repair/refresh/replace faded text on advance runaway truck ramp warning signs at MP 187.11, MP 183.72 and MP 183.24,
- Repair supplementary distance ahead plaque on right side steep grade warning sign for trucks near MP 184.15 so that it faces oncoming traffic,
- Issues related to departures/deviations from the Lower escape ramp arrester bed appear to have been addressed by a recent project in late 2021 to straighten the ramp, as such there are no material recommendations at this time, but CDOT should monitor uses of the ramp to ensure they are successful and trucks remain on the arrester bed without striking signs,
- Implement enhanced runaway truck signing, warning and guidance system to include blank-outs and flashing beacons on advance warning signs, as well as vehicle detection and guidance, overhead diagrammatic warning signs with pertinent locational information. Sufficient solar paneling and battery supply to be provided.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the westbound direction. Crash distribution is predominantly in the westbound direction, the direction of the escape ramp, with 68.5% of crashes occurring in that direction. It is in the westbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 5 – Upper and Lower Straight Creek Pass: I-70 Westbound, MP 213.00-207.70

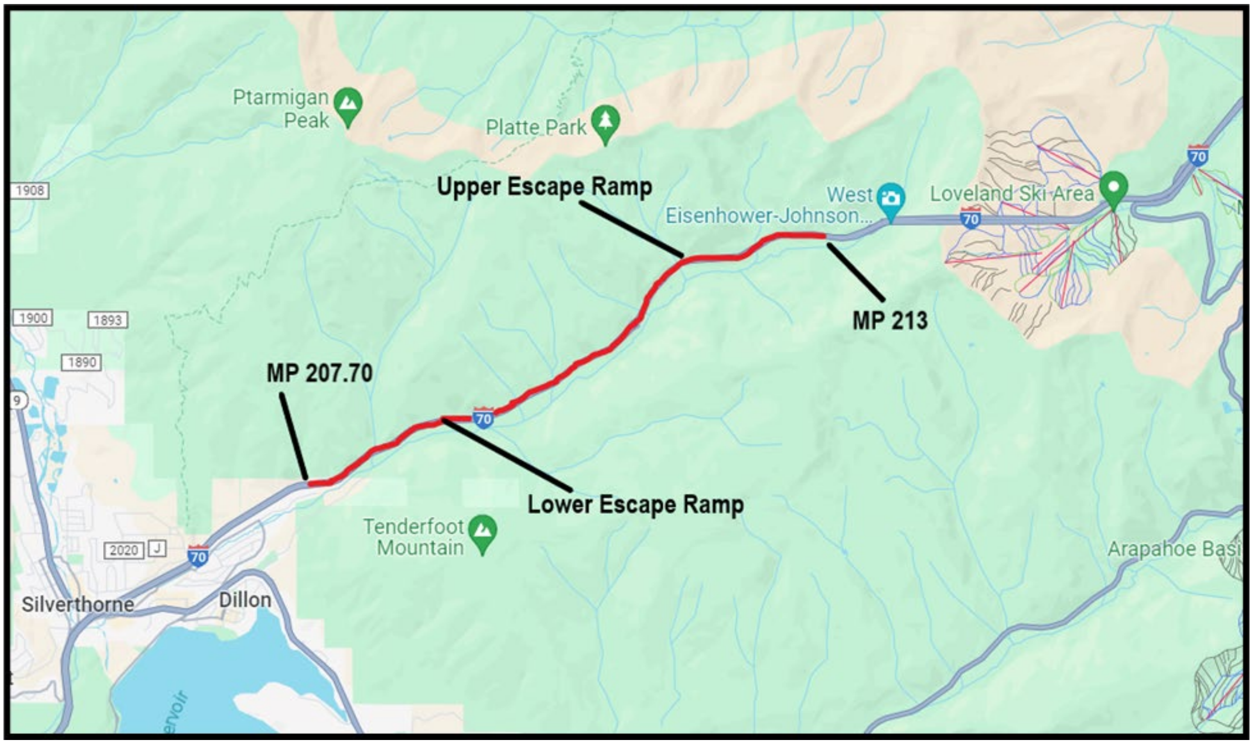

Figure 4-72: Upper and Lower Straight Creek Pass Study Limits

Site Location

The Upper and Lower Straight Creek Pass truck escape ramps are located on I-70 near mile point 211.68 and mile point 208.74 westbound, respectively. To capture a zone of influence, this study considers the corridor between MP 213.00 near to where the initial advance warning signs for the escape ramps and a lower commercial vehicle speed limit of 35 mph is seen, and MP 207.70, approximately 1 mile beyond the lower escape ramp. The included distance is approximately 5.30 miles.

Site Conditions

I-70 is classified as a rural interstate on mountainous terrain for most of the study corridor, except between MP 208.27 and MP 207.70, where it is classified as part of the urban Silverthorne-Frisco environment. I-70 is a 6-lane freeway with three 12’ lanes in each direction, and either a concrete barrier or a guardrail dividing eastbound and westbound traffic. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 37,000 and the percentage of truck traffic is 11%.

The speed limit eastbound and westbound is 60 mph. There is a lower posted speed limit of 35 mph westbound (the direction of our primary focus), for heavier vehicles at MP 212.98 and MP 207.73.

Outside shoulder width along the study segment varies from 6 ft at MP 207.71, for example, to 22 ft at MP 211.42, for example. There is no information for the inside secondary shoulder width. The corridor is characterized by a downgrade and changes in horizontal curvature. **Figure 4-73** below shows a typical section of the corridor westbound.

Figure 4-73: Typical Section of I-70, Westbound, MP 209.50 July. 2023

Westbound Commercial Vehicle Crashes

There were 84 recorded commercial vehicle crashes on westbound I-70 between MP 213.00 and MP 207.70 in the 10-year study period. This included 63 Property Damage Only crashes, 21 Injury level crashes, with 42 people injured, and no fatal crashes.

Figure 4-74 shows the distribution of crash types for truck involved crashes. When compared to the same distribution for all westbound crashes, truck involved crashes are also dominated by Fixed Object crashes, with Sideswipe same direction crashes accounting for the third most common crash type amongst trucks. However, a notable difference is that the second most frequent crash type for trucks is recorded as “Other Non-Collision” crashes at 21.4%. An examination of crash records and narratives showed that “other non-collision” crashes tended to be synonymous with truck-involved crashes where the vehicle lost control on adverse winter roads or jackknifed, colliding with its own trailer or departing the roadway colliding with a snow embankment.

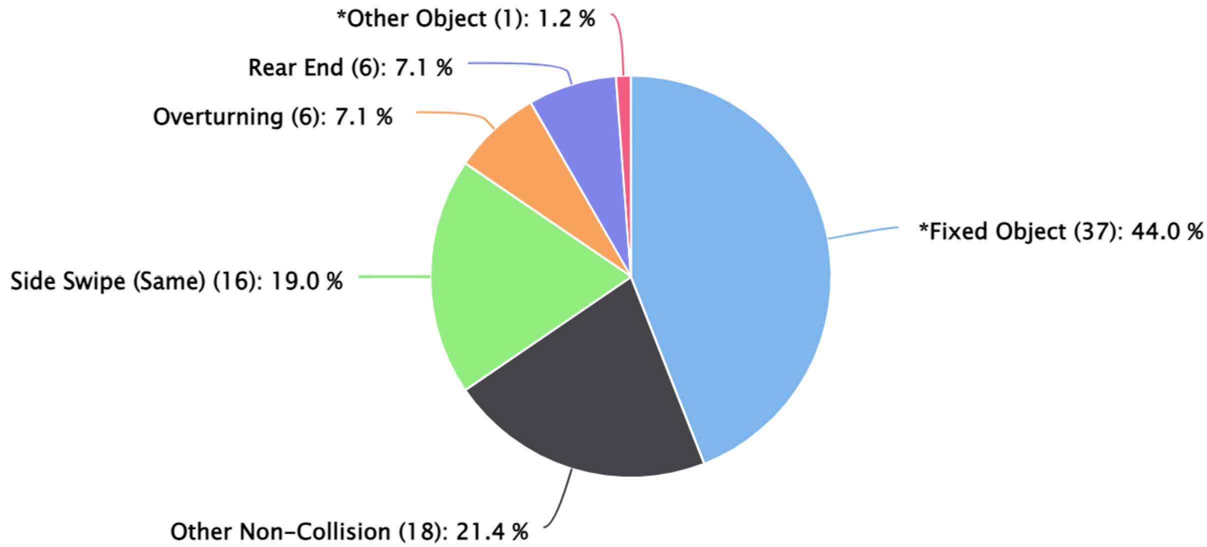

Figure 4-74: Crash Type Distribution for Commercial Vehicle Crashes

Regarding Sideswipe same direction crashes, these were mostly seen to occur in adverse winter road conditions (11 of 16). A review of data shows that 4 cases involved drivers changing lanes. However, a stronger trend was detected when narratives were consulted, with 6 incidents involving the sliding, rotating, or jackknifing of the trailer due to icy/adverse road conditions, and subsequent collision with the side of another vehicle. **Figure 4-75** shows that there is a slight clustering of Sideswipe same direction crashes near MP 212. Imagery indicates that this location is in the vicinity of a sharp curve-on-grade. Adverse road conditions of snow/icy might cause commercial vehicle trailers to slide as they navigate the bend (**Figure 4-76**). As was recommended as part of Pedestrian section in the full version of the report, CDOT is advised to erect gated Slippery Conditions warning signs (*MUTCD W8-5*) with supplementary "ICE" plaques (*MUTCD W8-5aP*) in advance of MP 212.

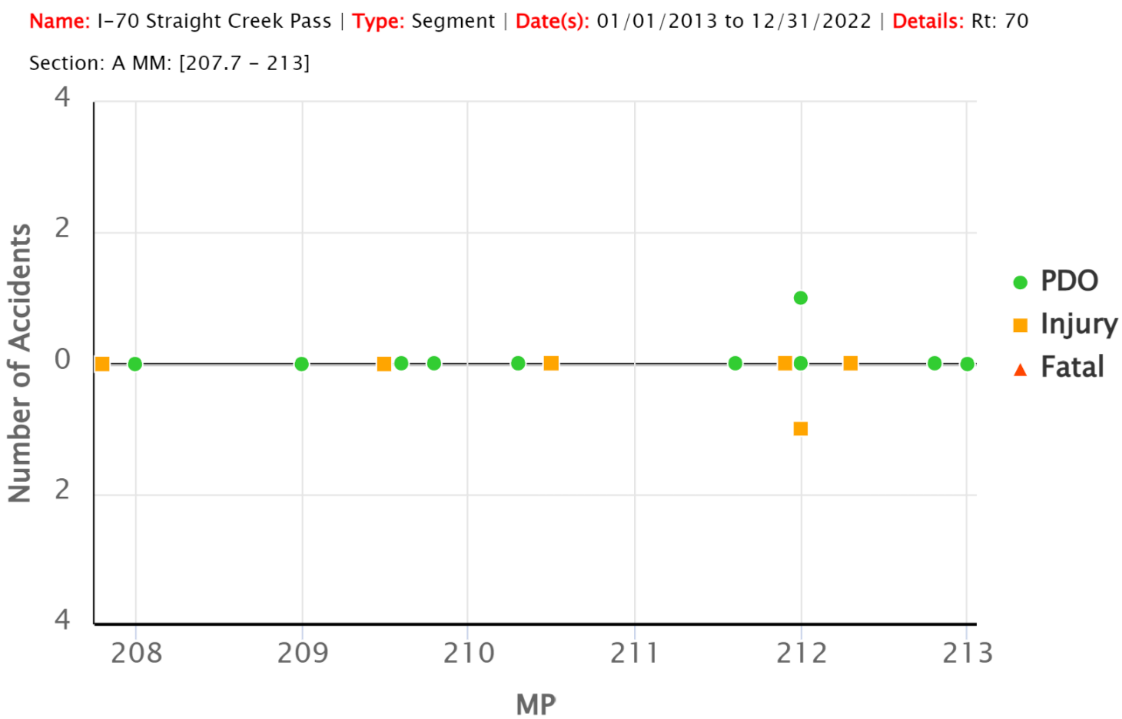

Figure 4-75: Trucks Sideswipe Crashes, Straight Line Diagram

Figure 4-76: Sharp Curve near I-70 WB MP 212

At least 50% of all truck crashes occurred in adverse winter road conditions (**Figure 4-77**), indicating that adverse weather and road conditions are sizeable contributory factors to truck crashes on the corridor. This is further supported by **Figure 4-78**, showing truck crashes were more likely to be recorded in the winter and spring months when adverse weather can be expected, rather than in the summer months when crashes might be due to brake failure or overheating, for example. With steep downgrades and frequent changes in curvature, adverse winter road conditions can exacerbate these already challenging driving conditions for truck operators.

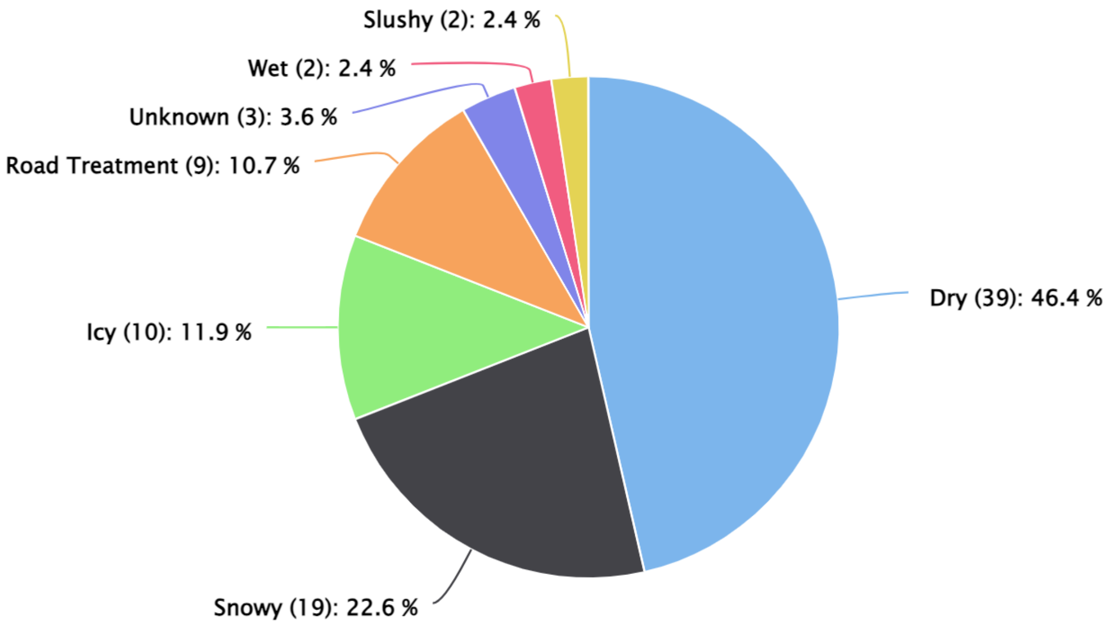

Figure 4-77: Commercial Vehicle Crashes, Road Conditions

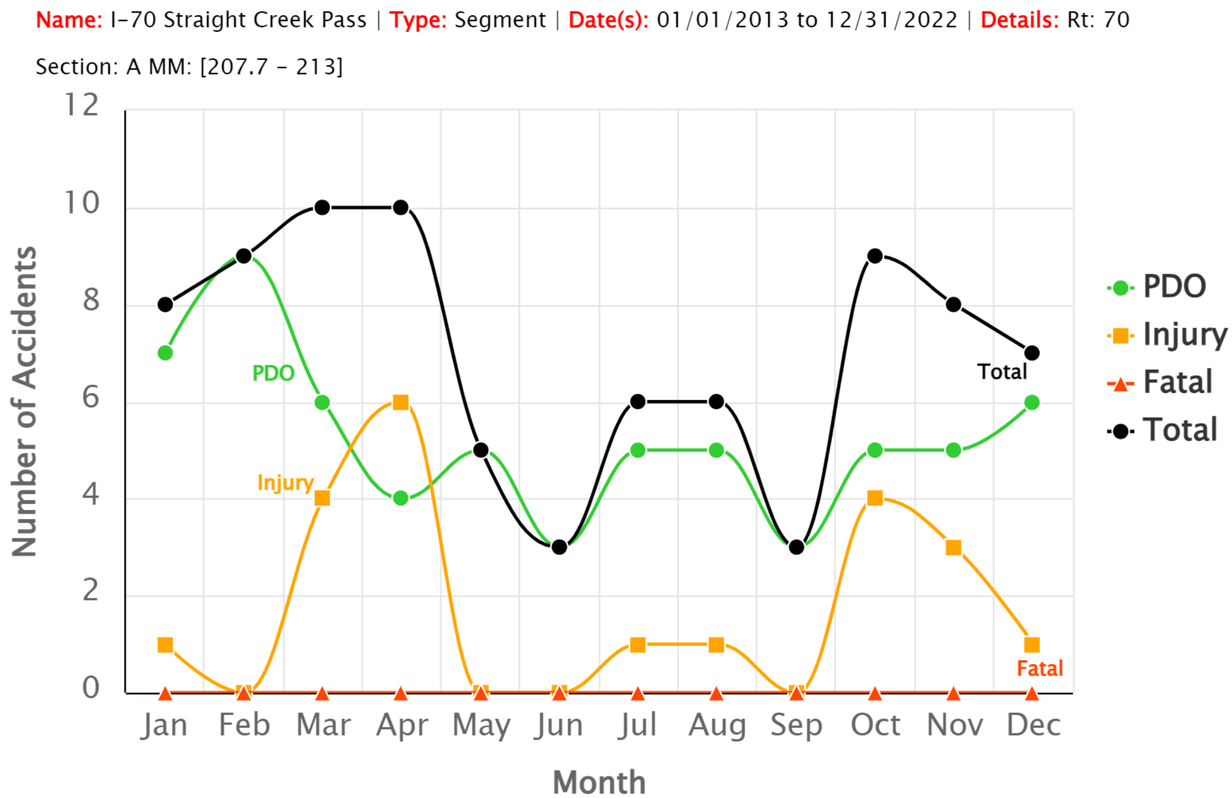

Figure 4-78: Commercial Vehicle Crashes, Month of Year

Figure *4-79* shows the location of truck crashes along the study corridor. The diagram indicates that, as per other patterns discussed in the full version of the report, crashes are seen to occur between MP 213 and MP 211, where more frequent and severe changes in curvature occur alongside a steep downgrade.

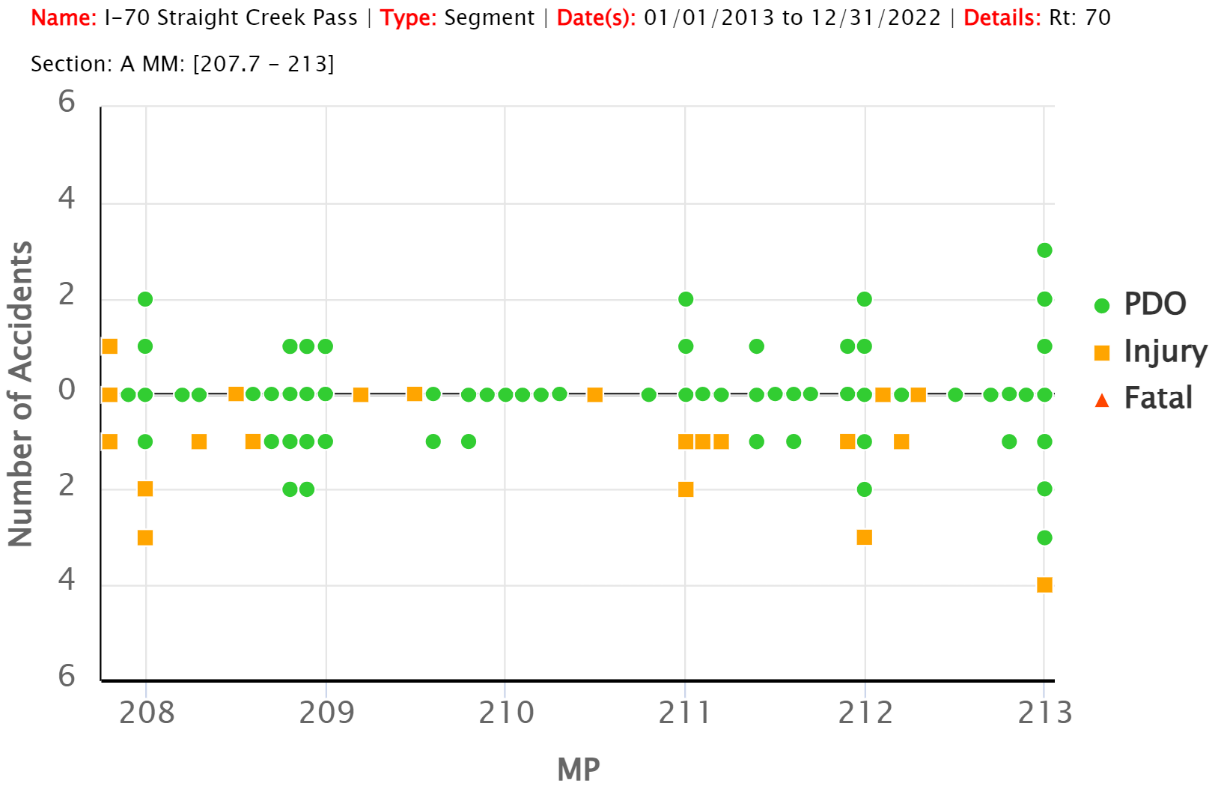

Figure 4-79: Truck Crashes, Straight Line Diagram

A review of crash record narratives for truck crashes reflects the statistics shown above in **Figure 4-77**, that is that at least 50% of crashes took place in adverse winter road conditions. Narratives were found to frequently cite a loss of control over the vehicle, as well as sliding or jackknifing in snowy or icy conditions. In fact, when a straight-line diagram is produced for commercial vehicle crashes under only adverse winter road conditions (**Figure 4-80**), it is even more pronounced that it is likely that the geometry of the corridor between MP 213 and MP 211 is contributing to crashes in adverse conditions.

Furthermore, this is also a section of the corridor which immediately follows the Eisenhower Memorial Tunnel, such that drivers may be adapting to the difference in road conditions from inside the tunnel to outside the tunnel. It is also an area adjacent to a brake check station, from which trucks can be merging. This is all in addition to being a section where the number of lanes increases from two to three after the tunnel, as such vehicle maneuvers/lane changes might be more frequent, and this can become more difficult in adverse conditions.

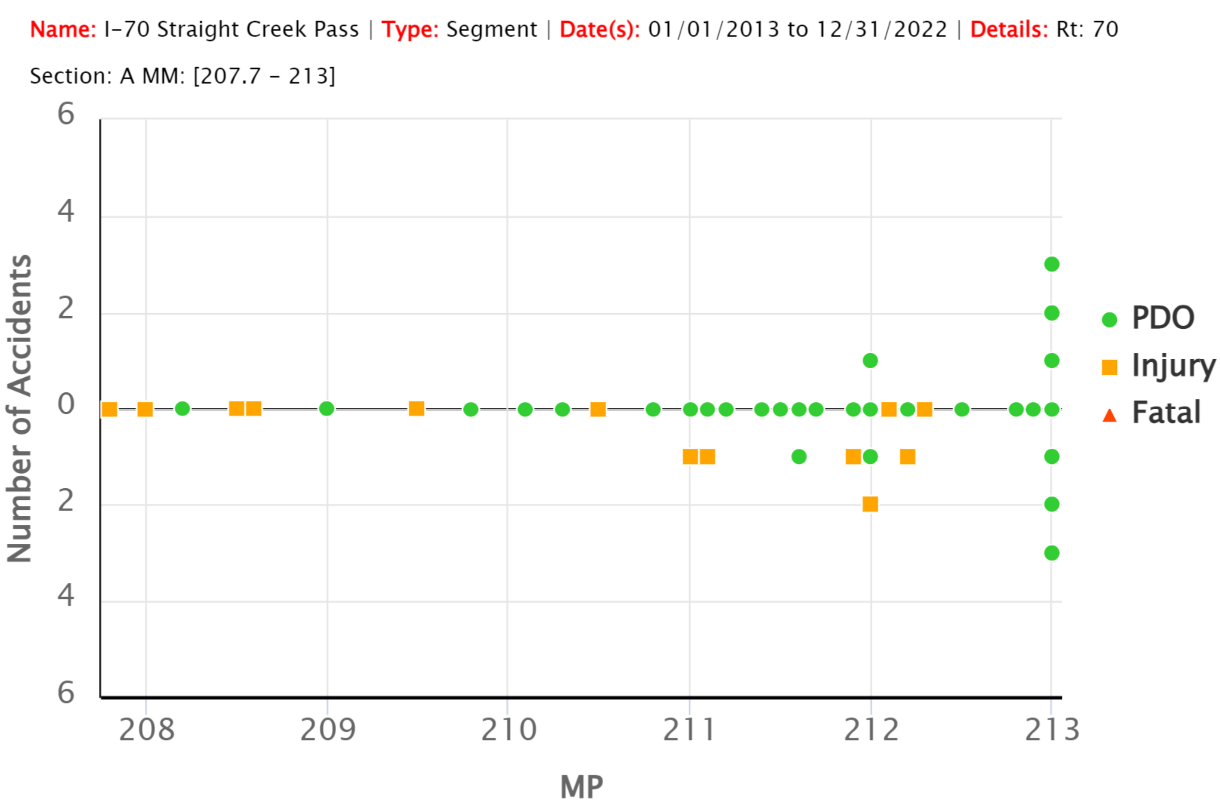

Figure 4-80: Truck Crashes in Adverse Road Conditions, Straight Line Diagram

As **Figure 4-79** showed, there is also a cluster of crashes near the Lower Straight Creek Pass escape ramp (MP 208.74 approximately). When crash history was examined for the 16 crashes recorded in the vicinity of the lower escape ramp, it was found that 9 of those crashes involved use of the escape ramp and were related generally to brake failure, apart from 1 case where the driver was asleep at the wheel.

Analysis of human contributing factors shows that 44% of truck crashes involved inexperienced drivers or drivers unfamiliar with the area (**Figure 4-81**). As stated above, the corridor is characterized steep downgrades and frequent changes to curvature which can prove challenging to navigate for drivers inexperienced in the mountainous environment or unfamiliar with the area and what to expect on the path ahead. All of this can be exacerbated by adverse road conditions making navigation with a commercial vehicle much more demanding and difficult.

In fact, in 3 out of the 9 incidents in which the lower escape ramp was used, 'Driver Inexperience' or 'Driver Unfamiliar with Area,' were cited contributory factors. There was one recorded case of the upper escape ramp being used, and in this instance driver inexperience was also cited as a contributory factor.

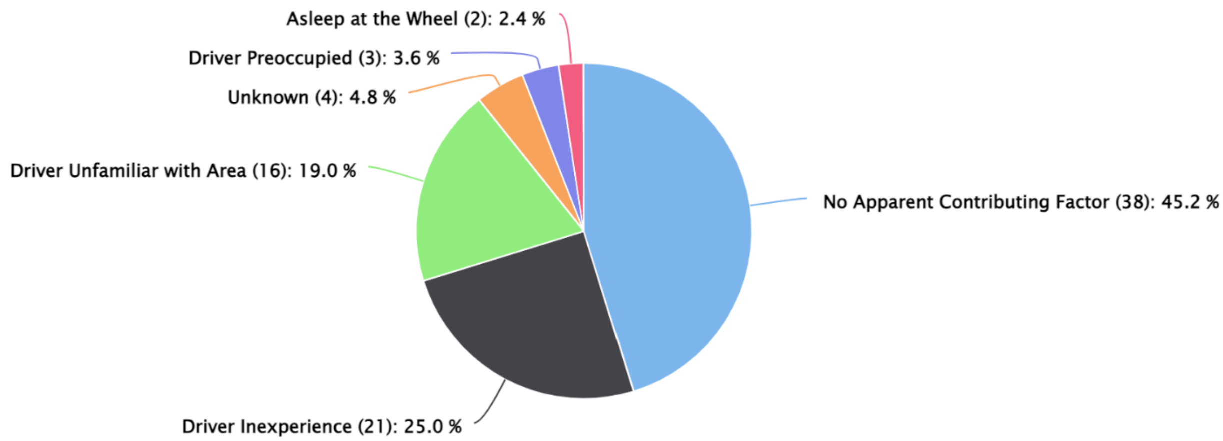

Figure 4-81: Commercial Vehicle Crashes, Human Contributing Factors

There were 10 recorded uses of truck escape ramps over the 10-year period we assessed. This included 1 use of the Upper escape ramp (near MP 211.68) and 9 uses of the Lower escape ramp (near MP 208.74). All recorded incidents were PDO crashes.

1. On 6/12/16 use of the Lower escape ramp was recorded as "other non-collision" near MP 208.60 when the truck lost brakes. The driver was recorded as asleep at the wheel. The narrative shows the truck jackknifed after entering the ramp.
2. On 8/12/16 use of the Lower escape ramp was recorded as "embankment/ditch" near MP 209.00 after the truck suffered brake failure. After entering the escape ramp the vehicle rolled backwards and jackknifed before coming to a rest. No additional factors were recorded.
3. On 9/07/16 use of the Lower escape ramp was recorded as "embankment/ditch" near MP 208.87 when a truck suffered brake failure. Upon entering the ramp, the truck jackknifed and collided with the embankment. Driver inexperience was cited.
4. On 9/19/16 use of the Lower escape ramp was recorded as "concrete barrier" near MP 208.97 when a truck suffered brake failure. After entering the ramp, the truck rolled backwards and jackknifed before coming to a rest. The crash occurred under dark conditions. No other factors were cited.
5. On 1/20/19 use of the Lower escape ramp was recorded as "embankment/ditch" near MP 208.80 when the truck lost brakes. After entering the ramp, the truck collided with a snow embankment and came to a rest. There were no additional factors cited.
6. On 7/12/20 use of the Lower escape ramp was recorded as "other non-collision" near MP 208.00 when the vehicle underwent engine break failure. The truck rolled backwards and jackknifed on the escape ramp, before coming to a rest on the concrete barrier. There were no other factors cited.
7. On 8/13/20 use of the Lower escape ramp was recorded as "concrete barrier" near MP 208.80. No reason was given in the crash records or narrative as to the precipitating factor in the need to use the ramp. The narrative does state that the truck collided with the concrete barrier on the way up the ramp before coming to a rest on top of the barrier. No other factors were cited.
8. On 9/7/20 use of the Lower ramp was recorded as "embankment/ditch" near MP 208.70. No reason is given in the crash records or narrative as to the precipitating factor in the

need to use the ramp. The narrative does include that the truck rolled backwards and jackknifed on the ramp before coming to a rest. Driver inexperience was a cited factor.

9. On 6/20/22 use of the Lower ramp was recorded as "other non-collision" near MP 208.80. The incident occurred due to a brake failure. After entering the ramp, the truck slid backwards and jackknifed before coming to a rest. This occurred in dark conditions. The driver was noted as being unfamiliar with the area.
10. On 2/21/22 use of the Upper ramp was recorded as "embankment/ditch" near MP 211.90. No reason is given in the crash records or narrative as to the precipitating factor in the need to use the ramp. The narrative does include that the truck hit a snowbank before coming to a rest. Driver inexperience was a cited factor.

The records show that regular use of the Lower escape ramp has been made over the 10-year study period, while conversely, the Upper ramp has only 1 recorded use. It is also clear that driver inexperience or unfamiliarity with the area contributed to some degree to 40% of cases. What is also clear from the records is that in 7 of 10 cases, the truck rolled back or jackknifed in the ramp. On the one hand, all incidents were PDO crashes, indicating overall successful ramp performance. However, instances of jackknifing and also instances where the trucks mounted the concrete barriers, make truck operators less confident about using escape ramps, as these circumstances can be more likely to result in injuries. Another trend that is visible is that most uses of the ramp occurred in warmer months and were due to brake failure, which is what we would expect.

The reason for the disparity in the number of recorded uses between the Upper and Lower ramp is not immediately clear, however it might be speculated that the Upper ramp occurs just over 2 miles into a roughly 7-mile stretch of steep downgrades and changes in curvature. More frequent use of the Lower ramp may thus be due to additional time spent on the downgrade and therefore more opportunity for brake failure to occur.

It is notable that the Lower ramp is at a particularly steep angle and must be intimidating for truck operators who might find themselves needing to use it (**Figure 4-82**). Furthermore, for the inexperienced operator, the alignment of the ramp presents more of a challenge and potential to incorrectly manage the entry, which could contribute to instances of jackknifing.

In **Figure 4-82** recent Streetview imagery shows the sign at the entrance to the ramp has been damaged and faces away from oncoming drivers. CDOT is advised to repair the sign if this has not already been completed.

Figure 4-82: Lower Escape Ramp Entrance, Nov. 2023

Otherwise, advance warning signage for escape ramps and general warnings for truck operators through the corridor appears to be in good condition, as seen on Streetview imagery.

The initial warning sign for trucks is seen near MP 213.35 with a low gear recommendation for 6 miles (**Figure 4-83**). Reminders are provided again at MP 211.42 for the following 4 miles, and near MP 210.32 for the following 3 miles. Additionally, there is a reduced truck speed limit of 35 mph which is posted with gated signs near MP 212.98 and MP 210.82, before coming to an end near MP 207.73 (see example **Figure 4-84**).

Figure 4-83: Initial Low Gear Warning Sign, I-70 WB MP 213.35, Aug. 2024

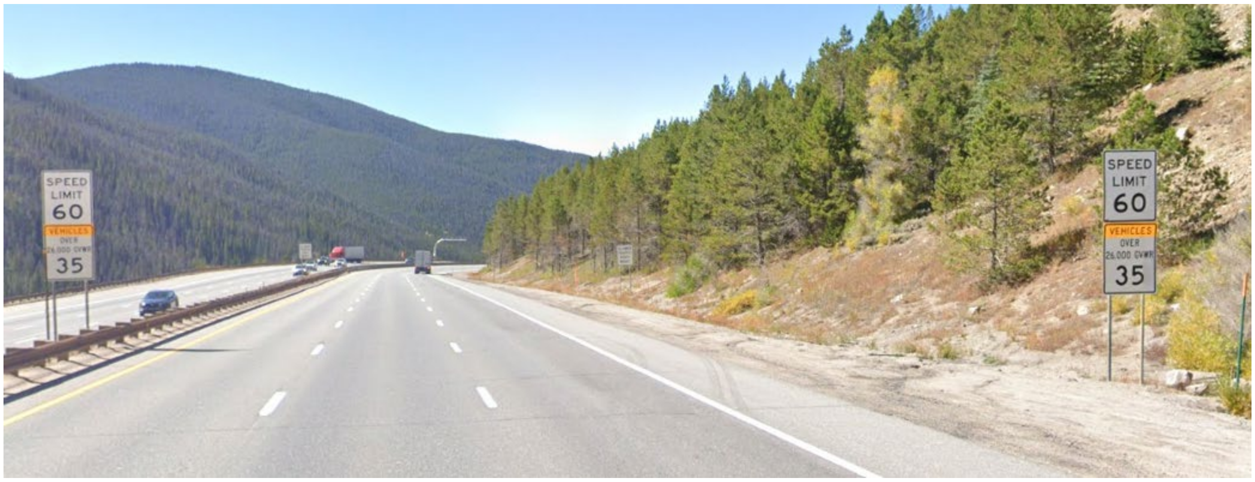

Figure 4-84: Lower Truck Speed Limit, MP 210.82

These signs are also supplemented with gated steep grades warning signs for trucks (MUTCD W7-1) near MP 211.57 and MP 208.65. However, Streetview imagery indicates that one of the signs at the former location is twisted away from oncoming traffic since sometime following 12/2018 and at least August 2023 (see **Figure 4-85** through **Figure 4-87**). If not already addressed, CDOT is advised to repair this sign so that it faces oncoming westbound traffic.

Figure 4-85: W7-1 Signs, WB I-70 MP 211.57, Dec. 2018

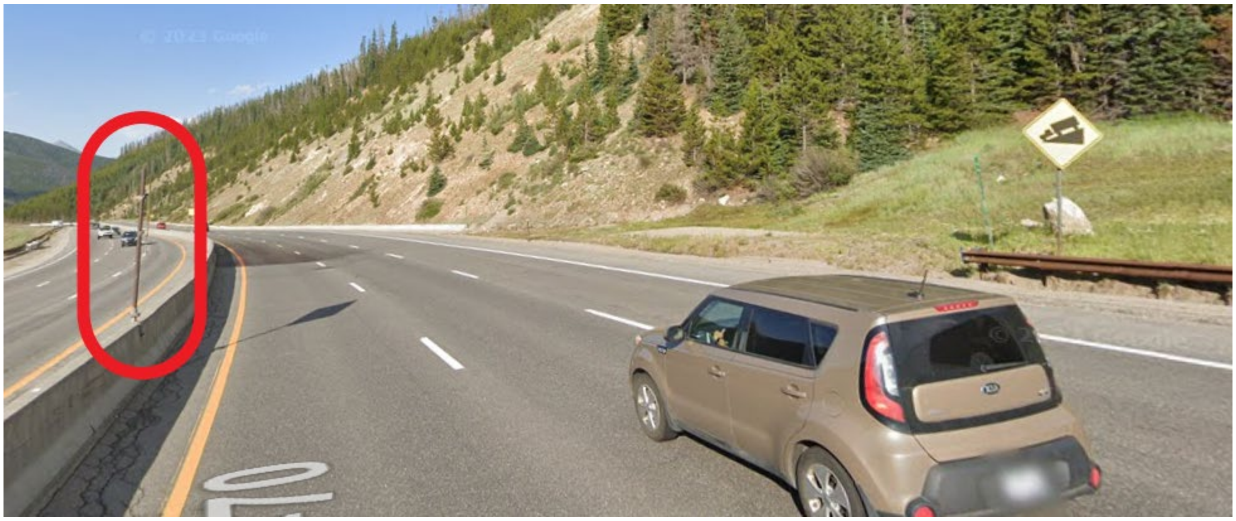

Figure 4-86: W7-1 Sign Twisted, WB I-70 MP 211.57, Aug. 2023 (facing West)

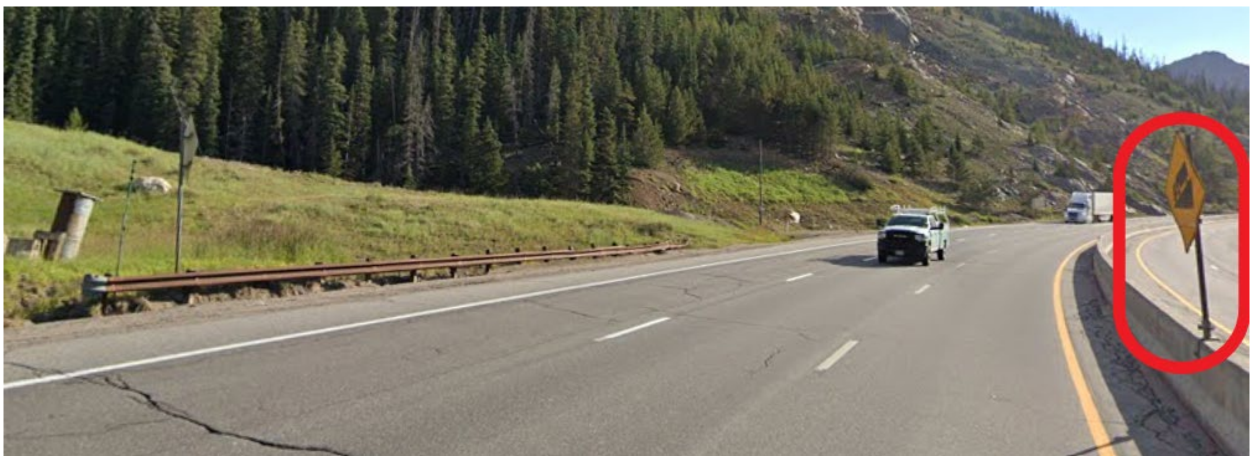

Figure 4-87: W7-1 Sign Twisted, WB I-70 MP 211.57, Aug. 2023 (facing East)

The initial warning signs for the truck escape ramps come near MP 212.94 (**Figure 4-88**). There is also a supplementary ½ mile warning for the Upper ramp near MP 212.21 (**Figure 4-89**).

Figure 4-88: Initial Escape Ramp Warnings, I-70 WB MP 212.94

Figure 4-89: Upper Escape Ramp Advance Warning, I-70 WB MP 212.21

The Lower escape ramp has more additional advance warning signs that the Upper, with one near MP 209.73 and one near MP 209.14 (**Figure 4-90** and **Figure 4-91**).

Figure 4-90: Lower Escape Ramp, 1-mile Advance Warning, I-70 WB MP 209.73

Figure 4-91: Lower Escape Ramp, Final Warning, I-70 WB MP 209.14

A comparison of both ramps by way of available imagery indicates that the arrester bed of the Upper ramp is not as long as that of the Lower ramp. In addition, the bed of the Upper ramp appears to be encroached upon by trees, while the Lower bed appears to be clear (see **Figure 4-92** and **Figure 4-93**). This might possibly make the Upper ramp less inviting to a truck operator in need, posing the possibility of an overshoot or collision with trees.

Figure 4-92: Upper Escape Ramp, Aug. 2022

Figure 4-93: Lower Escape Ramp, Aug. 2022

It is difficult to make a judgement on the performance of the Upper ramp, with only recorded use in the study period, and no detailed reason given for the need precipitating the use of the ramp. Furthermore, the incident occurred in snowy weather in February, with the truck hitting a snowbank on entry which brought it to a stop. It is possible the inexperienced driver lost control in icy conditions and chose to use the escape ramp rather than collide with other vehicles. It appears that use of the ramp was successful with the truck successfully arrested and only property damage resulting.

Regarding the Lower escape ramp, with 9 uses in 10 years all of which resulted in PDO crashes, it might be concluded that the ramp has been successful. The year 2016 saw 4 recorded uses between June and September, with 3 recorded uses, one each month, in 2020 between July and September. While trucks were all successfully arrested, there is some concern over the clear tendency of trucks to roll back and/or jackknife on the ramp, and while in these recorded cases injuries were not suffered, such a scenario presents greater opportunity for injury. It would be helpful to determine the reason behind the jackknifing i.e. operator inexperience or error, or arrester bed design.

As a more general observation it is interesting that the Lower ramp saw significantly more use than the Upper ramp, and more so due to brake failure. With the available data it is difficult to determine exactly why this is but as has been speculated above, it might be that the ramp is longer and less cluttered than the Upper ramp and that more time has passed since trucks entered the stretch of steep downgrade following the Eisenhower tunnel, such that brake failure might be more likely as this point.

As has been outlined previously, 40% of all recorded uses of the escape ramps involved inexperienced drivers or drivers unfamiliar with the area. Furthermore, it is clear most uses of the escape ramps were generated due to brake failure i.e. runaway trucks. In this regard, given the mountainous environment with steep downgrade and frequent changes in curvature, a system similar to that which is in operation on Wolf Creek Pass with diagrammatic warning signs coupled with a runaway truck detection and warning system, might benefit less experienced truck operators on the corridor.

This would involve enhancement of existing RUNAWAY TRUCK RAMP advance warning signage and other truck warning signage to include flashing beacons and blank outs, as well as diagrammatic signage depicting significant curves, upper and lower truck ramp locations and commercial vehicle speed advisory (see examples from Wolf Creek, **Figure 4-3** and **Figure 4-1**). Combined these measures would offer a guidance system providing real-time feedback to runaway trucks. The system would also benefit the inexperienced and out-of-town truck operator to be better prepared for changes in roadway geometry and to adopt a more appropriate driving style, as well as to be better prepared for entry onto the escape ramps if required.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the I-70 corridor surrounding the Upper and Lower Straight Creek Pass truck escape ramps located near MP 211.68 and MP 208.74, respectively, and to provide an evaluation of the performance of the escape ramps. The analysis was focused on the westbound I-70 corridor between MP 213.00 and MP 207.70 to capture the effects of the ramps.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area.

Westbound

Westbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-IV for the corridor in terms of both total crashes and crash severity. This represents high potential for crash reduction.

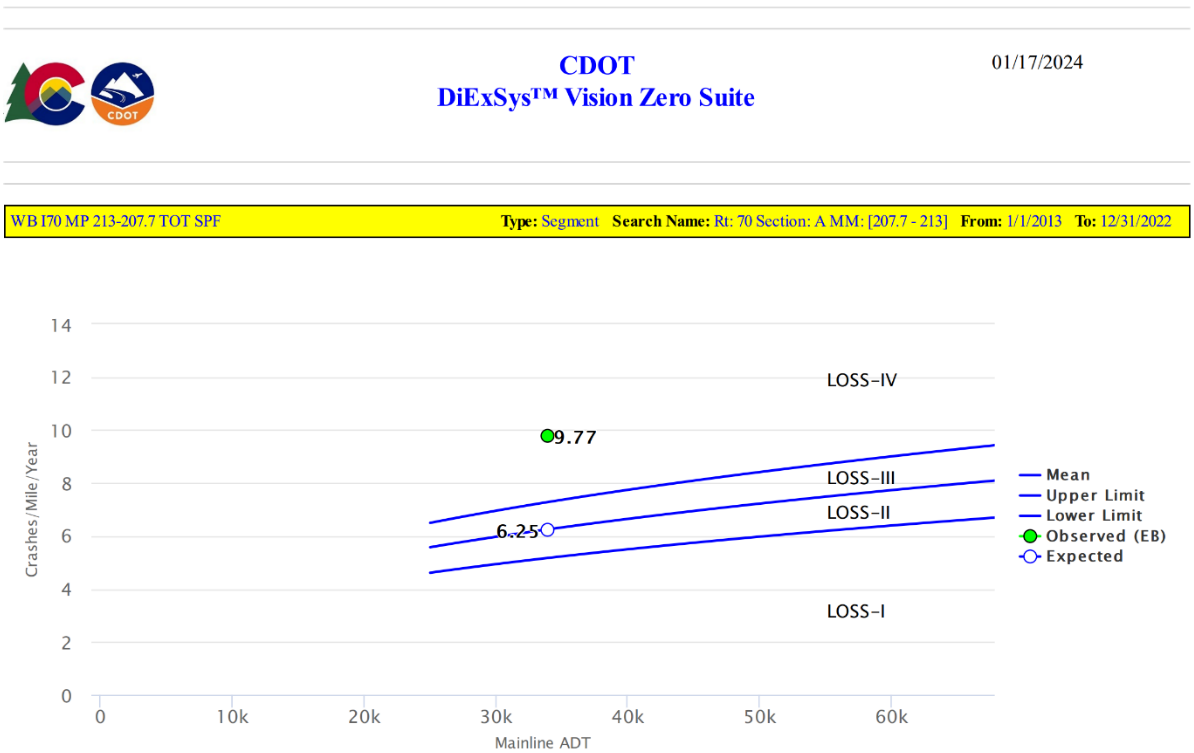

Figure 4-94: SPF Total Crashes I-70 Westbound

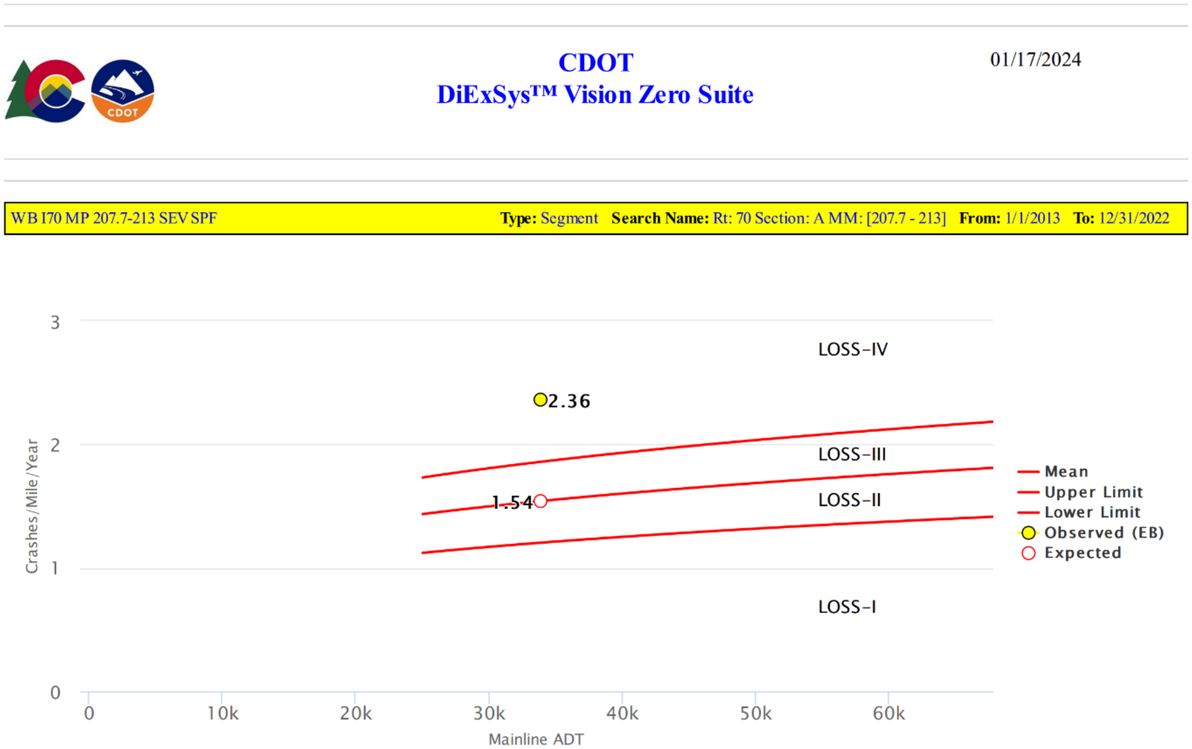

Figure 4-95: SPF INJ+FAT Crashes I-70 Westbound

Most patterns identified on the westbound corridor were substantially correlated with adverse winter weather and road conditions, which seem to compound challenges already posed by difficult mountainous roadway geometrics. There was also some correlation with driver familiarity with the area and driver inexperience. Crash patterns typically representative of run-off-the-road crashes were a pattern. Other patterns included injury level crashes, multi-vehicle crashes, collisions with debris and boulders/rocks, other non-collisions, and pedestrian collisions. There is an apparent overlap between the aforementioned crash patterns (except collisions with debris and boulders/rocks), and crashes in adverse winter weather and road conditions.

Regarding debris collisions, all incidents were found to be due to random human error of influence and there are no recommendations at this time. Regarding collisions with pedestrians, there was a notable pattern of the incidents involving the striking of a pedestrian attending to a vehicle on the roadway edge which had been previously involved in a collision due to adverse winter weather and road conditions.

A summary of general recommendations for the corridor can be made as follows:

- Gate FALLEN ROCK warning signs (*MUTCD W8-14*) near MP 213.30 and supplement with “NEXT 2 MILES” plaques (*MUTCD W16-3aP*),
- Install gated SLIPPERY CONDITIONS warning signs (*MUTCD W8-5*) with supplementary “ICE” plaques (*MUTCD W8-5aP*), particularly in advance of MP 212 and MP 209,

- Install gated regulatory signs modified as appropriate for Colorado state laws, requiring vehicles to slow or move over for stopped vehicles (*MUTCD R16-3*), in advance of MP 211,
- Install gated curve warning signs (*MUTCD W1-2*) in advance of the curve at MP 208.74,
- Implement a VSL system on the westbound corridor with a friction and weather-based component to reduce maximum speed limits, for all vehicle types, accordingly.

Truck crashes were found to be more dominant in the section preceding MP 211 westbound, likely due to more severe changes in curvature through this section, as well as the increase from two to three lanes possibly generating additional vehicle maneuvers. Crashes were clustered near MP 208.74 (Lower escape ramp), and there were 9 recorded uses of the Lower ramp. About 50% of all truck crashes occurred in adverse winter weather and road conditions, while about 50% involved inexperienced drivers or drivers unfamiliar with the area. The pattern of "other non-collisions" crashes was synonymous with truck crashes in which the vehicles slid, jackknifed, or otherwise lost control on adverse road conditions, colliding with their trailer, a snowbank or another barrier.

There were 10 confirmed uses of the ramps, (1 Upper and 9 Lower) in the 10-year study period. Most were found to be related to brake failure. All incidents were PDO, indicating the ramps have been successful. However uses of the Lower ramp frequently involved rolling back and jackknifing, which have the potential to result in more serious incidents. It might be speculated that the more frequent use of the Lower ramp compared to the Upper could be due to the accumulating time and distance over which the possibility of brake failure is increased on these steep downgrades, but also due to the longer length of the Lower ramp and the less cluttered arrester bed.

A summary of the recommendations made in relation to commercial vehicles crashes can be made as follows:

- Install gated SLIPPERY CONDITIONS warning signs in advance of MP 212,
- Repair and/or realign the 'Runaway Truck Ramp' entrance sign to the Lower escape ramp, which appears twisted,
- Repair the left side steep grade warning sign for trucks near MP 211.57, which appears twisted,
- Implement enhanced runaway truck signing, warning and guidance system to include blank-outs and flashing beacons on advance warning signs, as well as vehicle detection and guidance, overhead diagrammatic warning signs with pertinent locational information. Sufficient solar paneling and battery supply to be provided.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the westbound direction. Crash distribution is predominantly in the westbound direction, the direction of the escape ramp, with 63.8% of crashes occurring in that direction. It is in the westbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 6 – Mount Vernon Canyon: I-70 Eastbound, MP 253.70-258.50

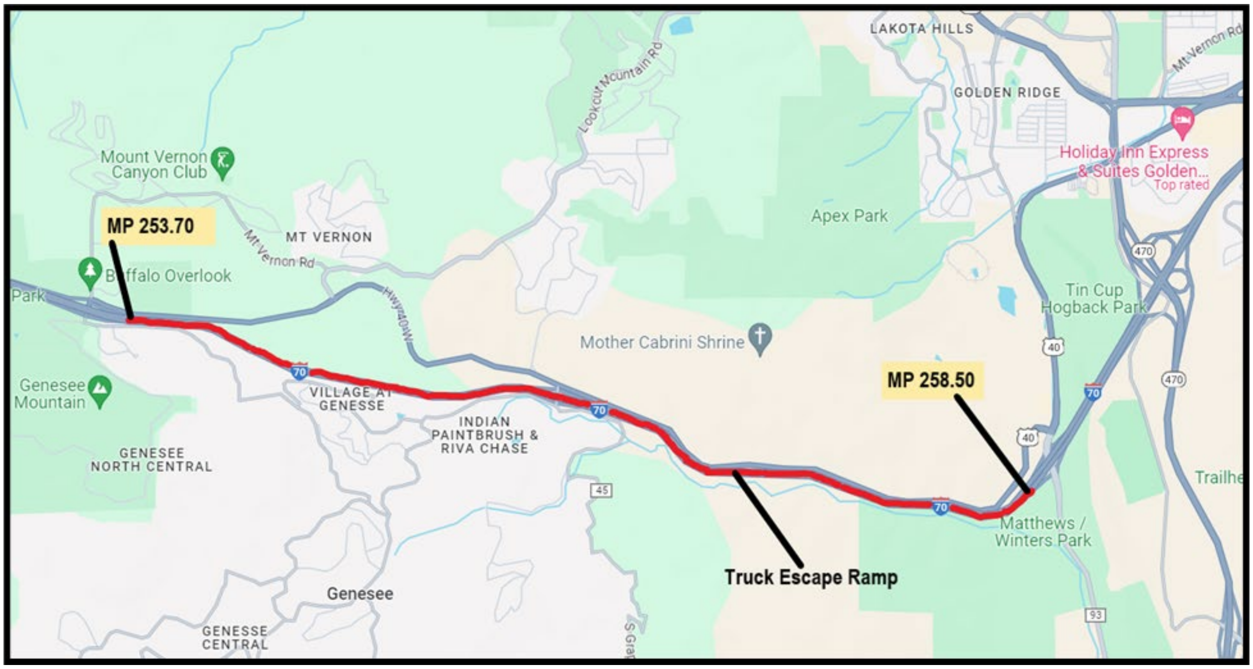

Figure 4-96: Mount Vernon Canyon Study Limits

Site Location

The Mount Vernon Canyon truck escape ramp is located on I-70 near mile point 256.93 eastbound. To capture a zone of influence, this study considers the corridor between MP 253.70, near to where the initial advance warning sign to trucks for steep grades and sharp curves is seen, and MP 258.50 1.5 miles beyond the escape ramp, where grades are considered to have returned to typical conditions. The included distance is approximately 4.80 miles.

Site Conditions

I-70 is classified as an urban interstate on mountainous terrain through the study corridor. Between MP 253.70 and MP 256.91, it is part of the urban Evergreen area, and between MP 256.91 and MP 258.50, it is part of the urban Denver-Aurora area. I-70 is a 6-lane freeway with three 12' lanes in each direction, and a guardrail with grass median of 20-30 feet divides opposing traffic, with much of the corridor being also grade separated. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 76,000 for the entire study corridor, and the percentage of truck traffic is 7.2%.

The speed limit eastbound and westbound is 65 mph. There is a lower posted speed limit of 45 mph eastbound (the direction of our primary focus), for heavier vehicles at MP 254.97, MP 256.32 and MP 257.40.

Outside shoulder width along the study segment varies from 0 ft, for example at MP 255.91, to 19 ft at MP 258.35, for example. There is no information for the inside secondary shoulder width. The corridor is characterized by a steep 6% downgrade and changes in horizontal curvature. **Figure 4-97** below shows a typical section of the corridor eastbound.

Figure 4-97: Typical Section of I-70 Eastbound, MP 256.50 Nov. 2023

Eastbound Commercial Vehicle Crashes

There were 33 recorded commercial vehicle crashes on eastbound I-70 between MP 253.70 and MP 258.50 in the 10-year study period. This included 23 Property Damage Only crashes, 10 Injury level crashes, with 15 people injured, and no fatal crashes. This crash distribution serves to echo the identified pattern of Injury level crashes on the eastbound corridor in general which was discussed in the full version of this report.

Figure 4-98 shows the distribution of crash types for truck involved crashes. When compared to the same distribution for all eastbound crashes, truck involved crashes are also dominated by Fixed Object and Rear-End crashes, but “Other Non-Collision” crashes are the third most frequent crash type when trucks are involved, at 15.2%. An examination of crash records and narratives for the 5 “other non-collision” crashes showed that crashes tended to be either roadway departure crashes due to a loss of vehicle control in snowy/icy conditions, often with the truck jackknifing, or instances of mechanical failure of some sort resulting in the truck departing the roadway, in one case the truck escape ramp was used.

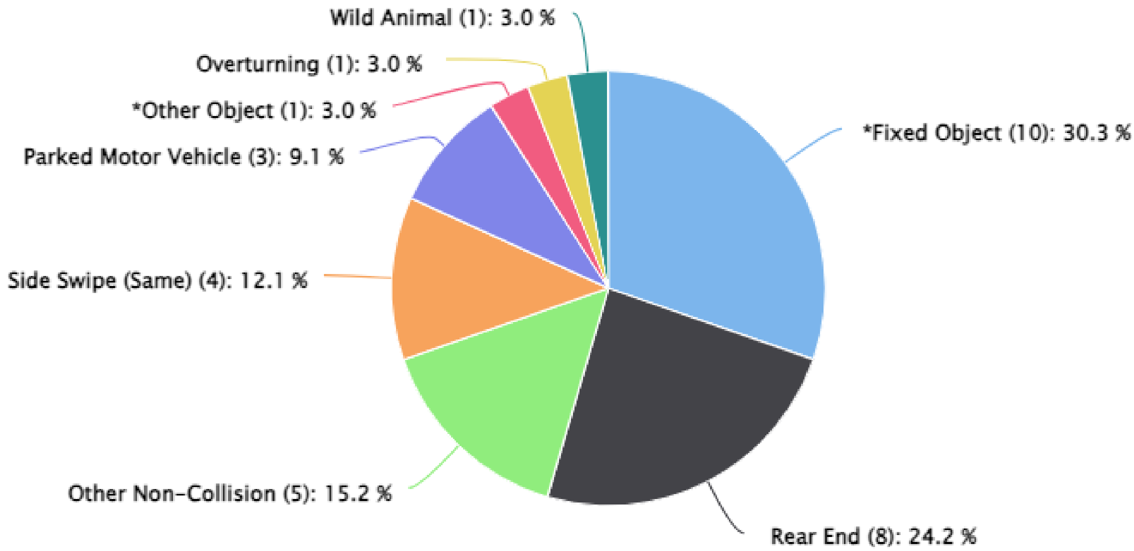

Figure 4-98: Crash Type Distribution for Commercial Vehicle Crashes

Regarding Fixed Object crashes, these were mostly collisions with Guardrail (60%), with the majority of crashes on dry roads, however, 40% were seen to occur in adverse road conditions. This echoes the identified crash pattern of crashes in adverse winter road conditions identified on the eastbound corridor for crashes involving all vehicle types. **Figure 4-99** shows the locations of Fixed Object crashes. While there is a slight cluster of crashes near MP 255.75, a review of crash records does not indicate a strong and clear pattern or trend amongst crashes near MP 255.75, nor for Fixed Object crashes at other locations. Narratives showed that there were two cases involving the use of the truck escape ramp near MP 257, 1 instance of a driver asleep at the wheel, 1 instance of being blown by wind, 1 tire blow out, 1 case of swerving to avoid stopped traffic and 3 cases of running off the road due to loss of control in snowy/icy/slushy conditions. Indeed, most truck-involved Fixed Object crashes (4 of 10) occurred in the month of February, when snowy or icy conditions can be experienced.

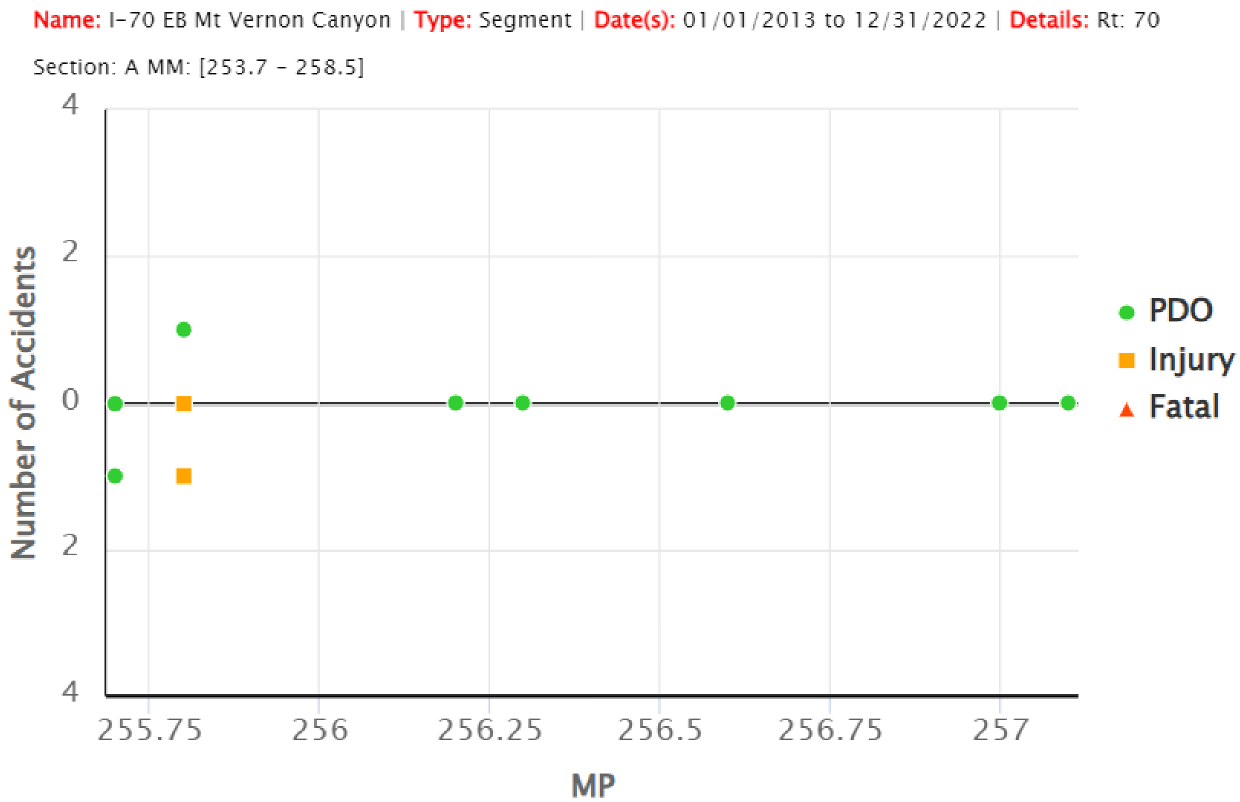

Figure 4-99: Fixed Object Truck Crashes, Straight Line Diagram

Regarding truck-involved Rear-End collisions, these echo the trend seen with rear-end collisions for all vehicles on the eastbound corridor, that is that they tend to be high-severity crashes, with 4 out of the 8 recorded crashes being at the Injury level. **Figure 4-100** shows that adverse road conditions played somewhat of a role in Rear-End collisions, being present in over 37% of cases. Adverse road conditions can make stopping more difficult on a corridor characterized by steep downgrades.

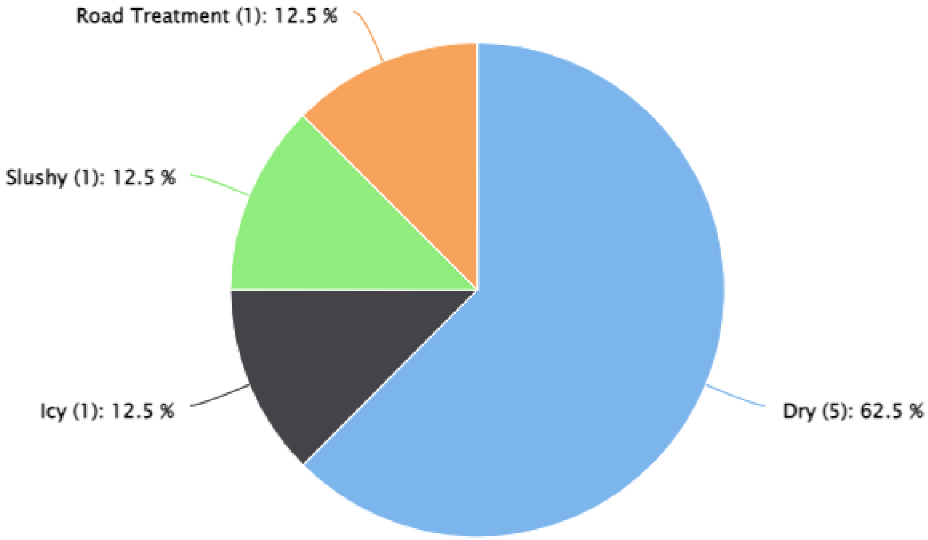

Figure 4-100: Rear-End Truck Crashes, Road Conditions

A review of crash records revealed that one Rear-End crash was not truly involving an at-fault truck. This crash involved a truck with brake failure stopped in the right-most travel lane being rear-ended by another vehicle but cited for occupying the lane.

Figure *4-101* shows that human contributing factors were influential in rear-end collisions, in particular driver inexperience and unfamiliarity with the area.

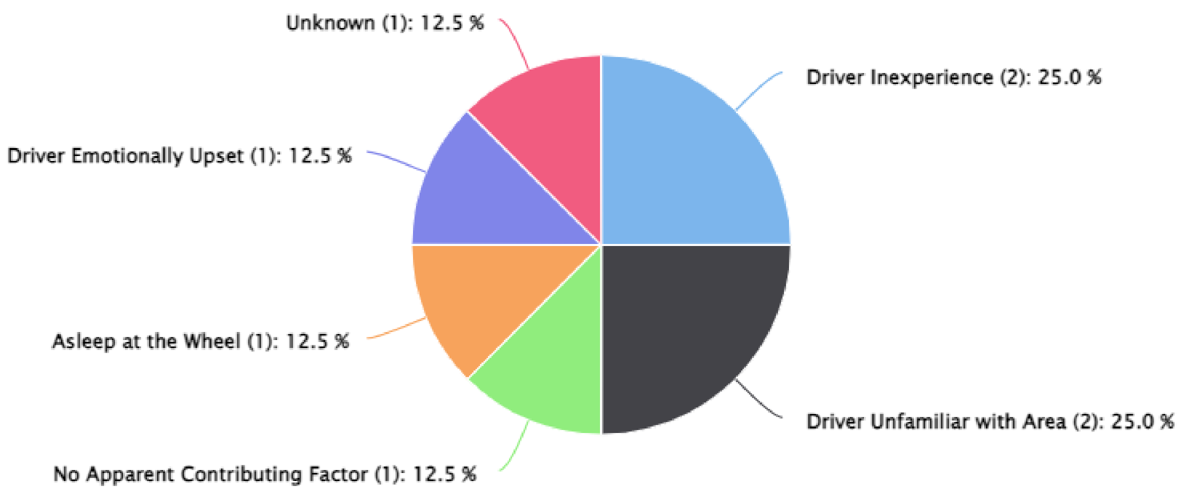

Figure 4-101: Rear-End Truck Crashes, Human Contributing Factors

The locations of Rear-End collisions are seen in **Figure 4-102**. While there is no pattern relating to one specific location, a review of the locations where some clustering is seen (MP 253.90-254.50, MP 256.20-256.80, and MP 257.90-258.40), shows that crashes appear to occur where there are changes in curvature on grade, and where potential for hidden traffic queues might occur (example **Figure 4-103** and **Figure 4-104**). A review of crash records showed that 3 cases involved the driver being unable to stop in time for traffic.

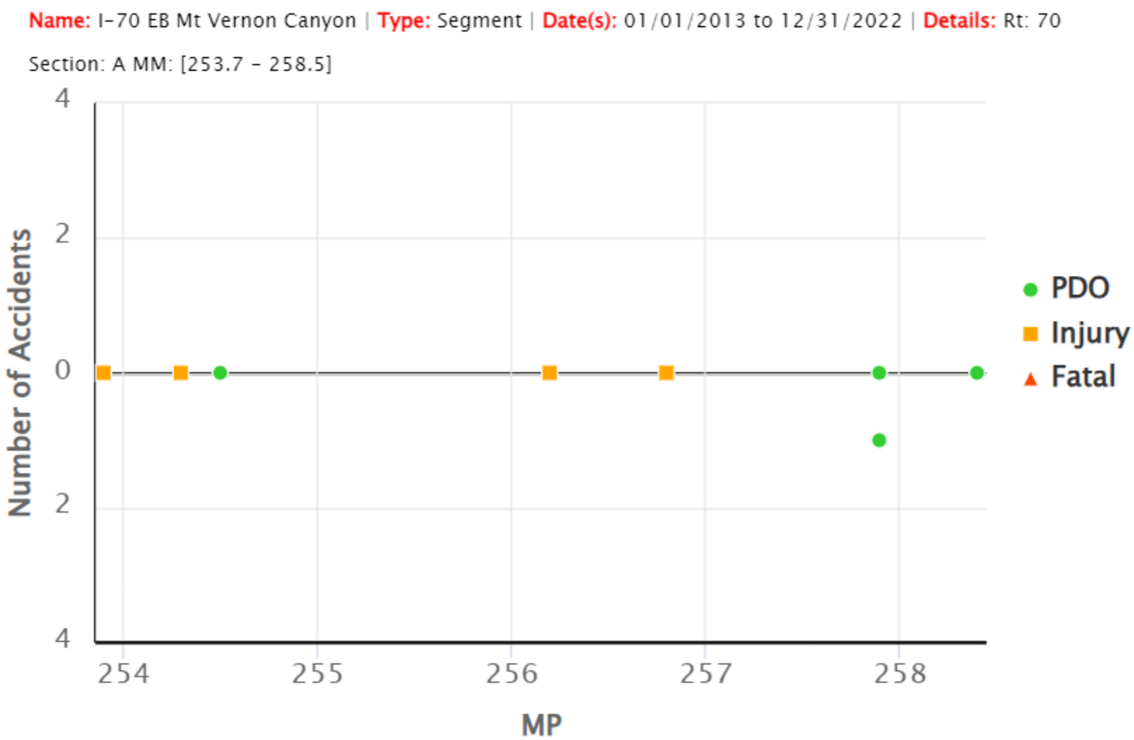

Figure 4-102: Rear-End Truck Crashes, Straight Line Diagram

Figure 4-103: View Approaching MP 256.20 Eastbound

Figure 4-104: Approaching MP 256.68 Eastbound

Crash records also showed that 1 case involved a driver asleep at the wheel. Further to this, records show that another rear-end involved the brake failure of a truck near MP 256.80, close to the escape ramp entrance, causing the truck to rear-end the lead vehicle. In this instance the driver elected not to use the escape ramp but instead “fled the scene” at Exit 259. The remaining crash involved a truck rear-ending another truck which was pulled into the right shoulder due to a flat tire, but partially occupying the right lane. The at-fault truck could not move into the adjacent lane due to traveling at a lower speed (45 mph) compared to the passenger vehicles in the lane to the left. Being unable to merge left, it must be deduced that the at-fault truck could not stop in time before striking the stopped truck.

A similar pattern regarding rear-end collisions and potentially hidden traffic queues has been discussed in the full version of this report as part of the general eastbound section. It was recommended that gated warning signs for traffic queues be installed on eastbound I-70 in advance of MP 254.50. Gated warning signs for traffic queues could also be included prior to MP 256 and MP 258.

There were 3 recorded successful uses of the truck escape ramp over the 10-year period we assessed. There was also 1 unsuccessful attempted use. Additionally, we identified 3 cases in which the escape ramp potentially might have been used but was not, for various reasons.

1. On 6/20/13 use of the escape ramp was recorded as “traffic sign/post/overhead sign structure” near MP 257.10. The truck departed the road hitting two signs on the right side of the road while accessing the escape ramp, before coming to a rest on the ramp. Driver inexperience was a recorded factor. This was a PDO level crash. Further details are not given in the crash record but it is possible brake failure was involved.

As part of the "COLLISIONS WITH SIGNS" section in the full version of this report discussing eastbound crashes involving all vehicle types, it was outlined that there were two passenger vehicle crashes with signs at this same location. It is likely that these collisions involved the object markers which during the study period delineated the arrester bed from the right shoulder of the traveled way, as seen in **Figure 4-105**. This configuration allowed the potential for not only passenger vehicles to accidentally and dangerously traverse the boundary and enter the escape ramp, but also for trucks on the ramp to re-enter the roadway.

Figure 4-105: Object Markers on Right Side near MP 257, June 2023

Google Streetview imagery indicates that there are several "EMERGENCY VEHICLE ONLY" regulatory signs on the approach to the arrester bed along the right side of the exclusive truck lane which provides entrance to the escape ramp. Imagery also indicates that, during the study period, the barrier wall on the right side which lined the entrance leading to the arrester bed had been struck and was damaged (**Figure 4-106** and **Figure 4-107**). This crash record in particular serves to demonstrate that trucks which do not approach the escape ramp entrance appropriately do have the potential to strike the barrier wall and other structures.

Figure 4-106: EB I-70 MP 256.70, Regulatory Signs & Barrier, June 2023

Figure 4-107: Escape Ramp Approach, Barrier Damage, June 2023

In its current configuration, a clear view of the escape ramp arrester bed is hidden behind a corner, such that a truck operator must commit to using the ramp and the dedicated access lane prior to getting a visual of the ramp itself. For the inexperienced driver, or the out-of-town driver, this might be intimidating. **Figure 4-108** shows the view near MP 256.31 which indicates the ramp is 2,000 feet ahead and drivers should enter the right most lane. As can be seen, drivers must still navigate a right curve and the ramp is not yet visible. Compounding this, **Figure 4-109** shows that the beginning of the exclusive ramp access lane begins on a curve, where the ramp is still not visible. If a driver has not committed at this stage and waits until the ramp become visible after rounding the corner (**Figure 4-110**), this could present a situation necessitating a sudden movement to the right, but also unsafe mounting of the ramp, and as has been described by this crash record, collisions with the barrier wall on the right.

Figure 4-108: Escape Ramp Warning Sign, MP 256.31

Figure 4-109: Start of Exclusive Escape Ramp Lane, MP 256.61, June 2023

Figure 4-110: View of Arrester Bed After Curve Left near MP 256.65, June 2023

Furthermore, Streetview imagery suggests that the overhead sign indicating the escape ramp position relative to the 3 through lanes was not present prior to 2020 (**Figure 4-111** and **Figure 4-112**). This may have caused further ambivalence for truck operators who were already lacking a clear head-on view of the ramp access leading up to this point.

Figure 4-111: MP 256.98, No 'TRUCK RAMP' Sign, Oct. 2020

Figure 4-112: MP 256.98, 'TRUCK RAMP' Sign, Oct. 2021

2. On 8/10/13 a "vehicle cargo/debris" crash involving a truck was recorded near MP 254.90. The truck lost part of the brake system with debris striking another vehicle. Both vehicles came to a rest on the right shoulder. This was a PDO level crash.

   It might be surmised that with only partial loss of the brake system the truck was still able to come to a stop, however, if this had involved complete brake failure, the location was still approximately 2 miles from the escape ramp. The first warning sign for the escape ramp is located near MP 255.32 and indicates the escape ramp is located 1.5 miles downstream. While there are still curves to be navigated between the point where this incident occurred and the escape ramp, it is not uncommon for more advanced notice to be provided as to the presence of truck escape ramps. CDOT could consider the erection of an additional advance warning sign approximately 2.5 to 3 miles in advance of the escape ramp.

3. On 9/3/14 near MP 257 what appears to be an unsuccessful attempt at the use of the escape ramp was recorded as an "overturning" crash, resulting in a level A injury. The truck suffered failure to shift gear, the truck swerved to the right (as outlined above the escape ramp entry is located on a curve) and hit the concrete barrier wall (confirming earlier observations regarding the potential for this to occur). Unfortunately, the truck was unable to access the arrester bed and overturned.

   This crash serves to highlight the situation described above, where the series of curves on the corridor combined with the current curved alignment of the ramp access lane, puts the ramp itself out of view until the last minute and requires drivers to commit the ramp before gaining a visual of it. As outlined, this can cause ambivalence and election by truck operators to not use the ramp until the last minute, resulting in unsafe maneuvers.

4. On 1/29/15 a "Sideswipe Same Direction" crash was recorded near MP 257 which appears to have been a case where use of the escape ramp could have been employed. A truck suffered

brake failure and picked up speed coming downhill approaching MP 257 on a curve. A second truck was in front of the runaway truck and in order to evacuate the way, moved to the shoulder, (which in this instance would also have been the access route to the escape ramp). The runaway truck struck the second truck to its right and then a passenger vehicle to its left. This was a PDO level crash. The driver was recorded as being unfamiliar with the area.

The crash record narrative states that all three vehicles continued to milepost 259 where they pulled over. This location is on the flat, so it is possible the runaway truck was able to come to a rest here because of the change in grade. It could be because of the second truck occupying the right shoulder, where the exclusive access lane to the runaway truck ramp is located, that the driver of the runaway truck elected to not use the escape ramp. As outlined, the driver was unfamiliar with the area, and as such would have been unfamiliar with the unique layout of the escape ramp here. As has been described above, a driver must commit to the ramp before a clear view has been established, and in order to do so must access the escape ramp lane on a curve. Compounded by another truck occupying the right shoulder, this might prove intimidating and off-putting for a truck operator unfamiliar with the area.

5. On 1/6/16 use of the escape ramp was recorded as "Other Non-Collision" near MP 257 when a truck lost its dual rear tires and veered off the road to the right before coming to a rest at the escape ramp. This incident was at the PDO level.
6. On 4/2/19 use of the escape ramp was recorded as "Traffic Sign/Post/Overhead Sign Structure" near MP 257. After entering the ramp, the truck collided with a sign on the left before coming to a rest. The crash occurred in dark conditions and was a PDO crash.

   It might be deduced that brake or other mechanical failure precipitated use of the escape ramp as no adverse weather conditions were present at the time. As has been described previously, the sign which the truck struck after entering the escape ramp was likely one of the object markers seen in **Figure 4-105**.
7. On 2/4/21 a "Rear-End" collision was recorded near MP 256.80, near the escape ramp, where could have been used but was not. The crash was at Injury level C. The crash narrative states that the truck "lost its brakes" before rear-ending the lead vehicle, after which it "fled the scene at mile marker 259."

   This was a clear case here the escape ramp could have been used by a truck suffering brake failure in the immediate vicinity of the ramp.

A review of Google Streetview imagery indicates that there are several warning signs for truck operators referring to steep grades and sharp curves for 5 miles, 4 miles, 3 miles and 1.5 miles ahead, located near MP 253.73, MP 254.46, MP 255.96, and MP 256.98, respectively. The latter two signs are both large overhead mounted signs supplemented by flashing beacons (example **Figure 4-113**).

Figure 4-113: Grade & Curve Warning Sign, MP 255.96

Imagery suggests that construction works might have obstructed the view of the warning signs near MP 254.46 (**Figure 4-114** and **Figure 4-115**). CDOT should review any ongoing construction works and if possible, make adjustments to maximize visibility of signs for truck operators.

Figure 4-114: Truck Warning Sign, MP 254.46, May 2023

Figure 4-115: Truck Warning Sign, MP 254.46, Sept. 2023

There is a lower speed limit of 45 mph in effect through the study corridor for commercial vehicles, as indicated by gated dual speed limit signs at several locations, for example near MP 256.32 (**Figure 4-116**).

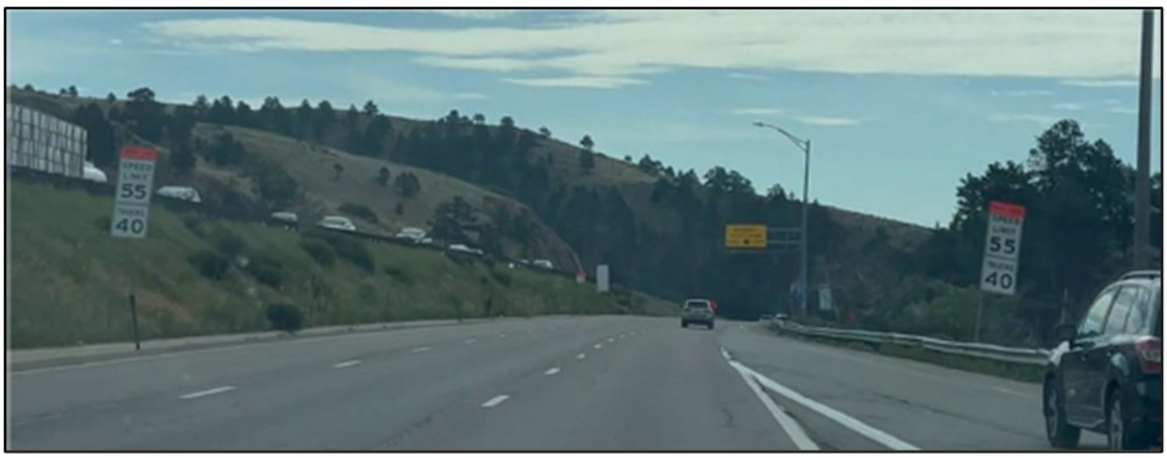

Figure 4-116: Lower Truck Speed Limits, MP 256.32, Aug. 2024

There are also steep downgrade warning signs (*MUTCD W1-7*) for trucks at two locations through the study corridor. However, imagery indicates that in the case of the gated warnings near MP 254.62, the last time the "6%" text was legible on the right-side sign was in 2018 (**Figure 4-117** and **Figure 4-118**). Additionally, the mileage/distance does not appear to be clear. CDOT should repair or replace the text on signs to ensure adequate visibility.

It also appears that in the case of the signs near MP 257.71, signs were staggered and gated up to late 2021 (**Figure 4-119**). However, imagery from mid-2022 indicates the right-side sign is missing (**Figure 4-120**). CDOT should replace the right sign to reinstate a gated warning.

Figure 4-117: Grade Warning, MP 254.62, Nov. 2018

Figure 4-118: Grade Warning, MP 254.62, Aug. 2024

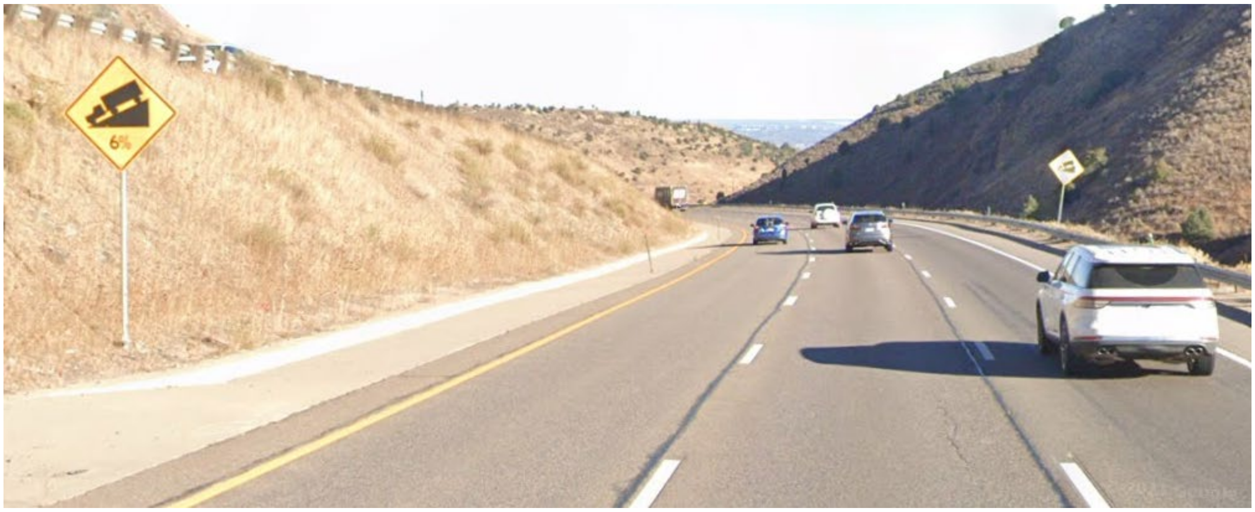

Figure 4-119: Staggered Gated Grade Warnings, MP 257.71, Oct. 2021

Figure 4-120: No Right-Side Warning, MP 257.71, Jun. 2022

Regarding the truck escape ramp itself, Streetview imagery indicates the initial warning is located near MP 255.32 approximately 1.5 miles ahead of the ramp, by way of large gated roadside warning signs (**Figure 4-121**). There is another set of similar gated roadside warning signs near MP 256.05 indicating the ramp is ¾ mile ahead. The next warning sign comes approximately 2,000 feet in advance of the ramp, near MP 256.31. This sign is a large overhead mounted sign with flashing beacons (**Figure 4-122**).

Figure 4-121: Initial Escape Ramp Warning, MP 255.32

Figure 4-122: Escape Ramp Warning, MP 256.31

As outlined previously, the exclusive truck lane for ramp access begins near MP 256.61 on a curve (**Figure 4-123**). (Despite some recent modifications in 2024 to the escape ramp, the entrance continues to be on curve). The entrance sign for the ramp is located near MP 256.70 and has flashing beacons, and is also located on a curve, without a view of the ramp itself (**Figure 4-124**). Following the curve, the ramp becomes visible, with an overhead sign, which as described previously, was added sometime around late 2021 (**Figure 4-111** and **Figure 4-112**).

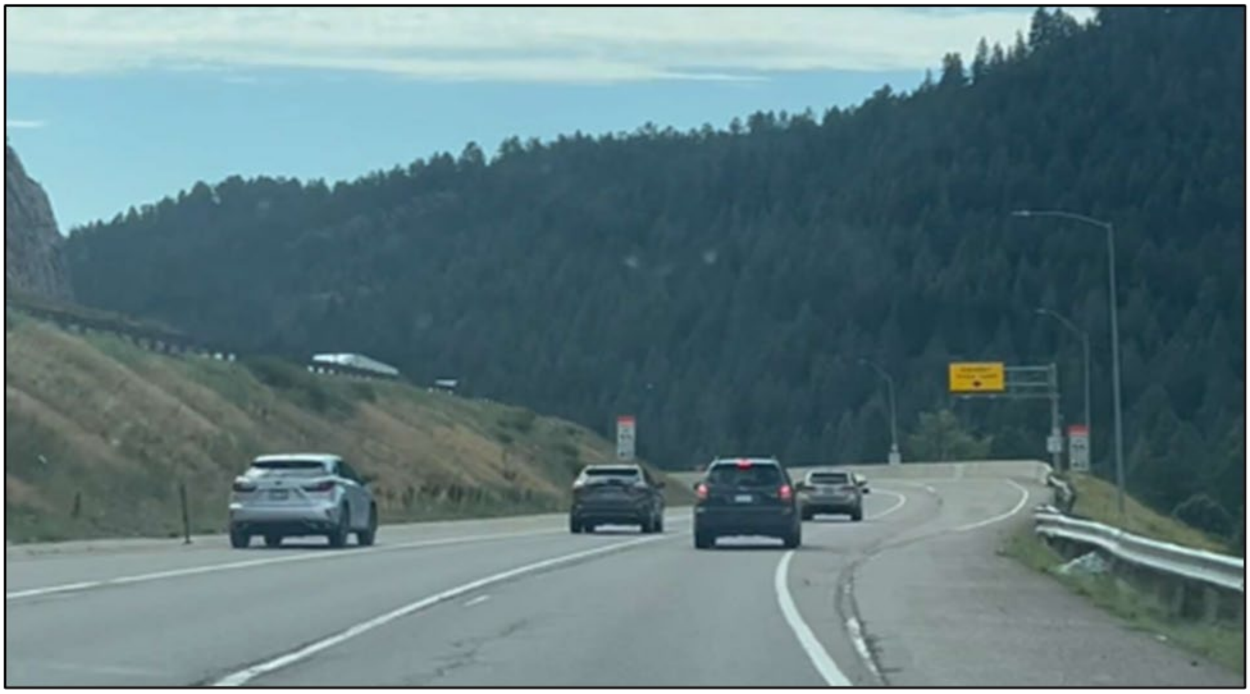

Figure 4-123: Start of Exclusive Truck Lane, MP 256.61, Aug. 2024

Figure 4-124: Escape Ramp Entrance Sign, MP 256.70, Aug. 2024

It has been described previously how the flat arrester bed was lined with object markers on the left and a shallow curb, delineating it from the traveled way, within the study period. There are impact attenuator barrels located at the end of the ramp, which is located near MP 257.26 (**Figure 4-125**).

Figure 4-125: Impact Attenuators at end of Escape Ramp

In summary, there are some sign repairs and/or replacement issues regarding warnings to truck operators which might require addressing by CDOT. The inclusion of additional warning signs for the escape ramp, possibly 2.5 to 3 miles in advance of the ramp, to account for cases of runaway trucks prior to MP 255.32, has also been recommended.

Apart from these issues, the uses and potential uses of the escape ramp which have been recorded and discussed above indicate that it is not feasible to say conclusively that the ramp in its current configuration operates entirely successfully. The narratives surrounding those successful uses of the ramp also include references to signs (likely object markers) being struck on entry by trucks, but also by errant passenger vehicles. Meanwhile the unsuccessful attempted use draws particular attention to the geometric shortcomings of the configuration during the study period, whereby the ramp itself is not visible at the same time a driver is required to commit to using the ramp access lane. (Indeed, the recent field visits indicate that, despite some modifications, the configuration still requires drivers to commit to the ramp on a curve prior to having a clear view of the ramp). As has been discussed, this can lead to drivers delaying a move to the right to access the ramp until it is in view, resulting in unsafe maneuvers and potentially impacting the barrier wall, or to drivers electing to not use the ramp at all. As has also been outlined, the study period configuration does not provide a substantial buffer between any truck on the ramp and passenger vehicle traffic on the traveled way.

At the time of writing this report it is understood that construction is currently underway as part of a reconstruction project which would see the escape ramp become shorter but deeper. It is understood that this reconfiguration would mean that access to the ramp would be moved further downstream (east). Furthermore, we also understand that the project would result in the entry lane to the ramp departing the mainline later, such that truckers would have rounded the curve which occurs near MP 256.80, thus allowing a clear view of the ramp to be obtained before committing to its use. This would certainly alleviate any ambivalence that unexperienced or out-of-town driers might have regarding employment of the ramp, by having a straight approach to it and a clear view prior to entry.

Moreover, as we understand it, replacement of the outside barrier wall, (which appears damaged in imagery from the study period), with a more substantial alternative is to be provided. It is also understood that barriers, such as the existing shallow curb, and object markers, will not be included as part of the reconfiguration to permit entry to the arrester bed by trucks at any point. This would also remove potentially dangerous curb mounting by trucks and/or passenger vehicles.

A field visit performed in August 2024 was able to confirm that some of these changes have occurred. **Figure 4-126** shows that the object markers on the left side of the ramp, as well as the raised curb have been removed, and the attenuator bed has also been shorted.

Figure 4-126: No Object Markers or Raised Curb, MP 257, Aug. 2024

Figure 4-127 shows that the barrier on the approach to and lining the escape ramp has been replaced with a taller, more robust, continuous (rather than segmented) structure. As such barrier damage has been addressed.

Figure 4-127: Escape Ramp Approach, Barrier Replaced, Aug. 2024

All successful recorded uses of the escape ramp resulted in PDO level crashes, which suggests that if the ramp geometric reconfiguration is undertaken as described, making it more attractive to be employed by truck operators, it would be expected to continue to perform successfully but with greater regularity.

It is understood that CDOT is planning to implement a VSL system on the corridor which would have friction and weather-based components, as well as volume and queuing-based components. This system would reduce the maximum speed limit permitted for commercial vehicles under adverse weather conditions and heavy traffic conditions. As such, this would be expected to be an appropriate countermeasure against those crashes which tend to be precipitated due to hidden traffic queues or winter road conditions.

It is notable that the approach to the ramp, even after the proposed reconfiguration occurs, would still see a series of sharp curves on a steep downgrade for approximately 4 miles in advance of the ramp. To exploit the benefits of the reconfiguration, by way of maximizing ramp use when necessary, a system similar to that in place for the Wolf Creek Pass escape ramp might be considered at this location by CDOT.

The system would provide diagrammatic warnings to truck operators including the locations of significant curves before the ramp, as well as an advisory speed limit (example **Figure 4-3**). A detection and warning system would also encourage truck operators to use the ramp rather than bypassing it in the case of brake failure, as was seen in a few circumstances. The Wolf Creek Pass system also includes blank outs for dynamic messaging. This might be used here in the case of adverse road conditions to alert truckers to adopt lower speed limits (**Figure 4-1**).

Commercial vehicle crashes involving adverse winter road conditions were seen in just over 37% of crashes on this eastbound corridor study segment in the 10-year study period (**Figure 4-128**).

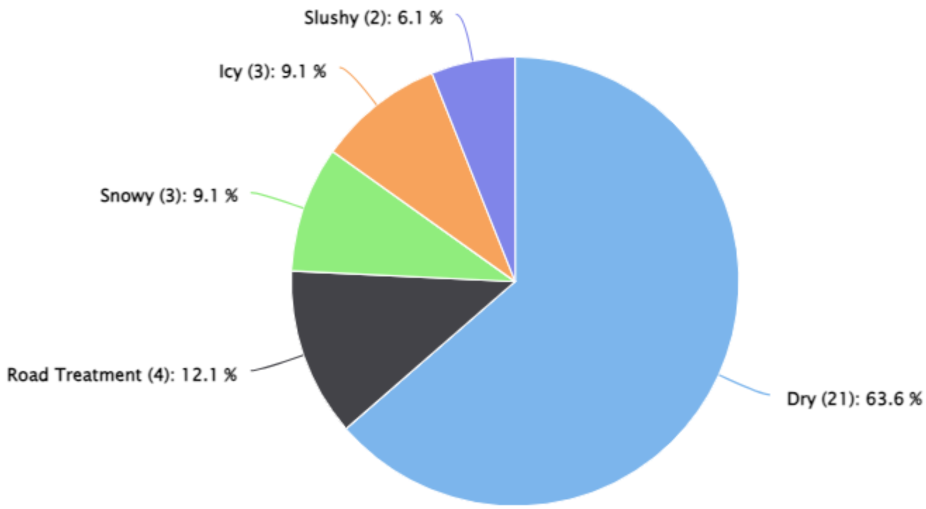

Figure 4-128: Commercial Vehicle Crashes, Road Conditions

Adoption of a system similar to that on the Wolf Creek Pass would involve enhancement of those existing RUNAWAY TRUCK RAMP advance warning signs which do not have them, with flashing beacons. Escape ramp advance warning signs might also be fitted with blank outs. Large overhead diagrammatic signage depicting significant hazardous curves, the ramp location and commercial vehicle speed advisory would be required also. Combined these measures would offer a guidance system providing real-time feedback to runaway trucks. The system would also benefit the inexperienced and out-of-town truck operator to be better prepared for changes in roadway geometry and to be better prepared for entry onto the escape ramp if required.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the I-70 corridor surrounding the Mount Vernon Canyon truck escape ramp located near MP 257, and to provide an evaluation of the performance of the escape ramp. The analysis was focused on the eastbound I-70 corridor between MP 253.70 and MP 258.50 to capture the effects of the ramp.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area.

Eastbound

Eastbound the study corridor is characterized by a steep downhill grade and frequent changes in horizontal curvature. The level of service of safety was determined to be LOSS-III for the eastbound corridor in terms of total crash frequency, representing moderate to high potential for crash reduction. The level of service of safety was determined to the LOSS-IV in terms of crash severity, representing high potential for crash reduction.

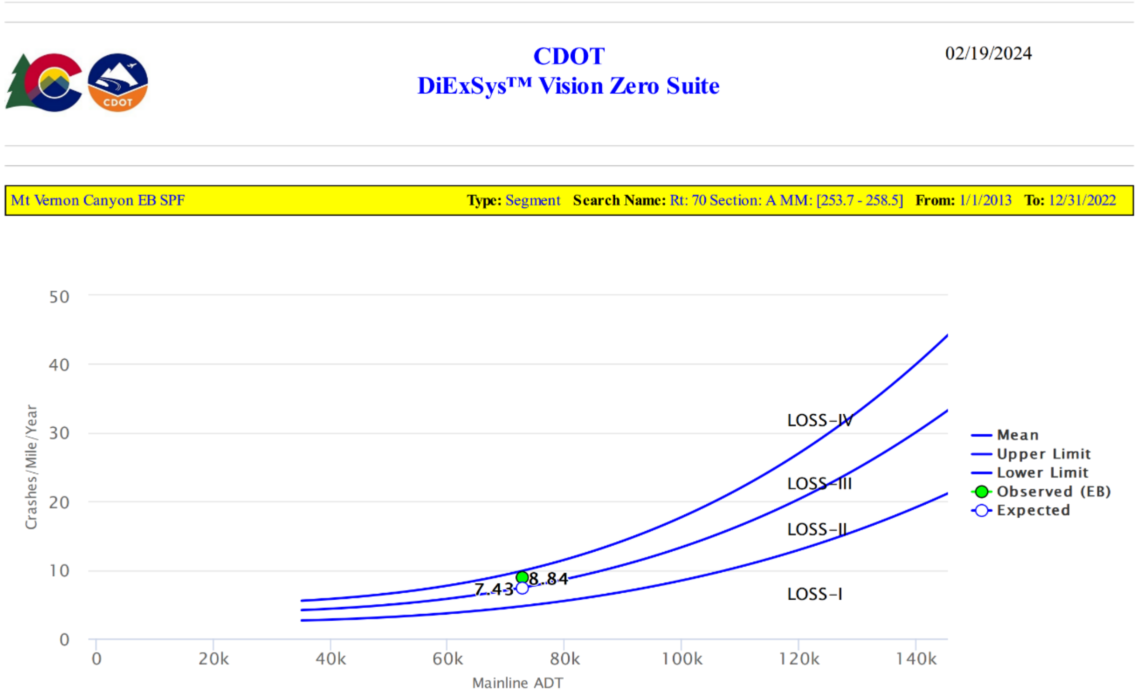

Figure 4-129: SPF Total Crashes I-70 Eastbound

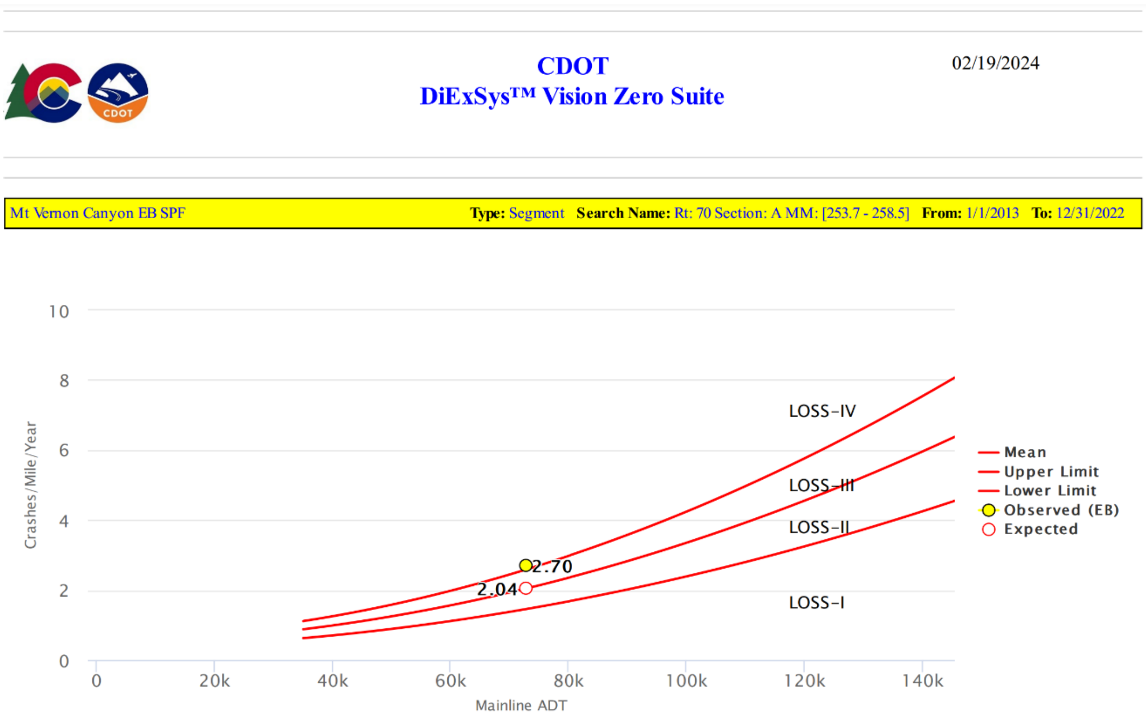

Figure 4-130: SPF INJ+FAT Crashes I-70 Eastbound

Most patterns identified on the eastbound corridor were substantially correlated with the geometry of the corridor, i.e. a steep downgrade combined with frequent changes from left to right curves. There was also some influence due to adverse winter road conditions exacerbating crashes. Crash patterns typically representative of run-off-the-road crashes were a pattern. Other patterns included injury and fatal level crashes, crashes in Fog and Wind conditions, Wild Animal collisions, collisions with Signs, and crashes in Dark-Unlighted conditions. There is a degree of overlap between the aforementioned crash patterns, however it was generally observed that geometrics play a significant part in crash precipitation, and in the case of Wind and Fog crashes, the natural topography of the corridor was observed to be a potential contributing factor.

Because of the influence of the geometry of the corridor several recommendations were made for increasing advance warning signs.

It was also identified that hidden traffic queues are potentially contributing to several crash types, again owing to the geometry of the corridor.

Collisions with Signs showed themselves to be most frequent near MP 257, involving collisions with either regulatory signs or object markers lining the ramp access lane. A new project which reconfigures the escape ramp should provide mitigation against collisions with regulatory signs and remove the potential for collisions with object markers.

Wild Animal collisions were observed to be persistent along the entire corridor.

It was observed that crashes in Dark-Unlighted conditions accounted for somewhere between 24-63% of other identified crash patterns between Exit 254 and Exit 265.

Collisions involving "Other Objects" were found generally to have involved either dead wild animal carcasses or debris from crashes.

Driver Fatigue displayed a tendency for crashes to occur between MP 255.50 and MP 257.50.

A summary of recommendations for the eastbound corridor in general for identified crash patterns is provided below.

- Install gated curve warning signs (W1-2) in advance of MP 254.20, MP 255.00, MP 255.50, and MP 257.50, or alternatively install gated curve series (W1-5) warning signs at the beginning of the eastbound corridor near MP 253.70 with supplementary "NEXT 4 MILES" plaques,
- Install gated traffic queues warning signs in advance of MP 254.50. (The planned VSL system on the corridor would have volume and queuing-based components, as such these could serve as supplementary measures if desired.),
- Install gated remotely controlled blank-out signs for "ICY ROAD" in advance of MP 253.70, MP 255.00 and MP 256.50, or alternatively a single set of gated remotely controlled blank-out signs for "ICY ROAD NEXT 3 MILES" in advance of MP 253.70. (These could be implemented as part of the planned VSL system on the corridor if desired.)
- Ensure DEER warning sign near MP 253.97 is gated and supplement each with "NEXT 5 MILES" plaques,
- Gate DEER warning signs (W11-3) near MP 256.51 and MP 258.50 and include supplementary distance plaques (W16-3aP).
- Erect lighting in the eastbound direction between Exit 254 and Exit 256,

- Install gated FOG warning signs (W8-22) near MP 254. (The planned VSL system for the corridor would have friction and weather-based components, as such these could serve as supplementary measures if desired.),
- Install gated “GUSTY WINDS AREA” signs (W8-21) in advance of MP 254.00,
- Install advisory signs for fatigued drivers to pull over and rest in advance of MP 255.50,
- Extend guardrail near MP 256.58 to mitigate the severity off-right crashes, and
- Review maintenance protocols for improved efficiency in identifying roadway collisions along the network, as well as cleanup operation protocols.

Commercial Vehicles And Truck Escape Ramp

Truck crashes were found to be predominantly Fixed Object crashes or Rear-End collisions. In the case of the former, there was no clear pattern in terms of location, however a review of crash records indicated that loss of control in icy/snowy conditions was a factor.

Rear-End collisions showed a similar trend to rear-end collisions involving passenger cars, that is they tended to be high-severity and attributable to corridor geometry, with hidden traffic queues also suspected as a contributory factor. Records show several instances of the driver being “unable to stop” for slowed traffic.

There were 3 recorded successful uses of the escape ramp, 1 unsuccessful and additionally we identified 3 cases in which the escape ramp potentially might have been used but was not, for various reasons.

There are some sign repairs and/or replacement issues regarding warning signs to truck operators which might require addressing by CDOT. The inclusion of additional warning signs for the escape ramp to account for cases of runaway trucks prior to MP 255.32, has also been recommended. Furthermore, any construction projects should be assessed to ensure works are not obstructing pertinent warning signs for truck drivers.

It is thought that the current configuration of the ramp, (access lane located on a curve and prior to truck operators having a clear view of the ramp), might have been causing, and may continue to cause truckers to elect not to use the ramp, or as in the case of the unsuccessful ramp use, electing to use the ramp too late, resulting in quick maneuvers to the right and possible collision with the barrier wall. As we understand, a construction project will move the ramp entry downstream providing a straight entry to the access lane and ramp itself and a clear view of the ramp for truckers.

Furthermore, the planned VSL system for the corridor would have a weather and visibility-based component, as well as volume and queuing-based component. As such this would be expected to be a suitable countermeasure against those crashes which tend to be precipitated by adverse winter road conditions or hidden traffic queues.

Based on ramp use history and cases where the ramp could have been used but was not, and considering the current project, it is recommended that CDOT consider the benefits a system similar to that at the Wolf Creek Pass ramp would bring, in terms of maximizing the returns of the current reconfiguration project. This would allow safer passing of commercial vehicles on a segment which experiences steep downgrades and frequent changes in curvature and would be more likely to promote use of the ramp in those cases where drivers previously elected to not use the ramp.

A summary of recommendations (in addition to the above listed general recommendations) which relate to contributory factors to commercial vehicle crashes specifically is made below:

- Install gated warnings for hidden traffic queues in advance of MP 256 and MP 258. (The planned VSL system for the corridor is understood to have a volume and queuing-based component, as such these could be supplementary if desired),
- Repair/refresh text on truck grade warning signs (W1-7) near MP 254.62,
- Reinstate right side truck grade warning sign near MP 257.71,
- Install additional truck escape ramp warning signs 2.5 miles to 3 miles in advance of the ramp,
- Assess visibility of truck warning signs at construction project sites, and
- Enhanced runaway truck signing, warning and guidance system to include blank-outs and flashing beacons on advance warning signs, as well as vehicle detection and guidance, overhead diagrammatic warning signs with pertinent locational information. Sufficient solar paneling and battery supply to be provided.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the eastbound direction. It is in the eastbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 7 – Slick Rock Hill: SH-141 Northbound, MP 15.85-19.65

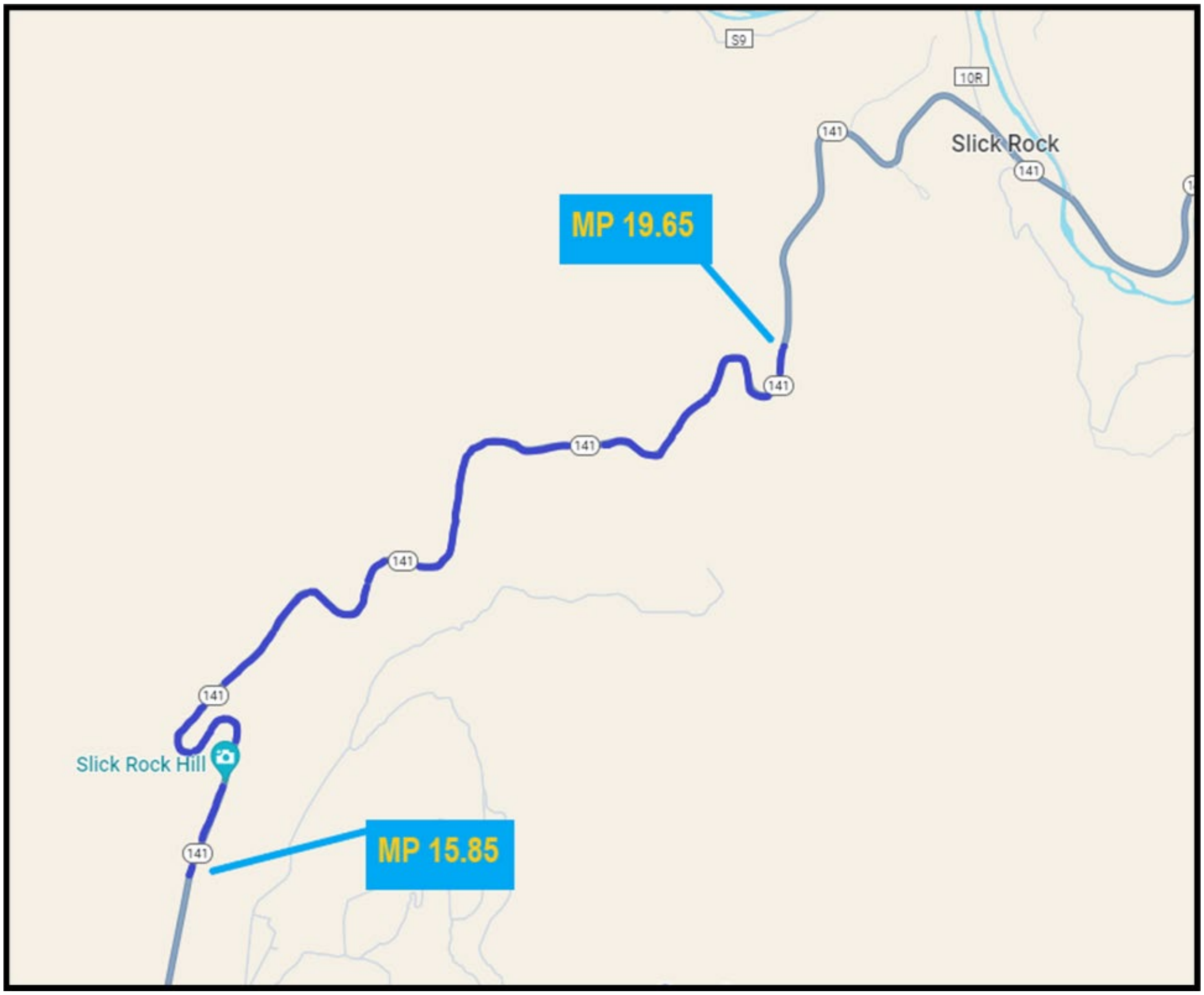

Figure 4-131: Slick Rock Hill Study Limits

Site Location

The Slick Rock Hill truck escape ramp is located on S.H. 141 near mile point 18.50 northbound. To capture a zone of influence, this study considers the corridor between MP 15.85 near to where the initial truck warning signs are seen in advance of the escape ramp, to MP 19.65 a little over 1-mile beyond the escape ramp. The included distance is approximately 3.80 miles.

Site Conditions

SH-141 is classified as a rural highway on mountainous terrain. SH-141 is a 2-lane, undivided highway with 12' lanes. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 170 and the percentage of truck traffic is 25%.

The speed limits northbound gradually decrease from 55 mph between MP 15.85 and MP 16.00, to 45 mph between MP 16.00 and MP 16.21, to 35 mph for the remainder of the study corridor.

Southbound the speed limit increases from 35 mph between MP 19.65 and MP 16.43, to 55 mph between MP 16.43 and MP 16.00, to 65 mph for the remainder of the study corridor. There are lower advisory speed limits in both directions throughout the study corridor.

Outside shoulder width along the study segment varies from 1 ft at MP 17.04 to 8 ft at MP 16.31, while there is no information for the inside secondary shoulder width. The corridor is characterized by frequent changes in horizontal curvature and northbound downgrades of 7%. **Figure 4-132** below shows a typical section of the corridor northbound.

Figure 4-132: Typical Section of SH-141, Northbound, May 2021

Northbound Commercial Vehicle Crashes

This safety assessment is primarily concerned with the history of commercial vehicle crashes along the study corridor. However, in the 10-year study period there was only 1 recorded commercial vehicle involved crash on the study corridor. This crash was the fatal collision which occurred near MP 19.30 in 2020 in which a truck overturned on the curve on a steep downgrade.

In the study period there were no crashes recorded in which the truck escape ramp at MP 18.50 was used. In fact, when the available crash history back to 2007 is consulted, only 2 additional northbound truck crashes were recorded on the study segment:

- 1 Overturning (INJ) in 2008 near MP 18.7 in snowy conditions entering a curve.
- 1 Large Boulder (PDO) in 2009 near MP 19.10 in snowy conditions entering a curve.

In both cases the weather and road conditions were contributory factors. In general, the changing horizontal alignment combined with the downgrade in the northbound direction on the study segment appear to be contributing to truck (and other) crashes rather than failing brakes as is often the case in these mountainous environments.

Without a history of use, or without crashes in the vicinity of the ramp with characteristics indicating the driver might have benefitted from the use of the ramp, it is not possible to make a determination on the performance of the truck escape ramp. If anything, it appears that the major problem appears to have been near MP 19.30 regarding run-off-the-road crashes. However, the location is not suitable for a truck escape ramp in the northbound direction, as **Figure 4-133** shows the curve is bordered by steep rocky terrain and narrow shoulders. Furthermore, crashes occurring here tend to be 'off-left' (i.e. vehicles cross over into the southbound lanes), as such an escape ramp on the northbound side on the apex of a hairpin curve would not make sense. Because the problem seems to be at the curve itself rather than in the lead up to the curve, placement of an escape ramp immediately before the curve is not intuitive either. Rather, effort should be placed into raising increased awareness around the presence of and location of the switchback curves, combined with emphasis on advisory speeds and potential risk of running off the road.

Figure 4-133: Northbound Approach to Curve at MP 19.30

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the SH-141 corridor surrounding the Slick Rock Hill truck escape ramp located near MP 18.50, and to provide an evaluation of the performance of the truck escape ramp. The analysis was focused on the northbound SH-141 corridor between MP 15.85 and MP 19.65 to capture the effects of the ramp.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area.

Northbound

Northbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-III for the corridor in terms of total crashes, and LOSS-IV in terms of crash severity. This represents moderate to high potential for crash reduction, high potential for crash reduction, respectively.

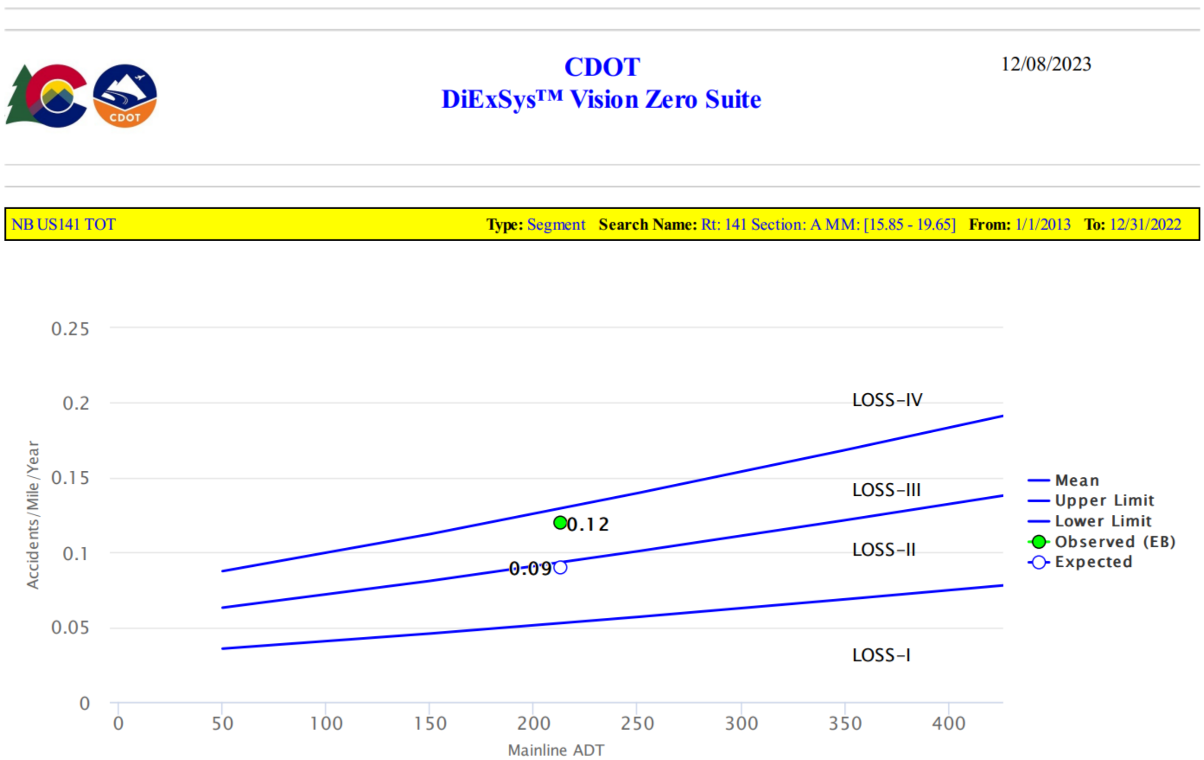

Figure 4-134: SPF Total Crashes SH-141 Northbound

CDOT
DiExSys™ Vision Zero Suite

12/08/2023

NB US 141 SEV **Type:** Segment **Search Name:** Rt: 141 Section: A MM: [15.85 - 19.65] **From:** 1/1/2013 **To:** 12/31/2022

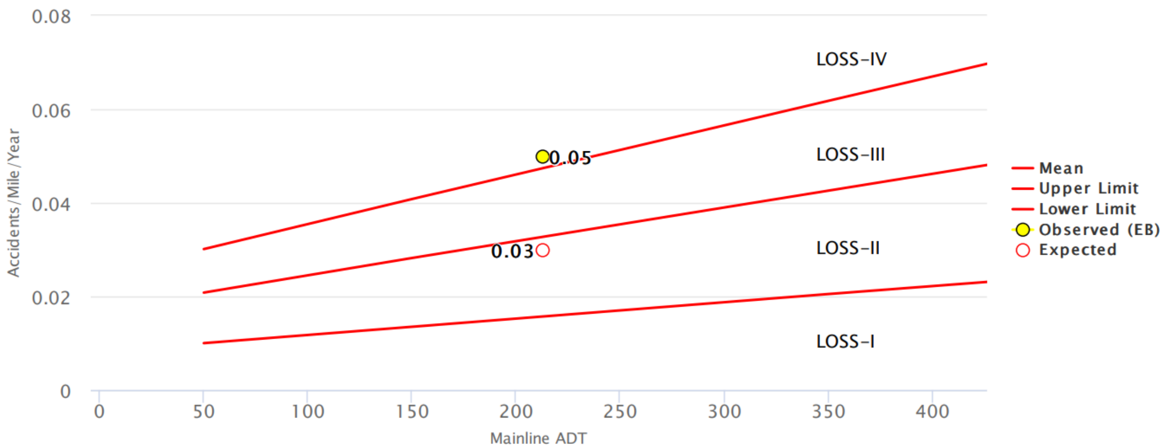

Figure 4-135: SPF INJ+FAT Crashes SH-141 Northbound

Off-Left crashes and crashes occurring under Dark-Unlighted conditions were both over-represented along the study corridor. The crash history also showed there is a degree of overlap between off-left crashes and crashes in dark conditions. Analysis of the crash history for both crash patterns determined that these crash types were correlated with roadway geometrics, including abrupt changes in horizontal curvature and a steep downhill grade, while in the case of crashes under dark conditions, crashes may also be correlated with insufficient conspicuity of curves.

Mile point 19.30 showed the only cluster of crashes, for off-left crashes. This location is characterized by switchback curves on a downgrade. All of the other locations which were analyzed have seen resurfacing of the pavement and installation of centerline rumble strips in recent years.

A summary of general recommendations for the northbound direction (which would also benefit the single truck crash seen at MP 19.30) can be made as follows:

- Extend northbound guardrail at the curve near MP 16.50 for approximately 300 feet and include reflective chevron sheeting on the guardrail,
- Install additional reflective delineator posts on the left side through the curve near MP 17.30 facing northbound traffic, alternatively install reflective chevrons through the curve for northbound traffic,
- Wrap existing sign supports near MP 18.01 with reflective tape/backing and increase the frequency of reflective delineator posts at this location,

- Extend the guardrail on the southbound side near the curve at MP 19.30 further to the south to benefit off-left northbound severe crashes, include reflective chevron sheeting on the guardrail at this location, and increase the frequency of reflective delineator posts on the northbound approach to this curve, and
- Install a diagrammatic "story" map in advance of the series of curves near MP 17.25 which shows the location of significant curves and switchbacks ahead on the study corridor to benefit all drivers, as well as the location of the escape ramp.

In terms of the performance of the truck escape ramp, there was only 1 commercial vehicle involved crash recorded in the 10-year study period, which occurred at MP 19.30, almost 1 mile beyond the truck ramp. There were no recorded uses of the ramp when the search was expanded to 2007, and no crashes were identified in which the ramp may have been used. As such, it is not possible to make a determination on the performance of the escape ramp and/or associated warning signs.

Furthermore, while a signing, detection and warning system like that on Wolf Creek Pass would provide a safety benefit, it is unlikely to prove cost effective on this corridor given the commercial vehicle crash history and the apparent lack of power and fiber network. As such, employing just some of the enhancements would be of assistance to both commercial and passenger vehicles.

A summary of recommendations regarding commercial vehicles can be made as follows:

- It is recommended that an advance Overturning warning sign (MUTCD W1-13R) with supplementary advisory speed limit plaque (MUTCD W13-1P) be erected northbound in advance of MP 19.30, and
- It is recommended that a solar powered radar speed feedback sign be included on the approach to MP 19.30 in particular, it might also be considered that existing runaway truck ramp warning signs be fitted with blank-outs possessing the same capabilities.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusion that the highest safety concerns regard the northbound direction. Crash distribution is predominantly in the northbound direction, the direction of the escape ramp, with 72.7% of crashes occurring in that direction. It is in the northbound direction that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Location 8 – Coal Bank Pass: US-550 Southbound, MP 54.50-51.00

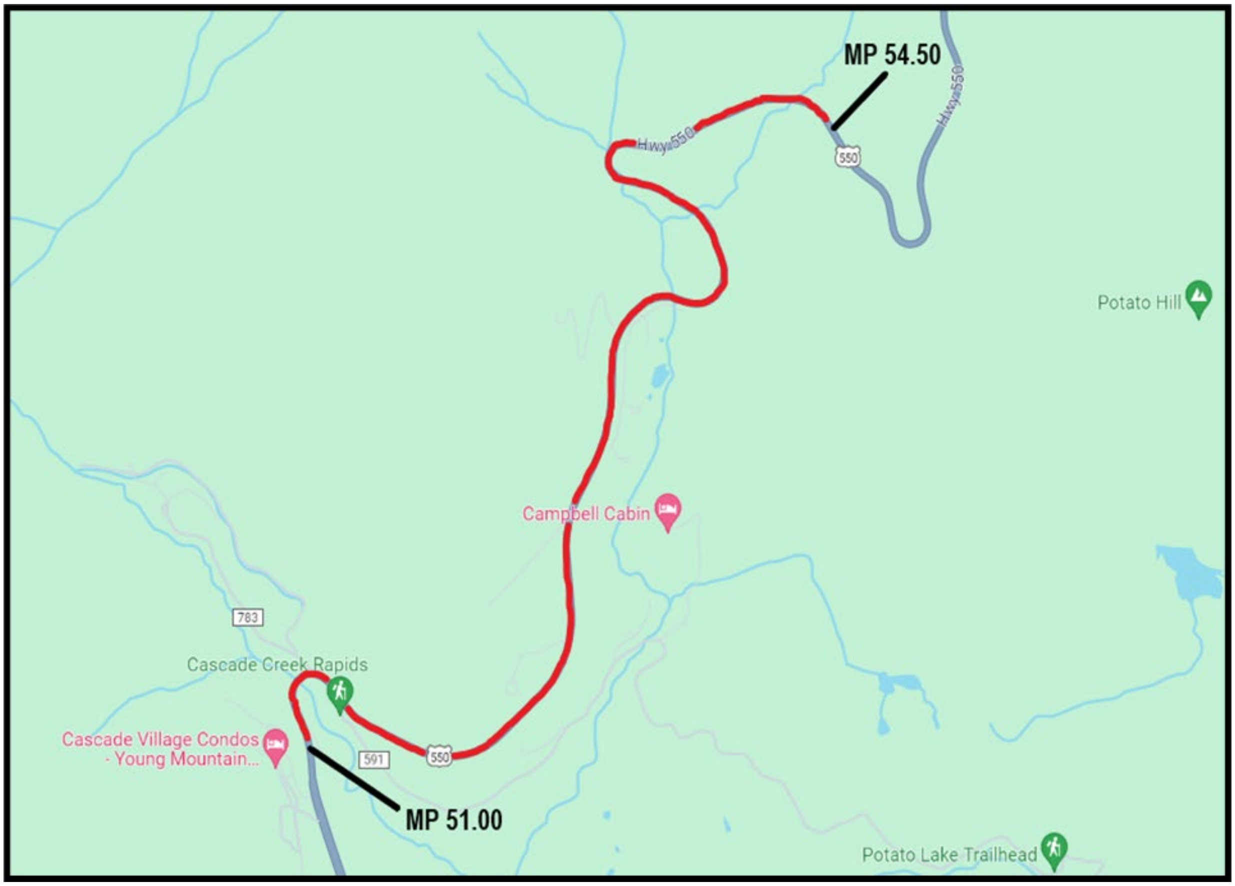

Figure 4-136: Coal Bank Pass Study Limits

Site Location

The Coal Bank Pass truck escape ramp is located on US-550 southbound near mile point 52.50. To capture a zone of influence, this study considers the corridor between MP 51.00 to the south beyond the escape ramp, to MP 54.50 at the initial warning sign for the escape ramp. The included distance is approximately 3.50 miles.

Site Conditions

US-550 is classified as a rural principle arterial on mountainous terrain. US-550 is a 2-lane, undivided highway with 12’ lanes. According to the most current information available on the CDOT OTIS website, the Average Annual Daily Traffic (AADT) is 2,000 and the percentage of truck traffic is 11%.

The speed limit in the northbound direction is: 45 mph between MP 51.00 and MP 51.50; 50 mph between MP 51.50 and MP 53.60; and 45 mph between MP 53.60 and MP 54.50. The speed limit in the southbound direction is: 40 mph between MP 54.50 and MP 53.66; 50 mph between MP 53.66 and MP 51.50; and 40 mph between MP 51.50 and MP 51.00. There are lower advisory speed limits in both directions throughout the study corridor.

Shoulder width along the study segment varies from 3 ft at MP 54.30 to 18 ft at MP 51.54 but is generally around 5 to 6 feet. The corridor is characterized by frequent changes in horizontal curvature and a steep downgrade. **Figure 4-137** below shows a typical section of the corridor southbound.

Figure 4-137: Typical Section of US-550, Southbound, Oct. 2021

Southbound Commercial Vehicle Crashes

There were 6 recorded commercial vehicle crashes on southbound US-550 between MP 51 and MP 54.50 in the 10-year study period. This included 2 Property Damage Only (PDO) crashes and 4 Injury level crashes, with 4 people injured. **Figure 4-138** shows the location of crashes involving commercial vehicles (trucks) on the southbound study corridor.

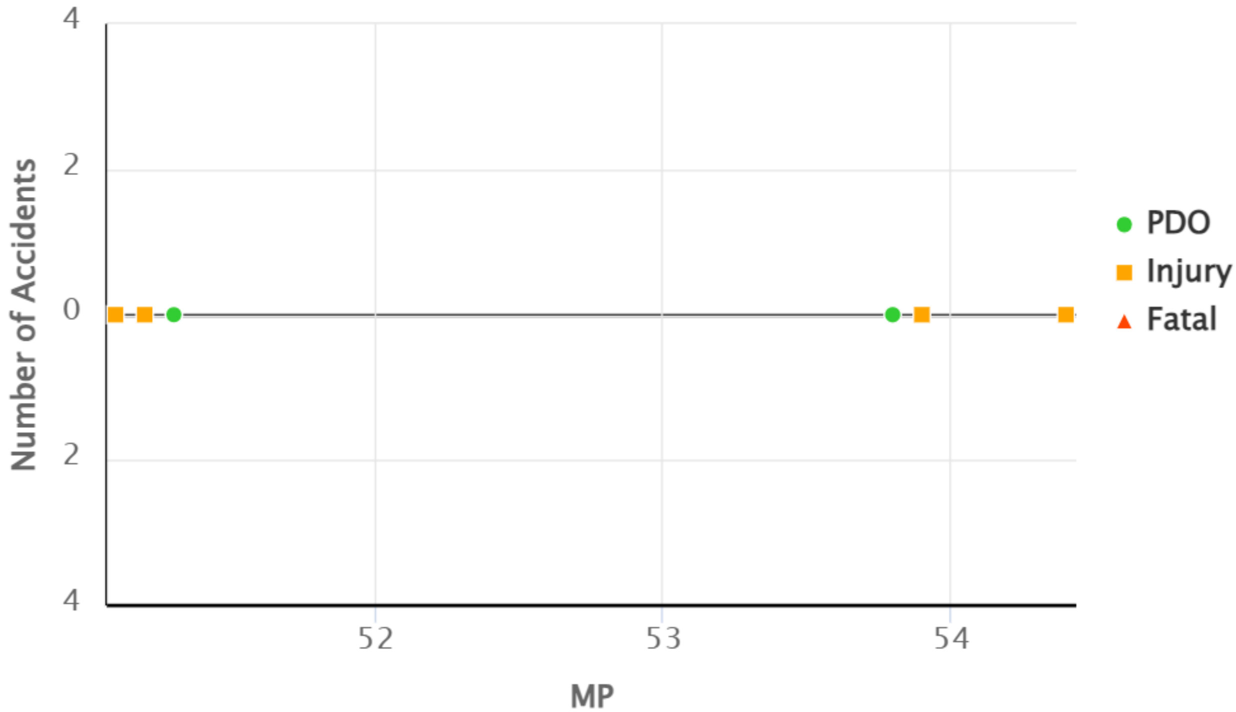

Figure 4-138: Truck Crash Locations, SB US550 MP 54.50-51

Figure 4-138 shows that truck crashes were not recorded at the truck escape ramp (MP 52.50) but did occur at the hairpin bend near MP 54, and the hairpin bend near MP 51. Crash records show that truck crashes tended to be predominantly high severity when they did occur (4 of 6 crashes were injury level).

Figure 4-139 shows the first hairpin bend, approximately 2 miles in advance of the escape ramp, and the second hairpin bend approximately 1.5 miles beyond the escape ramp. Both severe curves are on a downgrade.

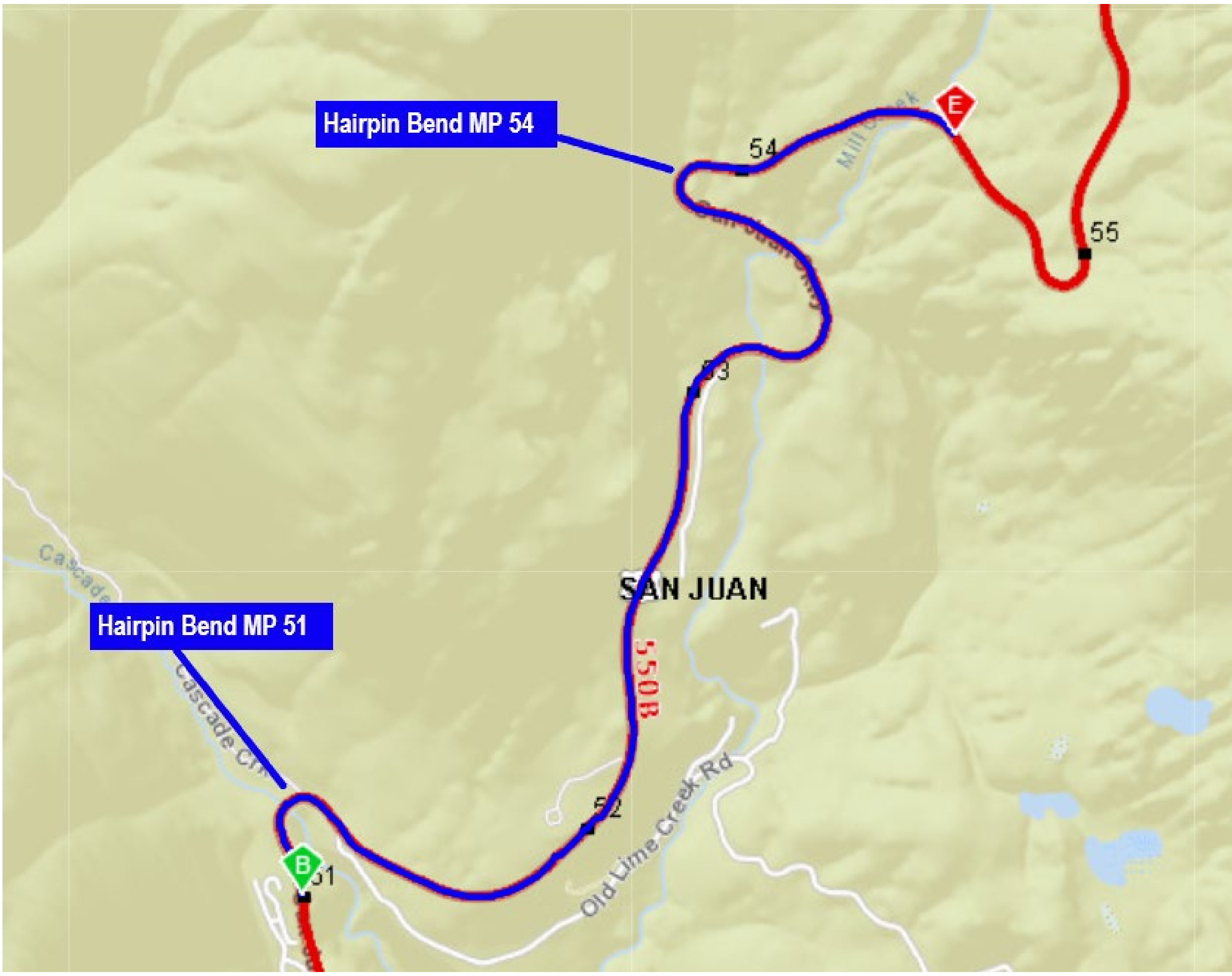

Figure 4-139: Hairpin Bends with Truck Crashes, US550

Figure 4-140 shows that there are currently advanced warning signs for the first hairpin bend (MP 54) in place. Additionally, prior to the bend at MP 51, there are warning signs for truck operators to maintain low gears due to curves and downgrades (**Figure 4-141** and **Figure 4-142**). Recent imagery and a field visit revealed that the previously in place curve warning and advisory speed limit sign near MP 51.51 for the hairpin bend at MP 51 (**Figure 4-143**), has been replaced with a dynamic speed feedback sign near MP 51.51 (**Figure 4-144**) and a solar powered curve warning sign near MP 51.40 (**Figure 4-149**).

Figure 4-140: Advance Warning Approaching Hairpin Bend near MP 54 US550 SB

Figure 4-141: Curve & Grade Warning Signs, MP 52.30 (Approx.) US550 SB

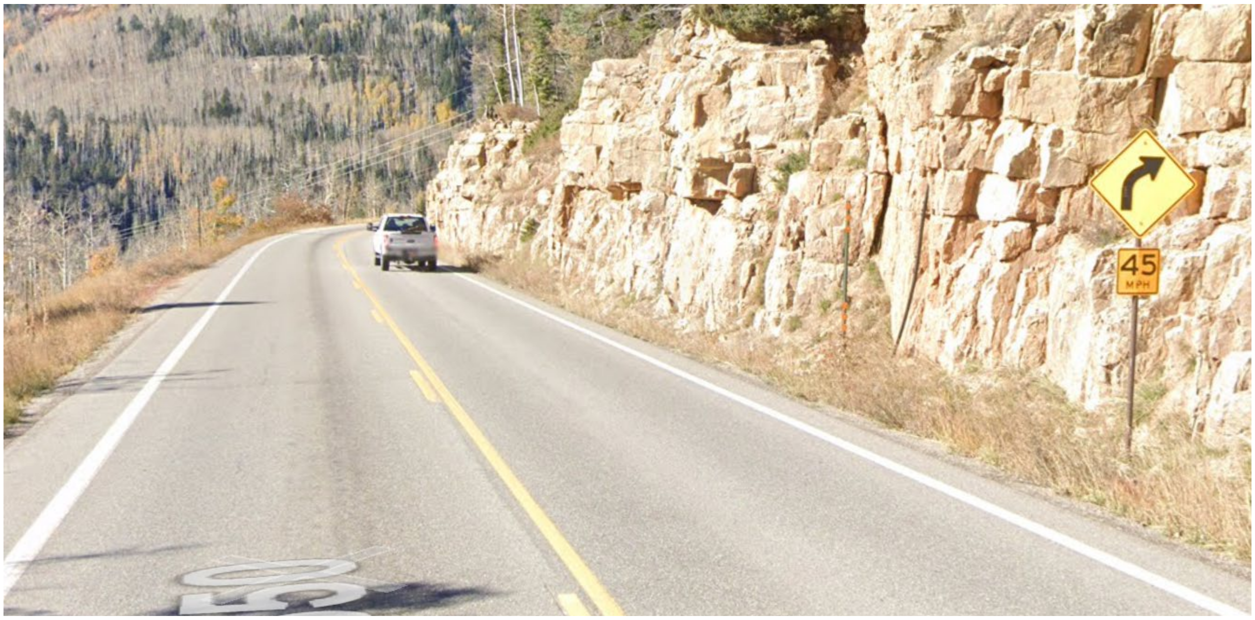

Figure 4-142: Curve Warning, MP 51.98 US550 SB

Figure 4-143: Advance Hairpin Warning Approaching MP 51 US550 SB, Oct. 2021

Figure 4-144: Dynamic Speed Warning Approaching MP 51 US550 SB, Nov. 2024

Figure 4-145 shows that truck crashes on the study segment were all run-off-the-road type crashes, Fixed Object and Overturning in this case. Both Fixed Object crashes were collisions with guard rail.

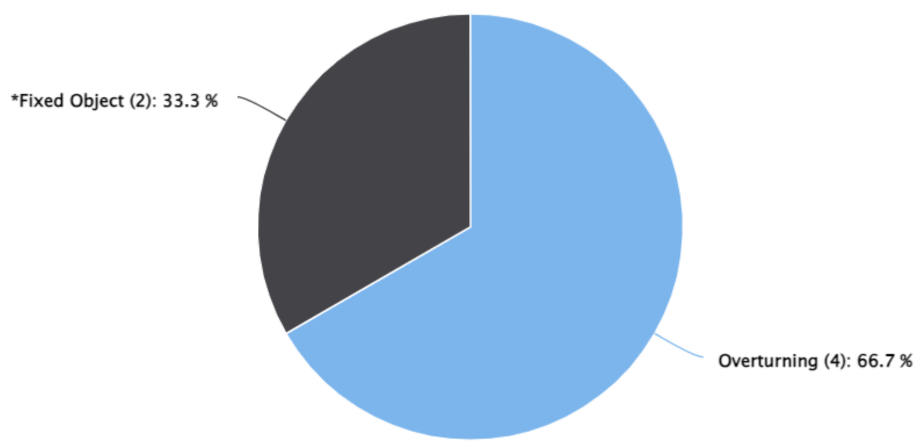

Figure 4-145: Truck Crashes, Crash Type Distribution, SB US550 MP 54.50-51

Crashes involving trucks were not in general substantially influenced by lighting conditions or road conditions, with only 2 crashes occurring under dawn/dusk conditions, and 1 in wet road conditions. Conversely, **Figure 4-146** shows that driver inexperience and unfamiliarity with the area were significant contributing factors to truck crashes on the study segment, having an influence on over 66% of all crashes.

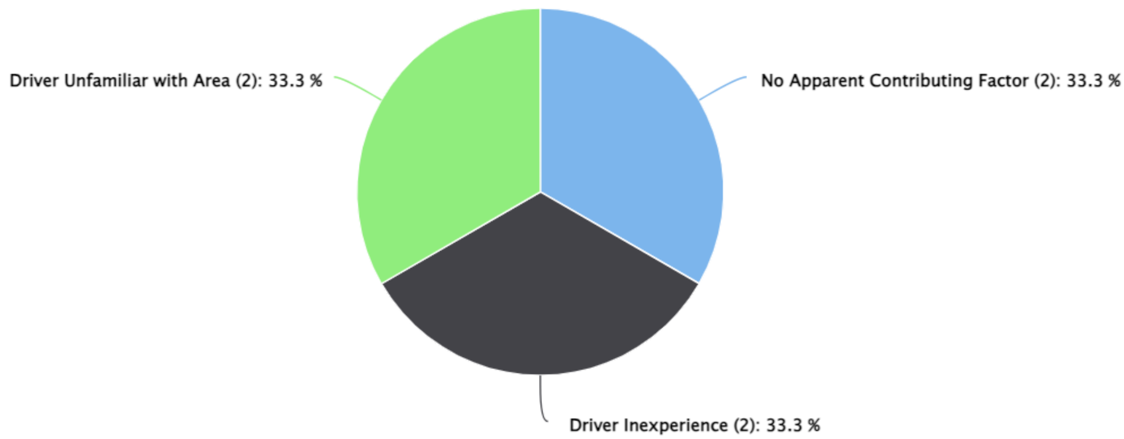

Figure 4-146: Truck Crashes, Human Contributing Factors

As witnessed in **Figure 4-138**, three crashes occurred prior to the escape ramp near the hairpin curve at MP 54 (1 PDO, 2 Injury). A review of crash history records shows that all 3 were Overturning crashes, not surprising, as the guard rail does not appear until the curve near MP 51. Two of these three crashes occurred under dawn/dusk conditions. As part of the section addressing "DAWN/DUSK" crashes in the full version of this report, it was recommended that the frequency of reflective delineator buttons be increased, or that delineator posts covered in reflective material be erected, in addition to the installation of reflective chevrons through the curve, and the wrapping of existing sign supports with reflective material or backing. One of the records refers to "rounding the bend," while another indicates the truck operator "lost control." Finally, 2 of the 3 crashes involved driver inexperience.

This points to a situation when the abrupt changes in alignment on a mountainous downgrade are creating challenging conditions for truck operators inexperienced in this driving environment, resulting in severe run-off-the-road crashes. As shown in **Figure 4-140** there is an advance warning sign for the hairpin curve with an advisory 25 mph speed limit. It is recommended that a system of enhanced warning signage be adopted to mitigate severe run-off-the-road truck crashes near MP 54 aimed at truck operators inexperienced in the mountainous environment. The addition of flashing beacons to the existing warning sign would be recommended, as seen for other warning signs on this corridor, and as seen on the Wolf Creek Pass corridor on SH-160. Additionally, the Region should consider the erection of an overturning warning sign with advisory speed and flashing beacon in advance of the current curve warning sign (see example **Figure 4-2**).

Furthermore, diagrammatic warning signage similar to that adopted on the Wolf Creek Pass corridor would be beneficial for the inexperienced driver to more readily identify and be prepared for upcoming changes in alignment, and in raising awareness of the location of the escape ramp (see example **Figure 4-3**).

Regarding the performance of the truck escape ramp, only 1 of the 3 crashes which occurred in advance of the ramp involved brake failure and was recorded at MP 54.40 in 2013. This is almost 2 miles in advance of the escape ramp, and in order to access the ramp the operator would have had to successfully navigate the hairpin curve at MP 54 without brakes, which is unlikely.

The remaining three truck crashes occurred near the hairpin curve at MP 51. Two were guard rail crashes, with one occurring on a wet road and both involving drivers unfamiliar with the area. **Figure 4-141**, **Figure 4-142** and **Figure 4-143**, show the advanced warning signs (in place at the time of the crashes) regarding alignment on the approach to the hairpin curve at MP 51. Despite what appears to be sufficient signage, crashes were still recorded.

A review of available imagery indicates that sometime after October 2021 additional warning signage was erected on westbound US-550 near MP 51.40 in advance of the hairpin bend. When **Figure 4-147** is contrasted with **Figure 4-148**, it is apparent that two additional signs have been erected. Recent imagery from 2024 (**Figure 4-149**) shows that these signs include a combined hairpin curve and advisory speed warning sign, which is solar powered and outlined with LED lights, and a keep left arrow sign. Additional warning signage serves to raise conspicuity of the hairpin curve and alert drivers of the need to slow down.

Figure 4-147: No Signs Present, US550 MP 51.40 SB (facing North), Oct. 2021

Figure 4-148: Additional Signage, US550 MP 51.40 (Approx.) SB (facing North), 2022 (OTIS)

Figure 4-149: New Warning Signs, US550 MP 51.40 (Approx.) SB, Oct. 2024

The third crash was an overturning crash in 2022 due to brake failure. The crash records specifically state that the truck operator "failed to use the runaway truck ramp." There are no details as to why the driver did not or could not use the escape ramp. The crash was recorded at MP 51.10, almost 1.5 miles beyond the escape ramp.

Imagery indicates the first sign for the escape ramp occurs at approximately MP 54.49, 2 miles in advance of the escape ramp (**Figure 4-150**). The second warning sign occurs 1 mile downstream and 1 mile in advance of the escape ramp near MP 53.60 (**Figure 4-151**). The final warning sign for the escape ramp is near MP 52.86, warning the ramp entrance is 1,500 feet ahead, this sign, unlike the previous two, appears to be illuminated (**Figure 4-152**).

Figure 4-150: 1st Escape Ramp Sign, US550 MP 54.49 SB

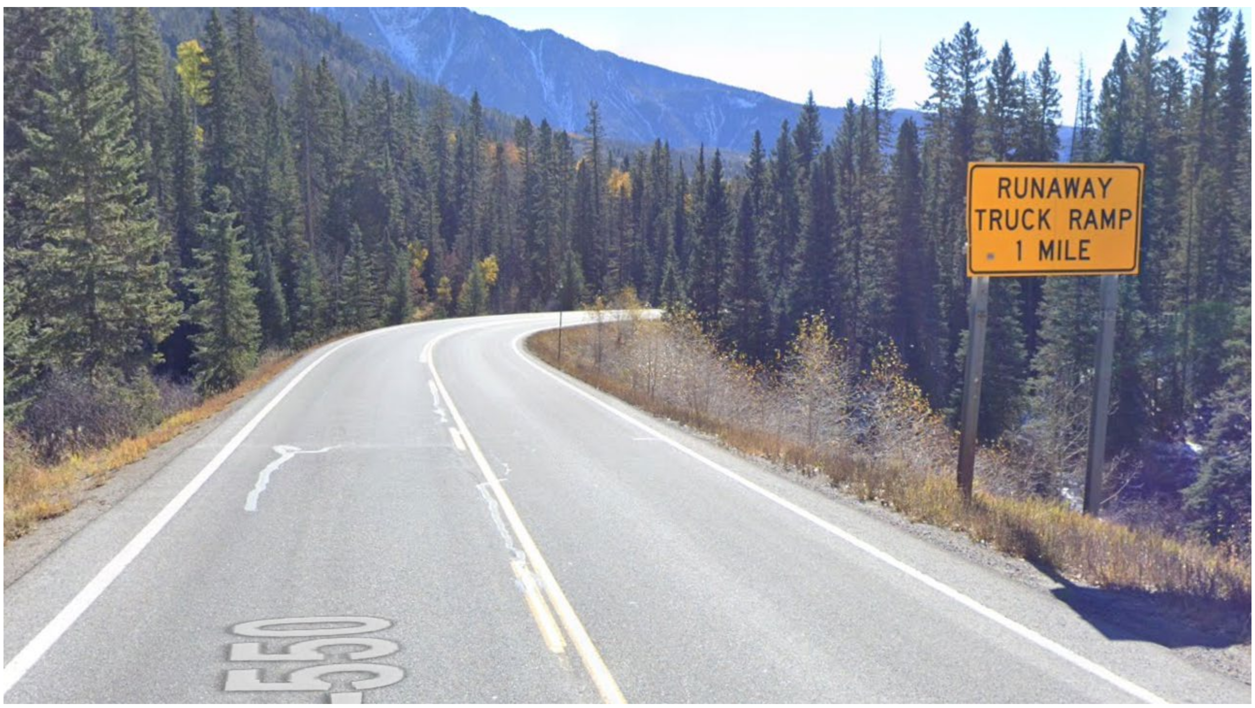

Figure 4-151: 2nd Escape Ramp Sign, US550 MP 53.60 SB

Figure 4-152: 3rd Escape Ramp Sign, US550 MP 52.86 SB

Figure 4-153 shows the entrance to the escape ramp near MP 52.50, the sign appears to be illuminated from below. This figure also shows that the ramp itself curves away from the mainline and out of the field of vision for approaching truck operators. This may cause operators to elect to not use the ramp out of fear of an unsuccessful attempt, which may result in rolling over the embankment.

Figure 4-153: Truck Escape Ramp Entrance, US550 MP 52.50 SB

Crash records are available in Vision Zero Suite from 1/1/2007. When the study window was expanded to include truck crashes on the study corridor from 1/1/2007 through 12/31/2012, records showed an additional 7 southbound crashes, including 4 PDO and 3 Injury level crashes. Crash types were similar to those seen in the 10-year study period, with 3 Overturning, 1 Parked Motor Vehicle and 3 Fixed Object (Guard Rail and Embankment). Road conditions appear to have been more of a contributory factor to crashes in this period, with 4 out of 7 occurring in snowy road conditions, and 1 on a wet road. The influence of driver inexperience/unfamiliarity with the area was still present, but not as high, at 42.9% (3 crashes), rather than over 66% in the more recent study period.

Figure 4-154 shows that southbound truck crashes in the 2007 through 2012 period show the same locational pattern as those in the more recent 10-year study period. That is, most crashes occurred near one of the hairpin bends, at either MP 51 or MP 54.

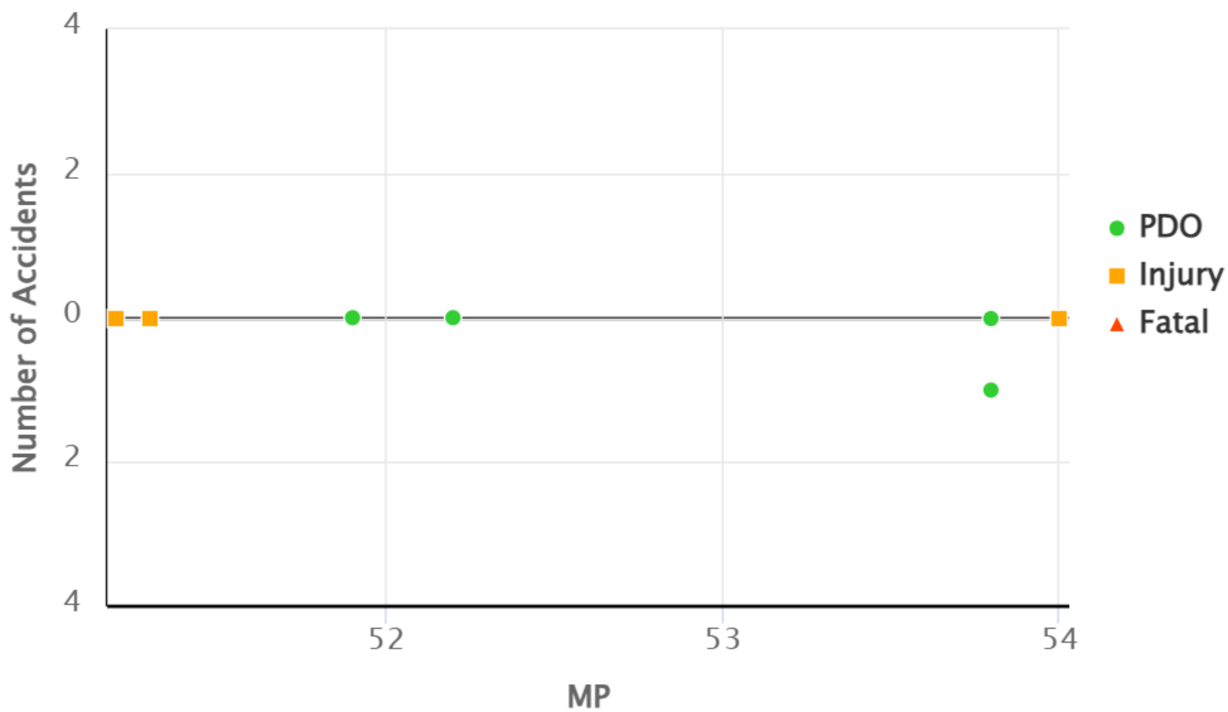

Figure 4-154: SB Truck Crashes, 2007-12, Straight Line Diagram

There are no records in this period either of the truck escape ramp having been used. While initially it may appear that 2 crashes, one at MP 51.90 and one at MP 52.20, might have been candidates for use of the escape ramp, a review of the crash records rules this out. The former was a crash with a parked motor vehicle. The crash record for the latter shows that this was a guard rail crash, however there is no guard rail present, nor has there been historically, at MP 52.20 (**Figure 4-155**). It might be the case that this crash location was incorrectly recorded, and rather occurred at MP 51.20, where there is guard rail.

Figure 4-155: US550 MP 52.20 SB

As such, from 2007 through 2022 there are no recorded incidents of the escape ramp having been used, and only one recorded instance which indicates that the ramp could have been used but was not. There was one other crash in the 2007-2012 period, and involved brake failure, which might indicate a scenario in which the escape ramp could have been utilized, depending on when failure occurred. The crash recorded at MP 51.28 in 2010, which resulted in a collision with guard rail, involved a driver unfamiliar with the area.

With two crashes which might have benefitted from use of the escape ramp, this emphasizes that reconsideration of the current warning and guidance signage along the corridor for truck operators should be made, moreover because the entrance to the ramp itself, being curved, is not particularly inviting for drivers. The previous recommendations made in this section would benefit run-off-the-road truck crashes westbound, especially for the unfamiliar/inexperienced driver. That is, a signing, detection and warning system similar to that employed at the Wolf Creek Pass (SH-160) would be appropriate. This would involve enhancing advance warning signs with flashing beacons and blank-outs, activated by detected runaway trucks, providing real-time feedback to truck operators, and implementation of diagrammatic "story" signs which outline in detail the location of severe curves and the truck escape ramp for truck operators, relative to their position, enabling them to make better informed decisions and adjust driving style appropriately. See **Figure 4-1**, **Figure 4-2** and **Figure 4-3** for example on Wolf Creek Pass.

Conclusions And Recommendations

The intent of the report was to provide a safety assessment using directional SPF analysis, of the US-550 corridor surrounding the Coal Bank Pass truck escape ramp located near MP 52.50, and to provide an evaluation of the performance of the truck escape ramp. The analysis was focused on the southbound US-550 corridor between MP 51.00 and MP 54.50 to capture the effects of the ramp.

This report is based on the comprehensive analysis of 10 years of crash history (1/1/2013-12/31/2022), traffic volume and operations data available from the CDOT OTIS website and databases. The Region is advised to verify through field survey the information included in this report regarding physical features and roadside characteristics in the study area.

Southbound

Southbound the study corridor is characterized by a downhill grade and horizontal curves. The level of service of safety was determined to be LOSS-IV for corridor in terms of both total crash frequency and crash severity. This represents high potential for crash reduction.

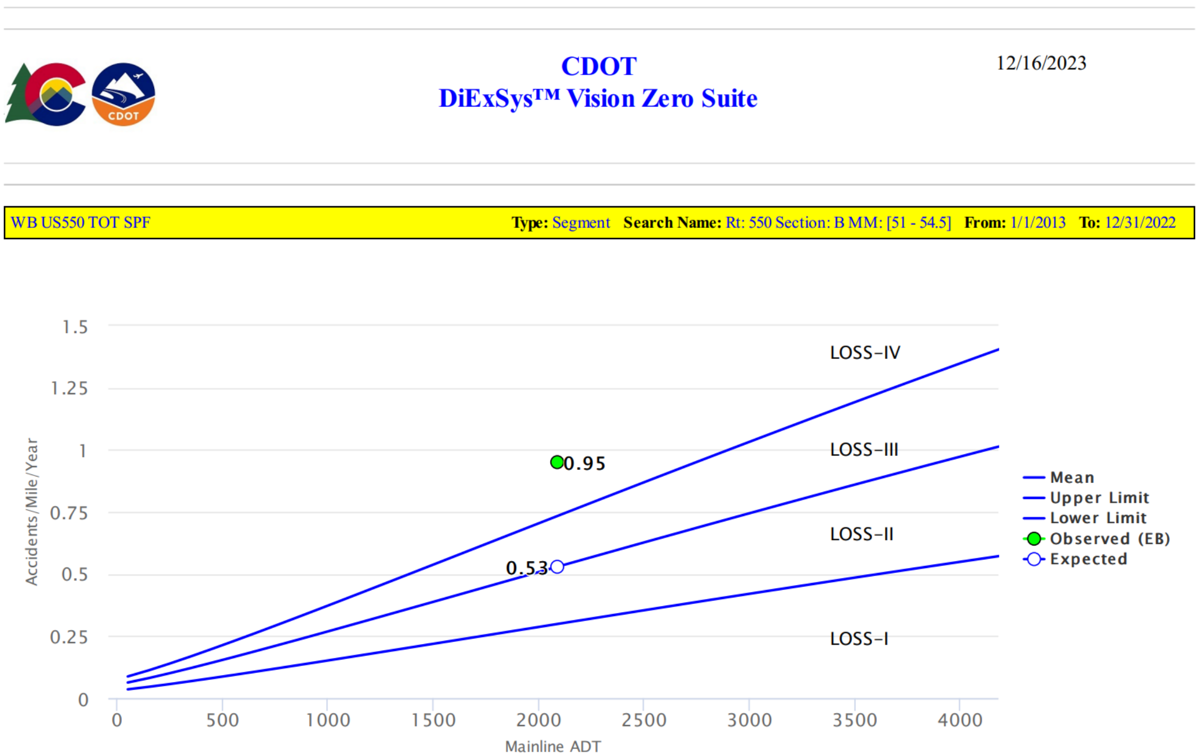

Figure 4-156: SPF Total Crashes US-550 Southbound

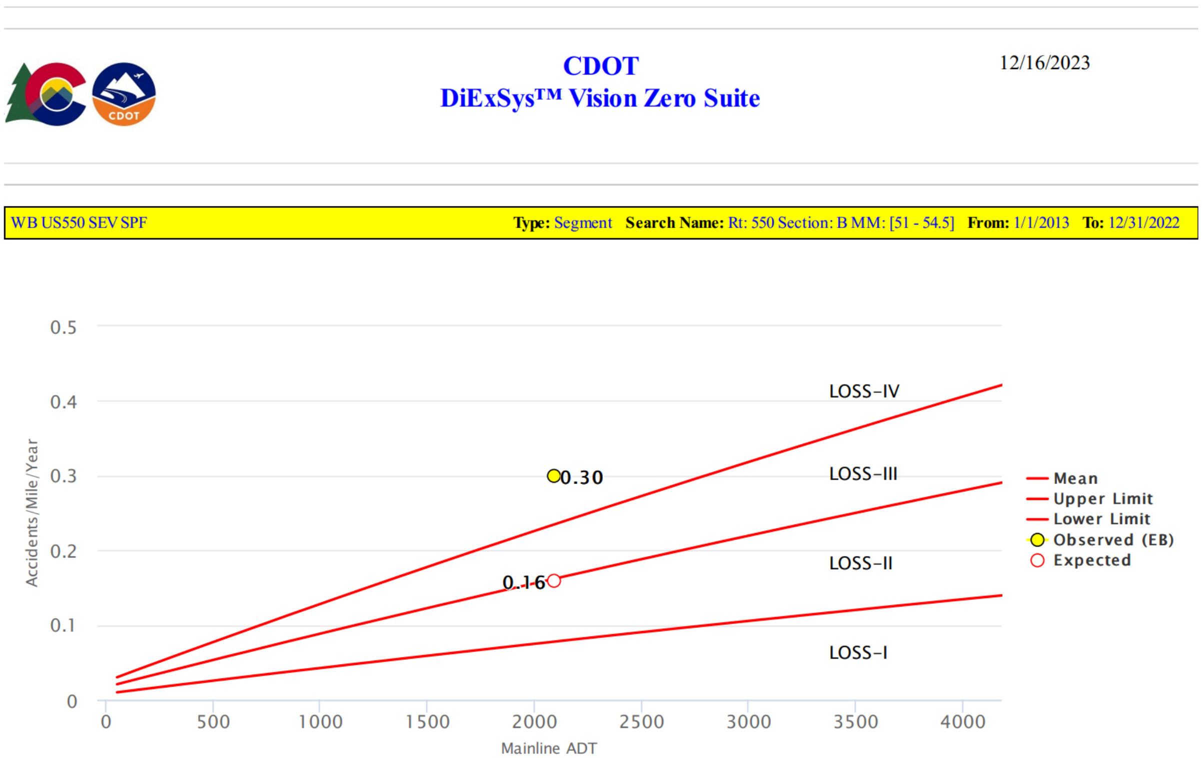

Figure 4-157: SPF INJ+FAT Crashes US-550 Southbound

Most southbound patterns were correlated with roadway geometrics and driver familiarity with the area/driver experience. Patterns were representative of run-off-the-road crashes, (e.g. overturning crashes, guard rail). The corridor also displayed a pattern of Injury level crashes. A large degree of overlap was found between all crash patterns. This indicates that the challenging mountainous environment with frequent changes in alignment on a downgrade, is proving increasingly hazardous for inexperienced drivers and drivers unfamiliar with the area. It was found that all crash patterns were heavily represented by motorcycles and trucks combined, but more so by motorcycles.

There are two hairpin curves, (MP 51, MP 54), at which most crashes were recorded, indicating motorcycle and truck operators are having particular difficulty navigating the hairpin bends. Crashes near MP 54 were also found to have an overlapping Dawn/Dusk conditions pattern. The guardrail crashes near MP 51 showed a tendency to occur under adverse winter road conditions involving inexperienced drivers and drivers unfamiliar with the area.

General recommendations for the southbound direction can be summarized as follows:

- Install a SLIPPERY CONDITIONS warning sign (MUTCD W8-5) with supplementary “ICE” plaque (MUTCD W8-5aP) in advance of MP 52.14,
- Install gated “MOTORCYCLES USE EXTREME CAUTION” warning signs with supplementary “NEXT 4 MILES” plaques near the beginning of the study corridor (MP 54.50), and
- Increase the frequency of reflective delineator posts between MP 54.40 and MP 53.30, include posts which are entirely covered in reflective material, (rather than just having

reflective buttons), and wrap existing sign supports in this segment with reflective tape/backing, alternatively, consider the erection of reflective chevrons through the segment. These measures will also benefit truck crashes on this segment.

Truck crashes were found to be either Overturning or Guard Rail crashes, all occurring near the hairpin bends. Driver inexperience and driver unfamiliarity with the area were found to be significant contributory factors to truck crashes (66.6%). A situation with abrupt changes in alignment on a mountainous downgrade are creating challenging conditions for truck operators inexperienced in this driving environment, resulting in severe run-off-the-road crashes.

There were no recorded uses of the escape ramp at MP 52.50, but one crash showed circumstances in which the ramp would have been of benefit. It involved brake failure, but why the driver did not or could not utilize the ramp was not included. When records for truck crashes back to 2007 were analyzed, they showed the same locational pattern. One additional brake failure crash was found in which the escape ramp might have been utilized but was not. Notably that the escape ramp curves away from the mainline and field of vision of truck operators, which may cause drivers to elect to not use the ramp due to a fear of unsuccessful access and overturning.

There are existing curve warning and low gear warning signs before the curve at MP 51, however crashes continue to be recorded there. There are advance warning signs for the escape ramp at 2 miles, 1 mile and 1,500 feet in advance of the ramp, but the ramp has not recorded a use in 16 years, although some cases might have merited it.

Recommendations for the southbound direction related to truck crashes can be summarized as follows:

- Add flashing beacons to the hairpin curve warning sign near MP 54,
- Add an OVERTURNING warning sign with advisory speed limit and flashing beacons or blank-outs in advance of the curve warning sign approaching MP 54,
- Install a diagrammatic “story” sign at the beginning of the corridor indicating driver’s location relative to significant curves and the truck escape ramp,
- Implement enhanced runaway truck signing, warning and guidance system to include blank-outs and flashing beacons on advance warning signs, as well as vehicle detection and guidance, overhead diagrammatic warning signs with pertinent locational information. Sufficient solar paneling and battery supply to be provided.

A primary feature of this report was the *directional* evaluation of the safety performance of the corridor. As such, it is necessary to acknowledge as part of any conclusions that the highest safety concerns regard the southbound direction. Crash distribution is predominantly in this direction, the direction of the escape ramp, with 66.9% of crashes occurring southbound. It is southbound that safety performance in terms of both total crash frequency and crash severity is poorer and that there is higher potential for crash reduction.

Chapter 5 - Breakeven Analysis and Project Ranking

Each truck escape ramp location which was evaluated is unique in terms of geometry, existing infrastructure (in terms of power supply and/or fiber cable access), and existing warning signage. For these reasons the most sensible approach to determining cost effectiveness of the implementation of any truck warning, detection and signage system is the break-even analysis.

The before/after study for Wolf Creek Pass indicated a reduction in all eastbound crashes, and eastbound commercial vehicle crashes, except for crashes at the fatal level. A factor to be considered, which is not always available via crash records alone due to under reporting of crashes, would be any data showing if there has been an increase in the use of the truck escape ramp post-implementation of the warning and detection system. This would be expected if the system has been as effective as crash records suggest. Furthermore, while results indicate that the truck signing, detection and warning system has very likely been influential in the reduction of eastbound truck crashes, it is difficult to say with certainty to what degree. This is due partly to the multi-factorial nature of the complete system effects: crash reduction may have been due to the overhead diagrammatic warning signage, or to detectors combined with the enhancement of existing warning signs with flashing beacons and blank-outs displaying real-time feedback for truck operators. Without more granular information on which aspect of the system exactly might have been more influential for truck operators, the most conservative measure is to assume that the system as a whole functions to precipitate crash reduction. As such, for locations where adoption of the system has been advised, it is recommended that *both* aspects of the system be deployed i.e. the overhead diagrammatic warning signage and the real time enhanced detection and warning signage.

Additionally, it must be remembered that all of these recommendations are being made within the context of crashes involving runaway trucks in mountainous environments where brake failure is often a precipitating factor. Because of the nature of these crashes, reaction time is of the essence. As such, it would not be advisable to implement any system which would necessitate a time lag, often due to the transfer of communication messaging between the controller for detection signage and a central data hub or traffic management location. Rather, it is necessary that decisions be made almost instantaneously on-location to deploy warning messages to affect the fastest response by truck operators. With this in mind, as well as practicality and cost-effectiveness, the most appropriate solution would be to implement solar powered detection and blank-out warning signage. However, because some cases of truck ramp access occurred in winter weather and given the mountainous climate within which these ramps are located, it is crucial that any design provide sufficient solar panels *and* battery power to equipment. Maintenance efforts should also be adjusted to ensure that panels are kept as clear as possible in winter weather. The incorporation of a potential recording system to notify a traffic management hub may be a consideration to include as an additional feature, however, as stipulated, with these crashes not having the luxury of time, it should not be the primary means of operation for warning activation.

In order to maintain appropriate levels of conservativism when approaching the Break-Even Analysis (BEA), while all eastbound crashes on the Wolf Creek Pass project were considered in estimating crash reduction factors as part of the before/after benefit cost analysis, only the results witnessed for commercial vehicle involved eastbound crashes are used in determining crash reduction factors for the BEA for other ramp locations. From the Wolf Creek Pass analysis these numbers were: a 59% reduction in eastbound truck PDO crashes, and a 48% reduction in the number of people injured in eastbound truck crashes. As outlined previously, there was no difference observed in fatal truck crashes.

Loveland Pass And Slick Rock Hill Pass

Crashes involving trucks on both the Loveland and Slick Rock Hill passes were particularly infrequent, even when the study period was expanded to a 10-year window (1/1/2013 – 12/31/2022). At both locations only 2 truck crashes were recorded in that period. Furthermore, no recorded uses of the escape ramps at these locations were identified.

Because of the commercial vehicle crash history at both locations, and because both corridors are characterized by an apparent lack of power and fiber network, while a signing, detection and warning system such as that on WCP might increase safety on the corridor, the measures would be unlikely to prove cost effective. In conclusion, a system similar to that on WCP is not recommended for either the Loveland or the Slick Rock Hill Pass locations and consequently a breakeven analysis has not been performed for these locations.

Breakeven Analysis Approach

A similar system to that on WCP was recommended at all other TER locations:

- Rabbit Ears Pass
- Monarch Pass
- Upper & Lower Vail Pass
- Upper & Lower Straight Creek Pass
- Mount Vernon Canyon and
- Coal Bank Hill

The field visits performed by Stolfus determined that:

- At the Mt. Vernon Canyon Pass escape ramp there is power available on both sides of the corridor through the study area, while fiber optic markers were visible on the western portion of the corridor, but not within one mile of the escape ramp,
- At the Upper and Lower Vail Pass escape ramps both power and fiber optic markers are present on the westbound side of the highway through the study area, including within 20 feet of both escape ramp entrances, and
- At the Upper and Lower Straight Creek Pass escape ramps both power and fiber optic markers are present on the westbound side of the study section.

Notwithstanding the above information, as has been outlined previously, because each location involved in this project is unique in terms of geometry, existing infrastructure (in terms of power supply and/or fiber cable access), and existing warning signage, the most sensible approach to determine cost effectiveness of the implementation of any truck warning, detection and signage system is the break-even analysis.

The breakeven analysis calculates the maximum cost of system implementation at each location, ensuring it equals the expected savings from reduced truck crashes at all levels of severity. It also factors in annual maintenance costs of $2,500.

To analyze breakeven costs at recommended locations, the study identified relevant commercial vehicle crashes that could have been prevented by the system. This involved evaluating each commercial vehicle crash using engineering judgment, knowledge of common crash patterns unique to Colorado's mountainous terrain, and findings from the Literature Review, to determine inclusion of exclusion of a crash from the analysis. This was completed for all of the truck escape ramp study locations.

Crashes were included or excluded based on their characteristics and whether the system on WCP would likely have helped mitigate them. Additionally, any crash where the use of an escape ramp was explicitly recorded was automatically included in the breakeven analysis.

For example, if a truck lost control on icy roads and jackknifed, the system was deemed unlikely to have helped. However, if a crash involved mechanical failure, or malfunction, or roadway departure in dry conditions within reasonable proximity of the escape ramp, it was considered likely that the system could have mitigated the incident.

For each location a table has been provided which outlines the date, location, severity, serial number, human contributing factor and crash type for each commercial vehicle crash. Additionally, the status was recorded as "include" or "exclude" and a brief "rationale" for the evaluation of status is also provided.

The following sections provide the detailed breakeven analysis for each of the six escape ramp locations listed above.

Breakeven Analysis – Rabbit Ears Pass (Westbound US-40, MP 145.00-141.00)

Table 5-1 provides the rationale and engineering judgment behind the inclusion or exclusion of recorded truck crashes on westbound Rabbit Ears Pass in the study period for use in the BEA.

Table 5-2 shows the BEA for the implementation of an enhanced truck signage, detection and warning system on westbound US-40 for the Rabbit Ears Pass escape ramp. Assuming a 20-year service life and up to $2,500 in annual maintenance, it shows the measure is estimated to be cost-effective up to approximately $2.48M.

Table 5-1: Included/Excluded Truck Crashes for Rabbit Ears Pass Break-Even Analysis

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
144.9	3/21/2013	No Injury (PDO)	13506593	Driver Inexperience	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road, distance from ramp.
144.8	4/22/2013	No Injury (PDO)	13509146	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road, distance from ramp.
144.8	1/23/2019	No Injury (PDO)	243814	Aggressive Driving	Embankment or Ditch	Exclude	Snow/ice, distance from ramp.
144	3/11/2016	No Injury (PDO)	16509416	Driver Preoccupied	Large Boulder	Exclude	Large rocks/boulders, distance from ramp.
144	10/25/2022	No Injury (PDO)	274681	Driver Unfamiliar with Area	Trees or Shrubs	Exclude	Lost control in snow/ice, off-left, distance from ramp.
143.5	11/21/2019	No Injury (PDO)	347515	No Apparent Contributing Factor	Large Boulder	Exclude	Large rocks/boulders, distance from ramp.
142.6	6/26/2014	No Injury (PDO)	14516780	Driver Unfamiliar with Area	Delineator Post	Include	Off-right, loss of brake pressure in close proximity to ramp.
142.1	4/16/2013	No Injury (PDO)	13508190	No Apparent Contributing Factor	Embankment or Ditch	Include	Escape ramp used.
142.1	2/19/2017	No Injury (PDO)	285	No Apparent Contributing Factor	Other non-collision	Include	Escape ramp used.
142.09	3/12/2015	Evident, Incapacitating (A)	15507419	No Apparent Contributing Factor	Overturning	Include	Overturning on curve at ramp.
142	11/20/2020	No Injury (PDO)	32525	Driver Inexperience	Trees or Shrubs	Include	Escape ramp used.
141.5	2/19/2019	No Injury (PDO)	257744	Aggressive Driving	Embankment or Ditch	Exclude	Lost control in snow/ice, distance from ramp.
141.19	9/8/2013	Possible/Complaint of Injury (C)	13518218	Driver Unfamiliar with Area	Overturning	Include	Brake loss, off-right, proximity to ramp.
141.1	11/13/2015	No Injury (PDO)	15531240	Driver Inexperience	Overturning	Include	Overturning on sharp curve beyond ramp in dry conditions (would benefit from diagrammatics).
141.1	11/22/2022	Evident, Incapacitating (A)	280660	Driver Inexperience	Concrete Barrier	Include	Overturning on sharp curve beyond ramp in dry conditions (would benefit from diagrammatics).
141.07	10/31/2016	Fatal (K)	16539667	Driver Unfamiliar with Area	Overturning	Include	Overturning on sharp curve beyond ramp in dry conditions (would benefit from diagrammatics).

Table 5-2: Breakeven Analysis of Enhanced Truck Signing, Detection & Warning System on WB US-40 MP 145.00 – 141.00

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/04/2025

WB Truck Signing Detection Warning System — **Loc:** 40 A **Begin:** 141 **End:** 145 **From:** 1/1/2013 **To:** 12/31/2022

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 5	1 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 1	0 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 0	2 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 2	1 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 1		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost:	$2,487,047
Years in Crash Search:	10.00
CRF 1 Type:	Runaway Truck Signage, Detection & Warning System for Curves & Escape Ramps
Notes:	Breakeven Analysis - Westbound commercial vehicle crashes.
Benefit/Cost Ratio:	1
CRF 2 Type:	
CRF 3 Type:	
CRF 4 Type:	

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Breakeven Analysis - Monarch Pass (Eastbound US-50, MP 201.00-204.75)

Table 5-3 provides the rationale and engineering judgment behind the inclusion or exclusion of recorded truck crashes on eastbound Monarch Pass in the study period for use in the BEA.

Table 5-4 shows the BEA for the implementation of an enhanced truck signage, detection and warning system on eastbound US-50 for the Monarch Pass escape ramp. Assuming a 20-year service life and up to $2,500 in annual maintenance, it shows the measure is estimated to be cost-effective up to approximately $2.02M.

Table 5-3: Included/Excluded Truck Crashes for Monarch Pass Break-Even Analysis

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
201.1	3/16/2021	No Injury (PDO)	103123	Driver Unfamiliar with Area	Head On	Exclude	Lost control in snow/ice, on road, distance from ramp.
201.4	8/3/2013	No Injury (PDO)	13515655	Driver Unfamiliar with Area	Guard Rail	Exclude	No mechanical failure, distance from ramp.
201.8	2/9/2015	Evident, Incapacitating (A)	15503986	No Apparent Contributing Factor	Guard Rail	Include	Described conditions suggest potential brake failure, overturning off road.
201.8	4/19/2016	No Injury (PDO)	16513180	No Apparent Contributing Factor	Head On	Exclude	Vehicle 1 snow plough.
201.8	5/29/2019	No Injury (PDO)	289611	No Apparent Contributing Factor	Rear End	Exclude	Rear end on road in snow/ice.
203.5	2/22/2016	No Injury (PDO)	16505890	Driver Inexperience	Parked Motor Vehicle	Exclude	Lost control in snow/ice, on road, avoiding parked emergency vehicle in lane.
203.5	2/22/2016	No Injury (PDO)	16506317	Other Factor (Describe in Narrative)	Parked Motor Vehicle	Exclude	Lost control in snow/ice avoiding previous crash.
203.5	9/19/2020	Fatal (K)	20399	Driver Unfamiliar with Area	Overturning	Include	Brake failure prior to ramp.
204.01	8/1/2018	No Injury (PDO)	220167	Driver Inexperience	Rear End	Exclude	Rear end on road in dry conditions.
204.3	1/9/2016	Evident Non-Incapacitating (B)	16500851	Driver Preoccupied	Overturning	Include	Lost control on curve near ramp, overturning (benefit from diagrammatics)
204.4	7/24/2017	No Injury (PDO)	51796	Driver Unfamiliar with Area	Large Boulder	Exclude	Large boulder.
204.5	7/16/2020	Possible/Complaint of Injury (C)	411732	Driver Unfamiliar with Area	Traffic Sign or Post or Overhead Sign Structure	Include	Lost control on curve near ramp, overturning (benefit from diagrammatics)
204.5	2/7/2022	No Injury (PDO)	200835	Driver Unfamiliar with Area	Embankment or Ditch	Include	Lost control on curve near ramp, overturning (benefit from diagrammatics)

Table 5-4: Breakeven Analysis of Enhanced Truck Signing, Detection & Warning System on EB US-50 MP 201.00 – 204.75

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/04/2025

EB Truck Signing Detection Warning System — **Loc:** 50 A **Begin:** 201 **End:** 204.75 **From:** 1/1/2013 **To:** 12/31/2022

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 1	2 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 1	1 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 1	1 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 1	1 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 1		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost: $2,020,537
Years in Crash Search: 10.00
CRF 1 Type: Runaway Truck Signage, Detection & Warning System for Curves & Escape Ramps
Notes: Breakeven Analysis - Eastbound commercial vehicle crashes.
Benefit/Cost Ratio: 1
CRF 2 Type:
CRF 3 Type:
CRF 4 Type:

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Breakeven Analysis – Upper and Lower Vail Pass (Westbound I-70, MP 181.30-189.60)

Table 5-5 provides the rationale and engineering judgment behind the inclusion or exclusion of recorded truck crashes on westbound Upper and Lower Vail Pass in the study period for use in the BEA.

Table 5-6 shows the BEA for the implementation of an enhanced truck signage, detection and warning system on westbound I-70 for the Upper and Lower Vail Pass escape ramps. Assuming a 20-year service life and up to $2,500 in annual maintenance, it shows the measure is estimated to be cost-effective up to approximately $6.32M.

Table 5-5: Included/Excluded Truck Crashes for Upper & Lower Vail Pass Break-Even Analysis

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
189.5	7/16/2016	No Injury (PDO)	16526257	Other Factor (Describe in Narrative)	Wild Animal	Exclude	Wild animal
189.5	11/19/2017	No Injury (PDO)	108491	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same on-road, distance from ramp.
189.5	2/9/2020	No Injury (PDO)	392885	Driver Inexperience	Embankment or Ditch	Exclude	Off-right in snowy conditions, distance from ramp.
189.2	9/9/2022	Evident Non-Incapacitating (B)	269127	Driver Unfamiliar with Area	Rear End	Exclude	Rear-end on road.
189.1	1/19/2016	No Injury (PDO)	16502224	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same on-road, distance from ramp.
189.1	6/20/2017	Possible/Complaint of Injury (C)	31578	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same on-road, distance from ramp.
189.1	12/14/2019	No Injury (PDO)	358590	Driver Unfamiliar with Area	Other non-collision	Exclude	Off-right in snowy conditions, distance from ramp.
189	4/17/2013	Possible/Complaint of Injury (C)	13508101	Driver Preoccupied	Rear End	Exclude	Rear-end on road in snow/ice, distance from ramp.
189	3/16/2021	No Injury (PDO)	104090	No Apparent Contributing Factor	Embankment or Ditch	Exclude	Embankment avoiding previous crash, distance from ramp.
189	12/1/2021	No Injury (PDO)	175829	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same on-road, distance from ramp.
189	5/20/2022	Evident Non-Incapacitating (B)	228565	Driver Inexperience	Overturning	Exclude	Lost control in ice/snow, distance from ramp.
188.9	2/3/2019	No Injury (PDO)	246655	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
188.9	2/20/2019	No Injury (PDO)	255278	Driver Unfamiliar with Area	Rear End	Exclude	Rear-end in ice on road.
188.9	2/27/2020	No Injury (PDO)	393210	No Apparent Contributing Factor	Embankment or Ditch	Exclude	Lost control in ice/snow, distance from ramp.
188.9	3/16/2021	No Injury (PDO)	103285	Unknown	Sideswipe Same Direction	Exclude	Avoiding previous crash lost control in ice/snow, distance from ramp.
188.9	3/16/2021	No Injury (PDO)	103385	Driver Inexperience	Embankment or Ditch	Exclude	Avoiding previous crash lost control in ice/snow, distance from ramp.
188.9	10/26/2021	No Injury (PDO)	303862	Unknown	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
188.8	11/20/2019	No Injury (PDO)	348143	Driver Inexperience	Embankment or Ditch	Exclude	Lost control in ice/snow, distance from ramp.
188.7	8/16/2016	No Injury (PDO)	16529667	No Apparent Contributing Factor	Overturning	Exclude	Distance from ramp & avoidance of leading vehicle.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
188.7	2/5/2018	No Injury (PDO)	134262	Driver Unfamiliar with Area	Embankment or Ditch	Exclude	Snow/ice conditions, distance from ramp.
188.5	12/28/2019	No Injury (PDO)	364092	Driver Inexperience	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
188.4	6/28/2015	No Injury (PDO)	15517017	No Apparent Contributing Factor	Concrete Barrier	Include	Loss of control on curve in dry weather.
188.3	1/29/2020	No Injury (PDO)	391076	No Apparent Contributing Factor	Embankment or Ditch	Exclude	Lost control in ice/snow, distance from ramp.
188.2	11/2/2021	No Injury (PDO)	304441	Driver Inexperience	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
188.1	12/5/2015	No Injury (PDO)	15533603	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
188	2/7/2014	No Injury (PDO)	14503951	No Apparent Contributing Factor	Concrete Barrier	Exclude	Avoiding previous crash lost control in ice/snow, distance from ramp.
188	1/20/2019	No Injury (PDO)	241355	No Apparent Contributing Factor	Embankment or Ditch	Exclude	Lost control in ice/snow, distance from ramp.
188	12/8/2021	No Injury (PDO)	306224	Driver Inexperience	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
187.9	2/2/2017	No Injury (PDO)	723	No Apparent Contributing Factor	Embankment or Ditch	Exclude	Snow/ice conditions, distance from ramp.
187.9	1/27/2022	No Injury (PDO)	307346	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
187.8	4/22/2013	No Injury (PDO)	13509257	Driver Unfamiliar with Area	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
187.7	1/26/2013	No Injury (PDO)	13501536	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
187.67	2/21/2022	No Injury (PDO)	206003	Driver Inexperience	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
187.6	1/20/2018	No Injury (PDO)	133133	Other Factor (Describe in Narrative)	Sideswipe Same Direction	Exclude	Sideswipe same on-road, distance from ramp.
187.6	4/16/2020	No Injury (PDO)	395093	No Apparent Contributing Factor	Concrete Barrier	Exclude	Snow/ice conditions, distance from ramp.
187.5	1/13/2014	No Injury (PDO)	14501281	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same on-road.
187.5	2/6/2014	No Injury (PDO)	14503244	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
187.5	8/28/2014	Possible/Complaint of Injury (C)	14521332	Driver Inexperience	Embankment or Ditch	Include	Lost control on curve in rain in advance of ramp.
187.5	4/5/2016	Evident Non-Incapacitating (B)	16512144	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
187.5	4/4/2017	No Injury (PDO)	8449	No Apparent Contributing Factor	Other non-collision	Exclude	Snow/ice conditions, distance from ramp.
187.5	2/7/2017	Evident Non-Incapacitating (B)	17504408	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
187.5	12/11/2020	No Injury (PDO)	37543	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
187.5	2/16/2021	Possible/Complaint of Injury (C)	108569	Driver Inexperience	Embankment or Ditch	Exclude	Lost control in ice/snow, distance from ramp.
187.25	4/12/2022	No Injury (PDO)	218345	Driver Unfamiliar with Area	Concrete Barrier	Exclude	Lost control in ice/snow, distance from ramp.
187.2	4/27/2014	No Injury (PDO)	14509606	No Apparent Contributing Factor	Rear End	Exclude	Rear end in ice avoiding previous crash.
187.2	10/23/2015	No Injury (PDO)	15528945	Driver Inexperience	Other non-collision	Exclude	Lost control in ice/snow, distance from ramp.
187.2	1/20/2019	No Injury (PDO)	243245	Aggressive Driving	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
187.1	2/7/2014	No Injury (PDO)	14503245	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice avoiding lead vehicle & previous crash.
187.01	12/11/2020	No Injury (PDO)	36351	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
187	3/7/2016	No Injury (PDO)	16508522	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
187	12/11/2020	No Injury (PDO)	38166	Driver Inexperience	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
186.6	12/21/2018	No Injury (PDO)	233581	Other Factor (Describe in Narrative)	Embankment or Ditch	Exclude	Avoiding previous crash.
186.4	4/15/2016	No Injury (PDO)	16512657	No Apparent Contributing Factor	Concrete Barrier	Exclude	Parked motor vehicle in snow/ice.
186.4	5/27/2016	Evident Non-Incapacitating (B)	16520155	No Apparent Contributing Factor	Embankment or Ditch	Include	Rain, proximity to ramp.
186.4	11/16/2021	Evident, Incapacitating (A)	305276	Driver Unfamiliar with Area	Large Boulder	Include	Overturning off-right dry conditions, proximity to ramp.
186.1	10/4/2013	No Injury (PDO)	13520816	Other Factor (Describe in Narrative)	Sideswipe Same Direction	Exclude	Sideswipe same direction in snow/ice.
186.1	10/4/2013	No Injury (PDO)	13520527	Other Factor (Describe in Narrative)	Sideswipe Same Direction	Exclude	Sideswipe same direction in snow/ice.
186.1	2/4/2014	Evident Non-Incapacitating (B)	14503566	No Apparent Contributing Factor	Rear End	Exclude	Violation blocking lane.
186.1	12/26/2016	Possible/Complaint of Injury (C)	16548076	No Apparent Contributing Factor	Embankment or Ditch	Include	Loss of control, intentionally drove off-right, proximity to ramp.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
186.02	11/20/2017	No Injury (PDO)	109541	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
186	10/30/2013	Possible/Complaint of Injury (C)	13522262	No Apparent Contributing Factor	Embankment or Ditch	Exclude	Avoiding previous crash jackknifed on ice.
186	10/30/2013	Possible/Complaint of Injury (C)	13522268	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Pile up due to previous crash blocking all lanes.
186	1/3/2015	Possible/Complaint of Injury (C)	15500104	Driver Inexperience	Embankment or Ditch	Exclude	Lost control in snow/ice jackknifing leaving the roadway.
186	3/14/2016	No Injury (PDO)	16509607	Driver Unfamiliar with Area	Other non-collision	Exclude	Lost control in snow/ice jackknifing.
186	10/23/2017	No Injury (PDO)	78788	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
186	4/11/2019	No Injury (PDO)	272347	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
186	4/2/2020	Evident Non-Incapacitating (B)	396192	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control on snow/ice off left.
186	4/2/2020	Evident Non-Incapacitating (B)	395547	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice.
186	4/27/2021	No Injury (PDO)	125407	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control on snow/ice off left.
186	3/9/2022	No Injury (PDO)	211585	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control on snow/ice, jackknifed on-road.
186	8/19/2022	Evident Non-Incapacitating (B)	253983	Driver Emotionally Upset	Concrete Barrier	Include	Overturning dry conditions, proximity to ramp.
185.9	10/10/2013	No Injury (PDO)	13520977	Driver Inexperience	Other non-collision	Exclude	Lost control on snow/ice, jackknifed on-road.
185.8	7/7/2014	Possible/Complaint of Injury (C)	14515873	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
185.8	11/19/2014	No Injury (PDO)	14529655	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
185.8	1/19/2022	No Injury (PDO)	196364	No Apparent Contributing Factor	Rear End	Exclude	Rear end on-road.
185.6	2/4/2020	No Injury (PDO)	392558	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
185.5	4/11/2013	No Injury (PDO)	13507973	Driver Inexperience	Embankment or Ditch	Include	Use of escape ramp.
185.5	3/29/2016	Possible/Complaint of Injury (C)	16510948	No Apparent Contributing Factor	Overturning	Include	Avoiding collision, left road prior to recorded MP, proximity to ramp.
185.5	1/21/2019	Possible/Complaint of Injury (C)	243086	Aggressive Driving	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
185.5	1/21/2019	No Injury (PDO)	243855	No Apparent Contributing Factor	Guard Rail	Exclude	Lost control in snow/ice, avoiding collision beyond ramp.
185.4	3/29/2016	No Injury (PDO)	16510904	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, jackknifed.
185.4	2/16/2020	No Injury (PDO)	394934	Driver Inexperience	Parked Motor Vehicle	Exclude	Positional violation.
185.2	10/5/2016	Possible/Complaint of Injury (C)	16538114	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice on road.
185.2	3/6/2017	No Injury (PDO)	3504	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice.
185.19	12/8/2022	No Injury (PDO)	319653	Driver Unfamiliar with Area	Other Object	Exclude	Lost control in snow/ice beyond ramp.
185.1	6/18/2015	Possible/Complaint of Injury (C)	15515382	No Apparent Contributing Factor	Rear End	Exclude	Rear end on road.
185	11/15/2014	No Injury (PDO)	14529285	Aggressive Driving	Concrete Barrier	Exclude	Lost control in snow/ice beyond ramp.
185	6/26/2019	No Injury (PDO)	297074	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
185	3/20/2020	No Injury (PDO)	393273	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction in snow/ice.
185	11/17/2021	No Injury (PDO)	172339	Driver Unfamiliar with Area	Overturning	Exclude	Lost control in snow/ice beyond ramp.
185	11/17/2021	No Injury (PDO)	174528	Driver Unfamiliar with Area	Other non-collision	Exclude	Lost control in snow/ice jackknifing in roadway.
185	11/17/2021	No Injury (PDO)	306309	Driver Unfamiliar with Area	Sideswipe Same Direction	Exclude	Sideswipe same direction in snow/ice.
184.99	3/14/2016	No Injury (PDO)	16509278	Driver Unfamiliar with Area	Concrete Barrier	Exclude	Lost control in snow/ice, distance from ramp.
184.97	12/16/2016	No Injury (PDO)	16546797	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice on road.
184.9	2/8/2014	No Injury (PDO)	14503422	Driver Inexperience	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on roadway.
184.9	3/27/2014	No Injury (PDO)	14508467	Driver Unfamiliar with Area	Sideswipe Same Direction	Exclude	Sideswipe same direction in snow/ice.
184.9	11/21/2016	Possible/Complaint of Injury (C)	16546333	No Apparent Contributing Factor	Other non-collision	Exclude	Sideswipe same direction in snow/ice.
184.8	5/3/2016	No Injury (PDO)	16514930	Aggressive Driving	Crash Cushion, Sand Barrels, or Impact Attenuator	Exclude	Hit construction crash cushion, distance from ramp.
184.8	2/3/2020	No Injury (PDO)	392266	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice on road.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
184.8	12/17/2021	Evident Non-Incapacitating (B)	181868	Driver Inexperience	Sideswipe Same Direction	Exclude	Sideswipe same direction in snow/ice.
184.7	2/2/2022	No Injury (PDO)	197497	Driver Emotionally Upset	Sideswipe Same Direction	Exclude	Rear end in snow/ice on road.
184.6	12/16/2016	No Injury (PDO)	16547040	No Apparent Contributing Factor	Traffic Sign or Post or Overhead Sign Structure	Exclude	Lost control in snow/ice, jackknifed on roadway.
184.5	2/23/2022	No Injury (PDO)	308829	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, jackknifed on roadway.
184.2	5/17/2014	No Injury (PDO)	14510924	No Apparent Contributing Factor	Traffic Sign or Post or Overhead Sign Structure	Exclude	Loss of unsecured trailer.
184.01	5/21/2019	Possible/Complaint of Injury (C)	286249	Driver Unfamiliar with Area	Concrete Barrier	Exclude	Slushy conditions, distance from ramp.
184	7/16/2016	No Injury (PDO)	16526250	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
184	9/15/2019	Possible/Complaint of Injury (C)	324831	No Apparent Contributing Factor	Rear End	Exclude	Rear end on road.
183.974	7/7/2022	No Injury (PDO)	244438	No Apparent Contributing Factor	Vehicle Cargo or Debris	Exclude	Loss of unsecured load.
183.8	3/17/2021	Evident Non-Incapacitating (B)	104335	Driver Inexperience	Rear End	Include	Brake failure in advance of ramp.
183.25	1/16/2019	No Injury (PDO)	243244	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Involving snow ploughs.
183	1/17/2016	No Injury (PDO)	16501385	No Apparent Contributing Factor	Rear End	Exclude	Rear end in snow/ice on road.
183	8/3/2019	Possible/Complaint of Injury (C)	308620	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
182.87	12/23/2021	No Injury (PDO)	189225	Driver Inexperience	Sideswipe Same Direction	Exclude	Lost control in snow/ice on road.
182.7	11/22/2016	No Injury (PDO)	16542986	Driver Inexperience	Concrete Barrier	Exclude	Overturning in icy conditions, off-left, distance from ramp.
182.7	2/16/2022	No Injury (PDO)	204633	Driver Unfamiliar with Area	Rear End	Include	Rear end in snow/ice on road.
182.5	12/10/2016	No Injury (PDO)	16548080	Driver Unfamiliar with Area	Concrete Barrier	Include	Off-right in close proximity to ramp entrance.
182.5	1/26/2021	No Injury (PDO)	47714	No Apparent Contributing Factor	Concrete Barrier	Exclude	Off-left in snow/ice.
182.5	12/27/2022	No Injury (PDO)	292305	Driver Emotionally Upset	Rear End	Exclude	Rear end in snowy conditions.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
182.46	9/21/2017	Fatal (K)	73234	No Apparent Contributing Factor	Other non-collision	Include	Overturning in dry conditions in close proximity to ramp.
182.3	5/24/2019	Evident, Incapacitating (A)	288956	Driver Unfamiliar with Area	Trees or Shrubs	Include	Brake failure adjacent to ramp.
182.3	7/27/2019	Evident, Incapacitating (A)	312011	Driver Inexperience	Rear End	Include	Attempting to access ramp.
182.2	5/31/2015	No Injury (PDO)	15513874	Driver Inexperience	Traffic Sign or Post or Overhead Sign Structure	Include	Escape ramp used.
182.2	8/21/2019	Evident Non-Incapacitating (B)	313432	No Apparent Contributing Factor	Traffic Sign or Post or Overhead Sign Structure	Include	Overturning off-right in dry conditions in close proximity to ramp.
182.1	6/16/2013	No Injury (PDO)	13512177	Driver Unfamiliar with Area	Traffic Sign or Post or Overhead Sign Structure	Include	Escape ramp used.
182.1	9/9/2015	No Injury (PDO)	15523481	No Apparent Contributing Factor	Rear End	Exclude	Rear end on-road beyond ramp.
182	3/9/2021	No Injury (PDO)	100460	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, off left.
182	6/23/2021	No Injury (PDO)	292566	Driver Inexperience	Traffic Sign or Post or Overhead Sign Structure	Include	Escape ramp used.
181.9	12/19/2022	No Injury (PDO)	287816	Driver Inexperience	Sideswipe Same Direction	Exclude	Sideswipe same direction on-road.
181.8	4/22/2015	No Injury (PDO)	15025563	Driver Inexperience	Sideswipe Same Direction	Exclude	Sideswipe same, wet, distance from ramp.
181.6	8/29/2016	No Injury (PDO)	16531831	No Apparent Contributing Factor	Other Object	Exclude	Wild animal
181.4	3/1/2017	No Injury (PDO)	4831	Driver Inexperience	Concrete Barrier	Exclude	Lost control in slush, off-left, distance from ramp.

Table 5-6: Breakeven Analysis of Enhanced Truck Signing, Detection & Warning System on WB I-70 MP 181.30 – 189.60

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/04/2025

WB Truck Signing Detection Warning System	**Loc:** 70 A	**Begin:** 181.3	**End:** 189.6	**From:** 1/1/2013	**To:** 12/31/2022

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 7	5 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 4	7 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 4	6 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 3	1 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 1		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost:	$6,324,226
Years in Crash Search:	10.00
CRF 1 Type:	Runaway Truck Signage, Detection & Warning System for Curves & Escape Ramps.
Notes:	Breakeven Analysis - Westbound commercial vehicle crashes.
Benefit/Cost Ratio:	1
CRF 2 Type:	
CRF 3 Type:	
CRF 4 Type:	

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Breakeven Analysis – Upper & Lower Straight Creek Pass (Westbound I-70, MP 213.00-207.70)

Table 5-7 provides the rationale and engineering judgment behind the inclusion or exclusion of recorded truck crashes on westbound Upper and Lower Straight Creek Pass in the study period for use in the BEA.

Table 5-8 shows the BEA for the implementation of an enhanced truck signage, detection and warning system on westbound I-70 for the Upper and Lower Straight Creek Pass escape ramps. Assuming a 20-year service life and up to $2,500 in annual maintenance, it shows the measure is estimated to be cost-effective up to approximately $2.67M.

Table 5-7: Included/Excluded Truck Crashes for Upper & Lower Straight Creek Pass Break-Even Analysis

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
213	4/21/2017	No Injury (PDO)	2708	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe on road in snow/sleet
213	12/12/2018	No Injury (PDO)	236408	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road, distance from ramp.
213	1/18/2021	No Injury (PDO)	47024	Driver Inexperience	Concrete Barrier	Exclude	Lost control in snow/ice, off-left, distance from ramp.
213	2/4/2021	No Injury (PDO)	50336	Driver Inexperience	Concrete Barrier	Exclude	Lost control in snow/ice, off-left, distance from ramp.
213	2/21/2021	No Injury (PDO)	53399	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road, distance from ramp.
213	3/4/2021	No Injury (PDO)	98772	Driver Inexperience	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road, distance from ramp.
213	10/20/2021	Possible/Complaint of Injury (C)	165286	No Apparent Contributing Factor	Rear End	Exclude	Rear end on road in traffic.
213	10/13/2021	No Injury (PDO)	303970	Driver Inexperience	Concrete Barrier	Exclude	Lost control in snow/ice, jackknifed, distance from ramp.
212.9	10/20/2019	No Injury (PDO)	341845	Driver Inexperience	Concrete Barrier	Exclude	Off-left in snow/ice, distance from ramp.
212.8	4/15/2018	No Injury (PDO)	218100	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, off-left, distance from ramp.
212.8	10/21/2021	No Injury (PDO)	163526	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe on road.
212.7	7/29/2016	No Injury (PDO)	16527307	Driver Unfamiliar with Area	Overturning	Exclude	Loss of trailer & jackknifing, distance from ramp.
212.5	2/28/2017	No Injury (PDO)	2509	No Apparent Contributing Factor	Overturning	Exclude	Overturning on-road in snow/ice, distance from ramp.
212.3	4/13/2014	Possible/Complaint of Injury (C)	14508432	Driver Preoccupied	Sideswipe Same Direction	Exclude	Sideswipe, loss of control in snow/ice, jackknifing on-road, distance from ramp.
212.2	4/20/2013	No Injury (PDO)	13508853	Driver Inexperience	Other non-collision	Exclude	Lost control in snow/ice, jackknifed, distance from ramp.
212.2	4/10/2019	Possible/Complaint of Injury (C)	274272	No Apparent Contributing Factor	Concrete Barrier	Exclude	Off-left in snow/ice, distance from ramp.
212.1	10/11/2018	Possible/Complaint of Injury (C)	230622	Driver Inexperience	Concrete Barrier	Include	Off-right, continued to travel forward after loss of control, proximity to ramp
212.01	7/22/2018	No Injury (PDO)	219969	No Apparent Contributing Factor	Large Boulder	Exclude	Large boulder.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
212	1/28/2017	No Injury (PDO)	2517	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe on road.
212	3/11/2014	No Injury (PDO)	14506332	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe, loss of control in snow/ice on-road.
212	12/14/2014	No Injury (PDO)	14532062	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, off left.
212	2/23/2022	No Injury (PDO)	206130	Driver Unfamiliar with Area	Other non-collision	Exclude	Lost control in snow/ice, jackknifed.
211.98	4/4/2017	Possible/Complaint of Injury (C)	1827	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe, loss of control in snow/ice, on-road.
211.9	1/13/2021	No Injury (PDO)	43786	Unknown	Embankment or Ditch	Exclude	Lost control in snow/ice, jackknifed prior to ramp.
211.9	4/23/2021	Possible/Complaint of Injury (C)	123873	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe in snow/ice, on-road.
211.9	2/21/2022	No Injury (PDO)	206828	Driver Inexperience	Embankment or Ditch	Include	Escape ramp used.
211.7	11/15/2014	No Injury (PDO)	14530861	Driver Unfamiliar with Area	Concrete Barrier	Exclude	Sideswipe, loss of control in snow/ice, off left.
211.6	1/11/2019	No Injury (PDO)	241816	Driver Unfamiliar with Area	Sideswipe Same Direction	Exclude	Sideswipe, loss of control in snow/ice.
211.56	11/1/2013	No Injury (PDO)	13523039	Driver Inexperience	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road.
211.5	11/22/2019	No Injury (PDO)	348520	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, off-left, distance from ramp.
211.41	5/27/2021	No Injury (PDO)	113685	No Apparent Contributing Factor	Other Object	Exclude	Overtaking & swerved, hit 'other object'.
211.4	12/23/2016	No Injury (PDO)	16547477	No Apparent Contributing Factor	Concrete Barrier	Exclude	Lost control in snow/ice, off-left, distance from ramp.
211.4	5/17/2022	No Injury (PDO)	310925	No Apparent Contributing Factor	Rear End	Exclude	Rear end on road in traffic.
211.22	8/28/2021	Evident, Incapacitating (A)	150785	Driver Unfamiliar with Area	Trees or Shrubs	Include	Loss of brakes prior to lower ramp.
211.2	1/9/2017	No Injury (PDO)	17500849	Driver Inexperience	Embankment or Ditch	Exclude	Lost control in snow/ice.
211.1	11/3/2013	Possible/Complaint of Injury (C)	13523252	Driver Preoccupied	Rear End	Exclude	Rear and in snow/ice on road.
211.1	3/9/2022	No Injury (PDO)	215215	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in snow/ice, jackknifed on road.
211.01	8/7/2014	No Injury (PDO)	14519263	Other Factor (Describe in Narrative)	Other Fixed Object	Exclude	Top of vehicle collided with overhead sign.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
211	11/14/2020	No Injury (PDO)	30495	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in snow/ice, jackknifed, distance from ramp.
211	12/10/2020	No Injury (PDO)	37847	No Apparent Contributing Factor	Other non-collision	Exclude	Lost control in snow/ice, jackknifed, distance from ramp.
211	12/15/2020	Evident Non-Incapacitating (B)	37894	No Apparent Contributing Factor	Overturning	Include	Loss of control, overturning in dry conditions, off-right, prior to lower ramp.
211	10/12/2021	Evident Non-Incapacitating (B)	165290	Driver Unfamiliar with Area	Concrete Barrier	Exclude	Lost control in snow/ice, off left, distance from ramp.
210.8	12/11/2020	No Injury (PDO)	37831	Driver Unfamiliar with Area	Other non-collision	Exclude	Lost control in snow/ice, distance from ramp.
210.5	4/5/2016	Possible/Complaint of Injury (C)	16511728	Other Factor (Describe in Narrative)	Sideswipe Same Direction	Exclude	Lost control in snow/ice avoiding traffic, distance from ramp.
210.286	5/30/2022	No Injury (PDO)	246050	Driver Inexperience	Sideswipe Same Direction	Exclude	Sideswipe in snow/ice, on-road.
210.2	3/9/2017	No Injury (PDO)	5426	No Apparent Contributing Factor	Embankment or Ditch	Include	Off-right in dry conditions into embankment/ditch prior to lower ramp.
210.06	2/23/2020	No Injury (PDO)	395928	Driver Unfamiliar with Area	Embankment or Ditch	Exclude	Hard braking in snow/ice, distance from ramp.
210	5/21/2016	No Injury (PDO)	16517363	Driver Unfamiliar with Area	Rear End	Exclude	Rear end on road in traffic.
209.9	5/1/2022	No Injury (PDO)	223552	Driver Unfamiliar with Area	Other non-collision	Exclude	Lost trailer, on road.
209.8	12/3/2013	No Injury (PDO)	13525283	Aggressive Driving	Sideswipe Same Direction	Exclude	Sideswipe in snow/ice, on-road.
209.8	6/10/2020	No Injury (PDO)	403526	No Apparent Contributing Factor	Other non-collision	Include	Mechanical failure proximity to ramp.
209.6	1/30/2017	No Injury (PDO)	128	No Apparent Contributing Factor	Embankment or Ditch	Include	Off-right in dry conditions into embankment/ditch prior to lower ramp.
209.6	4/25/2021	No Injury (PDO)	122989	Driver Preoccupied	Sideswipe Same Direction	Exclude	Driver inattention, swerving to avoid lead vehicle.
209.5	11/20/2019	Possible/Complaint of Injury (C)	350252	Driver Inexperience	Sideswipe Same Direction	Exclude	Lost control of trailer in ice/snow, sideswipe.
209.2	3/30/2015	Evident Non-Incapacitating (B)	15508872	Asleep at the Wheel	Guard Rail	Include	Ran off-right in dry conditions prior to lower ramp.
209	3/1/2013	No Injury (PDO)	13505884	Driver Inexperience	Sideswipe Same Direction	Exclude	Lost control of trailer in ice/snow, sideswipe.
209	8/12/2016	No Injury (PDO)	16528388	No Apparent Contributing Factor	Embankment or Ditch	Include	Escape ramp used.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
208.97	9/19/2016	No Injury (PDO)	16536197	No Apparent Contributing Factor	Concrete Barrier	Include	Escape ramp used.
208.87	9/7/2016	No Injury (PDO)	16533993	Driver Inexperience	Embankment or Ditch	Include	Escape ramp used.
208.87	2/19/2017	No Injury (PDO)	972	No Apparent Contributing Factor	Embankment or Ditch	Include	Off-right in dry conditions into embankment/ditch, proximity to ramp.
208.87	10/29/2017	No Injury (PDO)	103905	No Apparent Contributing Factor	Concrete Barrier	Include	Off-right in dry conditions into concrete barrier, proximity to ramp.
208.87	11/22/2017	No Injury (PDO)	109520	Driver Inexperience	Embankment or Ditch	Include	Off-right in dry conditions into embankment/ditch, proximity to ramp.
208.8	6/12/2016	No Injury (PDO)	16521375	Asleep at the Wheel	Other non-collision	Include	Escape ramp used.
208.8	1/20/2019	No Injury (PDO)	242517	No Apparent Contributing Factor	Embankment or Ditch	Include	Escape ramp used.
208.8	8/13/2020	No Injury (PDO)	10285	No Apparent Contributing Factor	Concrete Barrier	Include	Escape ramp used.
208.8	6/20/2022	No Injury (PDO)	241129	Driver Unfamiliar with Area	Other non-collision	Include	Escape ramp used.
208.7	7/9/2017	No Injury (PDO)	36944	Driver Inexperience	Concrete Barrier	Include	Off-right in dry conditions into concrete barrier, proximity to ramp.
208.7	9/7/2020	No Injury (PDO)	15303	Driver Inexperience	Embankment or Ditch	Include	Escape ramp used.
208.6	3/3/2019	Evident Non-Incapacitating (B)	266953	Driver Unfamiliar with Area	Rear End	Exclude	Rear end on road in snow/ice.
208.6	10/16/2022	No Injury (PDO)	300946	Driver Unfamiliar with Area	Overturning	Include	Overturning in dry conditions, off-right, close proximity to ramp.
208.5	1/4/2017	Evident Non-Incapacitating (B)	17501928	No Apparent Contributing Factor	Guard Rail	Exclude	Lost control in snow/ice, off left.
208.3	7/28/2017	Evident Non-Incapacitating (B)	54167	Driver Inexperience	Overturning	Include	Overturning in dry conditions in summer, proximity to ramp.
208.3	2/16/2020	No Injury (PDO)	393594	Driver Unfamiliar with Area	Other non-collision	Exclude	Lost control in snow/ice, jackknifed, distance from ramp.
208.2	3/21/2021	No Injury (PDO)	105695	Driver Inexperience	Other non-collision	Exclude	Lost control in snow/ice, jackknifed, distance from ramp.
208	2/7/2016	No Injury (PDO)	16504774	No Apparent Contributing Factor	Concrete Barrier	Include	Mechanical failure proximity to ramp.
208	7/3/2016	No Injury (PDO)	16523251	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Sideswipe on road.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
208	7/12/2020	No Injury (PDO)	429	No Apparent Contributing Factor	Other non-collision	Include	Brake loss, proximity to ramp.
208	11/9/2020	Evident Non-Incapacitating (B)	28023	No Apparent Contributing Factor	Guard Rail	Exclude	Lost control in snow/ice, off left.
208	8/3/2014	No Injury (PDO)	14518486	No Apparent Contributing Factor	Other non-collision	Include	Brake failure, proximity to ramp.
208	10/3/2018	Evident, Incapacitating (A)	227780	Driver Unfamiliar with Area	Overturning	Include	Overturning & loss of control in dry conditions, on curve, proximity to ramp.
207.91	8/26/2013	No Injury (PDO)	13517121	Driver Inexperience	Concrete Barrier	Include	Suggestive of brake loss.
207.8	3/9/2013	Evident Non-Incapacitating (B)	13505635	Driver Inexperience	Rear End	Exclude	Rear end on road in snow/ice.
207.8	3/12/2015	Possible/Complaint of Injury (C)	15507303	No Apparent Contributing Factor	Embankment or Ditch	Include	Overturning in dry conditions, entry to ditch, proximity to ramp.
207.8	4/28/2015	Possible/Complaint of Injury (C)	15510591	Driver Unfamiliar with Area	Sideswipe Same Direction	Exclude	Sideswipe on road.

Table 5-8: Breakeven Analysis of Enhanced Truck Signing, Detection & Warning System on WB I-70 MP 213.00 – 207.70

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WB Truck Signage Detection Warning System — **Loc:** 70 A **Begin:** 207.7 **End:** 213 **From:** 1/1/2013 **To:** 12/31/2022

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 21	5 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 2	6 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 3	2 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 2	0 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 0		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost: $2,678,858
Years in Crash Search: 10.00
CRF 1 Type: Runaway Truck Signage, Detection & Warning System for Curves & Escape Ramps
Notes: Breakeven Analysis - Westbound commercial vehicle crashes.
Benefit/Cost Ratio: 1
CRF 2 Type:
CRF 3 Type:
CRF 4 Type:

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Breakeven Analysis – Mount Vernon Canyon (Eastbound I-70, MP 253.70-258.50)

Table 5-9 provides the rationale and engineering judgment behind the inclusion or exclusion of recorded truck crashes on eastbound Mount Vernon Canyon in the study period for use in the BEA.

Table 5-10 shows the BEA for the implementation of an enhanced truck signage, detection and warning system on eastbound I-70 for the Mount Vernon Canyon escape ramp. Assuming a 20-year service life and up to $2,500 in annual maintenance, it shows the measure is estimated to be cost-effective up to approximately $0.85M.

Table 5-9: Included/Excluded Truck Crashes for Mount Vernon Canyon Break-Even Analysis

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
255.65	4/16/2013	No Injury (PDO)	13507931	Other Factor (Describe in Narrative)	Guard Rail	Exclude	Sliding after affixing chains, not a runaway truck situation.
257.1	6/20/2013	No Injury (PDO)	13515043	Driver Inexperience	Traffic Sign or Post or Overhead Sign Structure	Include	Escape ramp used.
254.9	8/10/2013	No Injury (PDO)	13515933	No Apparent Contributing Factor	Vehicle Cargo or Debris	Include	Brake failure in advance of ramp.
255.79	10/5/2013	Evident Non-Incapacitating (B)	13520449	Asleep at the Wheel	Guard Rail	Exclude	Off-left on curve, no mechanical failure.
257	1/6/2016	No Injury (PDO)	16500337	No Apparent Contributing Factor	Other non-collision	Include	Escape ramp used.
255.8	2/1/2016	Possible/Complaint of Injury (C)	16504061	No Apparent Contributing Factor	Guard Rail	Exclude	Sliding in snow, no mechanical failure.
254.2	2/1/2017	No Injury (PDO)	127	Driver Fatigue	Parked Motor Vehicle	Exclude	On-road, parked motor vehicle, distance from ramp.
254.3	4/29/2017	Possible/Complaint of Injury (C)	2838	Other Factor (Describe in Narrative)	Rear End	Exclude	On-road, rear-end in snow.
255.5	1/11/2019	No Injury (PDO)	240240	No Apparent Contributing Factor	Other non-collision	Exclude	Loss of control in ice.
257	4/2/2019	No Injury (PDO)	267847	Other Factor (Describe in Narrative)	Traffic Sign or Post or Overhead Sign Structure	Include	Escape ramp used.
253.95	7/13/2019	No Injury (PDO)	301175	No Apparent Contributing Factor	Wild Animal	Exclude	Wild animal.
257.5	10/29/2019	No Injury (PDO)	343479	No Apparent Contributing Factor	Other non-collision	Include	Close proximity to ramp.
258.4	11/27/2019	No Injury (PDO)	348956	Driver Unfamiliar with Area	Rear End	Exclude	Rear-end in traffic.
256	3/11/2014	Possible/Complaint of Injury (C)	14505821	Aggressive Driving	Parked Motor Vehicle	Exclude	Parked motor vehicle in snow/ice.
257	9/3/2014	Evident, Incapacitating (A)	14526139	Other Factor (Describe in Narrative)	Overturning	Include	Overturning, off-right adjacent to escape ramp.
254.5	1/9/2015	No Injury (PDO)	15500674	Driver Unfamiliar with Area	Rear End	Exclude	Rear-end in traffic.
255.2	2/1/2015	No Injury (PDO)	15502905	Other Factor (Describe in Narrative)	Other non-collision	Exclude	Loss of control in ice/snow, distance from ramp.

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
257	1/29/2015	No Injury (PDO)	15503371	Driver Unfamiliar with Area	Sideswipe Same Direction	Include	Brake failure in advance of ramp.
256.3	2/10/2018	No Injury (PDO)	135359	No Apparent Contributing Factor	Guard Rail	Exclude	Loss of control in ice/snow, distance from ramp.
255.2	2/7/2018	Possible/Complaint of Injury (C)	143334	Driver Preoccupied	Sideswipe Same Direction	Exclude	On-road Sideswipe same, no mechanical failure, distance from ramp.
255.9	7/16/2018	No Injury (PDO)	222561	Driver Preoccupied	Sideswipe Same Direction	Exclude	On-road rear-end.
256.2	10/2/2018	Evident Non-Incapacitating (B)	231764	Asleep at the Wheel	Rear End	Exclude	Asleep at wheel.
257.9	2/16/2021	No Injury (PDO)	51125	Driver Inexperience	Rear End	Include	Secondary crash due to truck stopped due to smoking brakes., which might have reasonably used ramp.
256.2	2/17/2021	No Injury (PDO)	51903	No Apparent Contributing Factor	Guard Rail	Exclude	Lost control in snow/ice.
256.8	2/4/2021	Possible/Complaint of Injury (C)	51949	No Apparent Contributing Factor	Rear End	Include	Brake failure in advance of ramp.
255.8	2/24/2021	No Injury (PDO)	53136	No Apparent Contributing Factor	Light or Utility Pole	Include	Tire blow-out in advance of ramp.
253.96	2/24/2021	No Injury (PDO)	96439	No Apparent Contributing Factor	Other non-collision	Include	Mechanical brake failure.
253.9	1/11/2022	Evident Non-Incapacitating (B)	192839	Driver Emotionally Upset	Rear End	Exclude	Rear-end in traffic.
256	5/5/2022	No Injury (PDO)	223600	No Apparent Contributing Factor	Sideswipe Same Direction	Exclude	Backwards motion.
257.87	9/19/2022	No Injury (PDO)	266608	Driver Inexperience	Rear End	Exclude	Not a runaway, citation for partially blocking road.
257.525	2/11/2022	Evident Non-Incapacitating (B)	308016	No Apparent Contributing Factor	Parked Motor Vehicle	Exclude	Sliding in snow, no mechanical failure.
256.556	7/28/2022	No Injury (PDO)	314272	Unknown	Delineator Post	Exclude	Wild animal.
255.749	12/21/2022	No Injury (PDO)	319641	Driver Preoccupied	Guard Rail	Exclude	Wind precipitating factor, distance from ramp.

Table 5-10: Breakeven Analysis of Enhanced Truck Signing, Detection & Warning System on EB I-70 MP 253.70 – 258.50

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EB Truck Signing Detection Warning System — **Loc:** 70 A **Begin:** 253.7 **End:** 258.5 **From:** 1/1/2013 **To:** 12/31/2022

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 9	2 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 1	0 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 0	1 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 1	0 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 0		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost: $854,353
Years in Crash Search: 10.00
CRF 1 Type: Runaway Truck Signing, Detection & Warning System for Curves & Escape Ramps.
Notes: Breakeven Analysis - Eastbound commercial vehicle crashes.
Benefit/Cost Ratio: 1
CRF 2 Type:
CRF 3 Type:
CRF 4 Type:

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Breakeven Analysis – Coal Bank Hill (Southbound US-550, MP 54.50-51.00)

Table 5-11 provides the rationale and engineering judgment behind the inclusion or exclusion of recorded truck crashes on southbound Coal Bank Hill in the study period for use in the BEA.

Table 5-12 shows the BEA for the implementation of an enhanced truck signage, detection and warning system on southbound US-550 for the Coal Bank Hill escape ramp. Assuming a 20-year service life and up to $2,500 in annual maintenance, it shows the measure is estimated to be cost-effective up to approximately $0.93.

Table 5-11: Included/Excluded Truck Crashes for Coal Bank Hill Break-Even Analysis

Milepost	Date	Severity	Serial No	Veh1 Human Contr Factor	Crash Type	Status	Rationale
54.4	8/31/2013	Possible/Complaint of Injury (C)	13518257	Driver Inexperience	Overturning	Exclude	Brake failure but almost 2 miles with frequent curves.
54	9/4/2011	Possible/Complaint of Injury (C)	11051995	Driver Inexperience	Embankment or Ditch	Include	Off-left, Embankment/Ditch dry conditions at hairpin (benefit from diagrammatic signage).
53.87	10/22/2021	Evident Non-Incapacitating (B)	163713	Driver Inexperience	Overturning	Include	Off-right, Overturning dry conditions at hairpin (benefit from diagrammatic signage).
53.8	6/18/2018	No Injury (PDO)	222169	No Apparent Contributing Factor	Overturning	Include	Off-right, Overturning dry conditions at hairpin (benefit from diagrammatic signage).
53.8	10/24/2007	No Injury (PDO)	7002597	Driver Unfamiliar with Area	Overturning	Include	Overturning, (benefit from diagrammatic signage).
53.8	8/14/2008	No Injury (PDO)	8322180	No Apparent Contributing Factor	Overturning	Include	Off-right, Overturning, (benefit from diagrammatic signage).
52.2	8/6/2009	No Injury (PDO)	9309630	No Apparent Contributing Factor	Guard Rail	Exclude	Swerved to avoid oncoming vehicle in wrong lane.
51.9	7/7/2009	No Injury (PDO)	9043022	No Apparent Contributing Factor	Parked Motor Vehicle	Exclude	On-road in snow, parked motor vehicle.
51.32	12/7/2021	No Injury (PDO)	305933	Driver Unfamiliar with Area	Guard Rail	Include	Off-right in wet conditions at hairpin (benefit from diagrammatic signage).
51.28	4/3/2010	Evident Non-Incapacitating (B)	10304357	Driver Unfamiliar with Area	Guard Rail	Include	Brake failure, Guardrail, proximity to ramp, near hairpin.
51.2	12/2/2013	Possible/Complaint of Injury (C)	13524977	Driver Unfamiliar with Area	Guard Rail	Include	Off-right, Guardrail, dry conditions at hairpin (benefit from diagrammatic signage).
51.2	11/21/2011	Evident Non-Incapacitating (B)	11510072	No Apparent Contributing Factor	Overturning	Include	Off-right, Overturning, wet conditions at hairpin (benefit from diagrammatic signage).
51.1	1/9/2022	Evident Non-Incapacitating (B)	306635	No Apparent Contributing Factor	Overturning	Include	Overturning, brake failure prior to escape ramp.

Table 5-12: Breakeven Analysis of Enhanced Truck Signing, Detection & Warning System on SB US-550 MP 54.50 – 51.00

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SB Truck Signing Detection Warning System — **Loc:** 550 B **Begin:** 51 **End:** 54.5 **From:** 1/1/2013 **To:** 12/31/2022

Benefit Cost Ratio Calculations

Crashes		Crash Reduction Factors (Composite)	Other Information
PDO: 4	3 :Injured C	CRF for PDO: 41%	Cost of PDO: $17,500
INJ C: 2	5 :Injured B	CRF for INJ C: 39%	Cost of INJ C: $126,000
INJ B: 4	0 :Injured A	CRF for INJ B: 39%	Cost of INJ B: $232,000
INJ A: 0	0 :Killed	CRF for INJ A: 39%	Cost of INJ A: $1,066,000
FAT: 0		CRF for FAT: 39%	Cost of FAT: $1,869,000
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $2500

Improvement Cost: $930,760
Years in Crash Search: 10.00
CRF 1 Type: Runaway Truck Signage, Detection & Warning System for Curves & Escape Ramps.
Notes: Breakeven Analysis - Southbound commercial vehicle crashes.
Benefit/Cost Ratio: 1
CRF 2 Type:
CRF 3 Type:
CRF 4 Type:

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Location Prioritization

Completion of a breakeven analysis for each of the six escape ramp locations for which a runaway truck enhanced signage, warning and detection system similar to that on WCP was recommended facilitated a locational prioritization to be made. Escape ramp locations were ranked according to breakeven cost, with the location with the lowest associated breakeven cost being ranked in the first priority position, and the location with the highest associated breakeven cost being ranked in the last position in terms of priority.

The breakeven analysis resulted in the location prioritization ranking seen in **Table 5-13**, where the number in parentheses indicates the number of people injured.

Table 5-13: Escape Ramp Study Locations Prioritization Ranking

Rank	Location	Included Truck Crashes	Breakeven Cost
1st	Upper & Lower Vail Pass	19 Total 1 Fatal (1 killed) 3 Level A (6 injured) 4 Level B (7 injured) 4 Level C (5 injured) 7 Property Damage Only	**$6,324,226**
2nd	Upper & Lower Straight Creek Pass	28 Total 2 Level A (2 injured) 3 Level B (6 injured) 2 Level C (5 injured) 21 Property Damage Only	**$2,678,858**
3rd	Rabbit Ears Pass	8 Total 1 Fatal (1 killed) 2 Level A (2 injured) 1 Level C (1 injured) 5 Property Damage Only	**$2,487,047**
4th	Monarch Pass	4 Total 1 Fatal (1 killed) 1 Level A (1 injured) 1 Level B (1 injured) 1 Level C (2 injured) 1 Property Damage Only	**$2,020,537**
5th	Coal Bank Hill	10 Total 4 Level B (5 injured) 2 Level C (3 injured) 4 Property Damage Only	**$930,760**
6th	Mount Vernon Canyon	11 Total 1 Level A (1 injured) 1 Level C (2 injured) 9 Property Damage Only	**$854,353**

The ranked prioritization of locations in **Table 5-13** indicates that implementation of an enhanced runaway truck detection and guidance system should in the first instance consider the Upper and Lower Vail Pass ramps location in order the maximize cost-effectiveness against potential safety benefits. The Upper and Lower Vail Pass ramp corridor is expected to have the highest benefit for cost output for system roll out, with a breakeven cost of approximately $6.32M dollars. This ramp is located on the busy I-70 corridor and appears to already possess power and fiber network supply.

Conversely, the breakeven analysis indicated that the Mount Vernon Canyon escape ramp corridor is expected to carry the lowest benefit for output costs for system implementation. Therefore, when difficult decisions have to be made in terms of budgetary resource allocation, **Table 5-13** allows CDOT to better prioritize investment in safety improvements on the state highway system.

Chapter 6 – Conclusions

It is a widely held view that there is a reduction in the frequency and severity of crashes involving runaway trucks due to the use of truck escape ramps (TERs). The degree of crash reduction which can be expected due to a TER is not known to the same level of precision as other crash reduction factors. This research project conducted an observational before and after study at the Wolf Creek truck escape ramps, where an experimental truck warning system has been recently deployed on westbound SH-160. To our knowledge observational before and after studies with proper correction for the regression to the mean bias have not been conducted to evaluate TER effectiveness. In conjunction with this, tools were developed to assess highway safety performance specifically by direction using Colorado-specific crash prediction models. Another objective was to examine the feasibility of deployment of a similar truck warning system to that on Wolf Creek Pass at all TERs in Colorado.

The evaluation of the performance of the WCP runaway truck system allowed quantification of the benefits of the experimental signing, detection and warning system for trucks and escape ramps. The results indicated that for commercial vehicle involved crashes a reduction of 41% in total crash frequency and of 39% in severe crash frequency was witnessed between the before and after periods on WCP.). It cannot be said that the system has been 100% effective in removing all runaway truck crashes, however, it is very likely that the system has contributed in large part to the reduction in the frequency and severity of truck involved crashes on WCP.

An evaluation of each of the historical escape ramp performance at the other 8 escape ramp locations across the state employed sound engineering judgment and rationale to assess each recorded truck crash in the study period to evaluate if it would have been likely to have benefited from a system similar to that on WCP, or if it would have been unreasonable to expect the system to have affected the crash outcome. In conjunction with this a breakeven analysis was performed at each location to rank locations in terms of priority for any future consideration of budgetary allocations. The results of the escape ramp performance and breakeven analysis resulted in the determination that the Loveland Pass and Slick Rock Hill escape ramp locations would be unlikely to prove feasible in terms of cost-effective for implementation of an enhanced truck warning and guidance system. The ranking of the remaining 6 locations by breakeven cost determined that the prioritization of any project should be made in the following order to maximize cost-effectiveness:

1. Upper & Lower Vail Pass ($6,324,226)
2. Upper & Lower Straight Creek Pass ($2,678,858)
3. Rabbit Ears Pass ($2,487,047)
4. Monarch Pass ($2,020,537)
5. Coal Bank Hill ($930,760)
6. Mount Vernon Canyon ($854,353)

One notable finding of this research is the uncertainty around the causative nature of the crash reduction witnessed. It is difficult to separate the effects of the two countermeasures (diagrammatic signing, or dynamic detection and warning system). That is, whether crash reduction can be primarily attributable to the diagrammatic signage, or the dynamic warning system, or if it is in fact a result of a more complex interaction of both elements. As such, we recommend that **both** elements always be included in any system adopted for the reduction of runaway truck crashes at escape ramps on mountainous routes.

Following this study, Colorado Department of Transportation (CDOT) has at its disposal tools to evaluate safety performance *by direction* using Colorado-specific crash prediction models for the mountainous environment. Furthermore, the findings of this research have provided an initial effort in the quantification of the degree of crash reduction which can be expected due to a TER. Finally, these findings of this research effort have the potential to reduce runaway truck crashes not just in the Colorado mountainous environment, but elsewhere nationally.

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