



Truck safety evaluation on Wyoming mountain passes

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ARTICLE INFO

Keywords:

Runaway truck crashes
Crash risk evaluation
Wyoming mountain passes
MUTCD hill signs
Grade severity rating systems
Weight specific speed signs

ABSTRACT

The Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways recommends hill signs be placed in advance of downgrade descent of mountain passes. Mountain passes increase the risk of a runaway, or out of control trucks and so the advance warning signs inform the driver to take special precautions such as reducing speed or using lower gears during the descent. The Wyoming Department of Transportation has installed steep grade advance warning systems on Wyoming mountain passes. However, concerns for out of control trucks on the mountain passes persist. The objective of this study is to evaluate the safety effectiveness of steep grade advance warning signs for trucks on Wyoming mountain passes. The safety evaluation was carried out by implementing a zero-inflated negative binomial modeling technique for predicting truck crashes on mountain passes. The outcome was two models that showed the risk of runaway truck accidents were high at locations where either the grades were steep and long or the grades were long with multiple vertical curves. The analysis showed the current advance warning systems were not significantly impacting truck crash risks at the high risk locations. The study, therefore, recommends some improvements to the current advanced warning signs or implementing an improved Federal Highway Administration Grade Severity Rating System based warning system that will significantly improve truck safety at the hazardous locations. The study informs policy makers on the safety issues on Wyoming Mountain passes with regards to runaway trucks and makes recommendations for reducing the risk of runaway truck crashes on mountain passes.

1. Introduction

Runaway or out-of-control truck crashes are high on mountain passes compared to other sections of typical routes. Crash risks are generally higher on steep downgrades as corroborated in a study by Ahmed et al. that modeled adverse weather crash data along mountain passes to gain an understanding of why they occurred (Ahmed et al., 2011). The Wyoming Department of Transportation (WYDOT) attributes some of the runaway truck crashes to driver unfamiliarity with the road and terrain (VanOstrand, 2014; WYDOT, 2016). On a downgrade section of US14 near Dayton, Wyoming, seven runaway truck crashes were recorded from January to September 2014. To mitigate the problem, a reduced speed zone of 40 mph (64 kmph) was introduced at the location but this measure could not prevent a fatal truck crash in December 2015 (Burr, 2015). The crash was attributed to brake failure and was a strong indication for the need to evaluate the safety effectiveness of the mountain pass warning systems in dealing with runaway trucks. This paper discusses a safety evaluation study of Wyoming Mountain passes and makes recommendations for improving the warning systems used to alert drivers to take special precautions on steep downgrades.

Previous research in the 1970s (Bowman, 1989) led to the development of a Grade Severity Rating System (GSR) that was aimed at reducing the risk of out of control or runaway vehicles resulting from brake failure during downhill descent by heavy trucks. The GSR model was implemented by the Federal Highway Administration (FHWA) in the form of a computer program on the Microsoft Disc Operating System (MS-DOS) that utilized the grade, and length of grade to predict a safe speed at which trucks of various weight categories could descend a hill without brake failure. The implementation of the GSR model required the use of Weight Specific Speed (WSS) signs for communicating speed advisories relevant to truck drivers. According to the Highway Safety Design and Operations Guide, the WSS signs are effective in substantially reducing speed where there are steep downgrades (AASHTO, 1997). Fig. 1 shows an illustration of a WSS sign derived from the FHWA GSR model in use.

The literature indicates the FHWA GSR model is mostly used for determining the locations of truck escape ramps (AASHTO, 2011). The process involves using the GSR software to generate a brake temperature profile for various truck weight categories. The brake temperature profile is then used to determine truck escape ramp locations where the brake temperature is likely to result in brake failure. The

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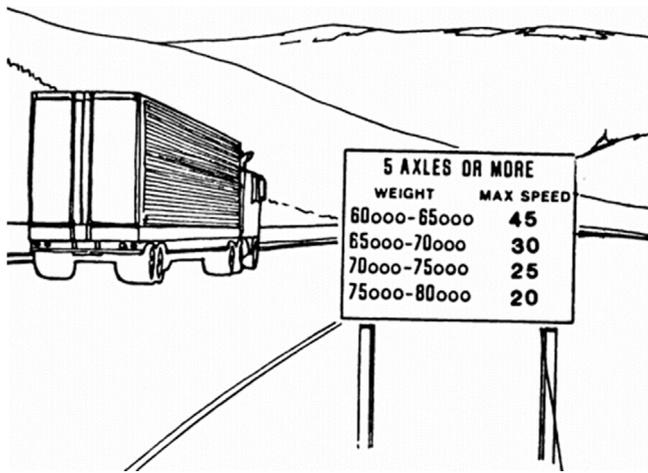


Fig. 1. A GSRS based weight specific speed sign (VanOstrand, 2014).

GSRS model also serves as a tool for downhill truck accident analysis.

The current advance warning systems for mountain passes in Wyoming are based on the Manual on Uniform Traffic Control Devices (MUTCD) recommendations for Hill Signs. The guide identified a combination of grades and lengths that will require special precautions on the part of road users. The conditions requiring the advance warning signs are (FHWA, 2009):

- a five percent (5%) grade that is more than 3000 ft. (914.4 m) in length,
- a six percent (6%) grade that is more than 2000 ft. (609.6 m) in length,
- a seven percent (7%) grade that is more than 1000 ft. (304.8 m) in length,
- an eight percent (8%) grade that is more than 750 ft. (228.6 m) in length, and
- a nine percent (9%) grade that is more than 500 ft. (152.4 m) in length.

The various mountain pass warning signs recommended by the MUTCD are shown in Fig. 2. The manual recommends installing the Hill (W7-1) sign with supplemental grade (W7-3P) plaque, or the W7-1a sign used alone to warn road users at locations with steep grades or where the risk of crashes during descents are high.

The signs recommended by the MUTCD provide information to the road user about a steep descent ahead together with an indication of the

steepness of the grade. The driver is ultimately responsible for determining an appropriate speed with which to descend the gradient safely. However, inexperienced drivers or drivers unfamiliar with a given area will have difficulty selecting the right speed for a safe descent.

This paper carried out an evaluation of the safety effectiveness of steep slope advance warning systems for trucks on Wyoming mountain passes. Information on the mountain pass locations on two-lane two-way roads was obtained from the Wyoming Department of Transportation (WYDOT) together with crash data, horizontal and vertical alignment data, percent grade, and the location and type of advance warning signs. Ten-year crash data for all the locations were modeled to determine the variables that impacted crash occurrence on the selected sections. The results of this study will be useful for policy makers to determine appropriate actions aimed at reducing the incidence of runaway truck crashes on mountain passes.

Truck runaway accidents are mainly due to brakes losing their ability to effectively slow vehicles during descents of steep, long grades; a condition commonly called brake fade. At high temperatures, brakes lose their effectiveness due to lower lining-to-drum friction coefficient and thermal drum expansion. This consequently lowers brake torque for a given brake line pressure as well as decreases the pushrod actuation force (Limpert and Andrews, 1987).

Driver experience and technique have been found to be critical in conducting truck braking during downgrade descents. A study by Fancher et al. (1992) to gauge the impact of braking strategy on brake temperatures showed that the appropriate method to descend steep downgrades is to use a low gear and a slow descent speed. A control descent speed that is not too fast for the weight of the vehicle, length and steepness of the grade ensures that brakes will be able to get rid of enough heat so that they work as they should. The study also indicated that the snubbing technique in braking prevents brake fade in comparison to the dragging method.

Johnson et al. (1982) indicated that runaway truck accident rates are dependent on grade steepness and length, ADT on the grade, and the number of downhill lanes. The study revealed that improper maintenance of brakes increases the likelihood of a runaway. An example is the effect of brake imbalance which results in a condition where some brakes do more work, and thus get hotter, than others. Scott et al. (2003) mention in their study that runaway trucks are most likely to result in crashes when the loss of control happens in a curve or when there is the risk of collision with a slower moving vehicle.

Several studies have been carried out to build advance warning systems for trucks and heavy vehicles approaching steep downhill slopes (VanOstrand, 2014). The first system was developed by the Bureau of Public Roads (BPR) before 1960. This system posted arbitrary ratings for downhill slopes as warnings about the severity of descent for road users (Hykes, 1963). The BPR rating system was developed by surveying grades and placing them in three categories:

- Greater than 3% and greater than 10 mi. (16 km) long.
- Greater than 6% and greater than 1-mi. (1.6 km) long.
- Greater than 10% and greater than 1/5-mi. (0.32 km) long.

The arbitrariness of the BPR system and problems with classifying some slopes that varied from the three categories led to other studies that developed improved grade severity rating systems and associated warning systems.

Fisher in 1961 developed a mathematical model that rated brakes by their overall heat dissipation capacity, and Hykes utilized Fisher's ratings to develop a grade severity rating system in a paper published by the Society of Automotive Engineers (SAE) in 1963. The system by Hykes predicted the downhill performance capabilities of commercial trucks and represented the risk of brake failure with ten downhill grade categories (Hykes, 1963). Hykes recommended posting the grade before each descent for road users to use their experience and training to

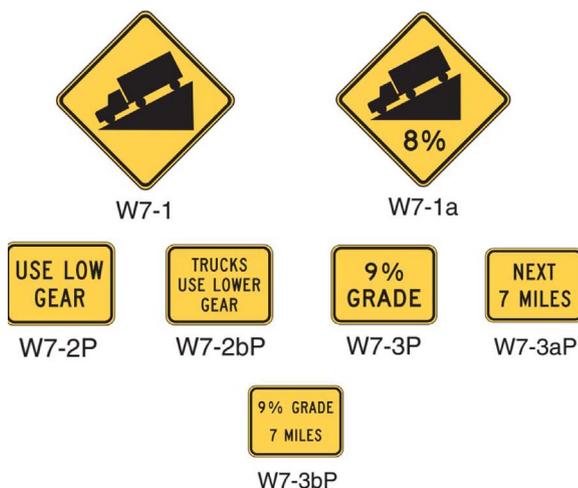


Fig. 2. MUTCD advance warning signs. source: MUTCD 2nd Edition.

determine the appropriate gear and speed for descending the downgrade.

A subsequent grading system was developed by Lill in 1975 that improved on the Hykes Grading System (Lill, 1975). Lill's model was based on the work-kinetic energy equation applied to braking on a grade. The model included brake variables and factors developed by Hykes. The equation was used to solve for the maximum descent speed which will allow stopping in a criterion distance. Lill's model introduced a brake equivalent time concept. This concept is defined as the hill descent time multiplied by the percent of brake use. The concept allowed the computation of a maximum safe speed that would allow stopping within a criterion of 250 ft. (76.2 m). Based on Lill's concept, a grade severity rating system was introduced with various speed bands indicating the severity of grades with higher speed bands corresponding to least severe, and lower speed bands corresponding to most severe.

A study of national truck crashes in the 1970s (Lill, 1977) found that six percent of all the truck crashes were downgrade related crashes but that small proportion of the crashes contributed to 40% of the truck accident fatalities (Lill, 1975). The investigations found the downgrade truck accidents to be caused by five primary factors:

- Failure to downshift on the grade, improper shifting, or the use of excessive speed (82% of the downgrade accidents).
- Drivers who were inexperienced or at least unfamiliar with the specific area (43% of the accidents).
- Inadequate signing for the downgrade (14% of the accidents).
- Defective truck brakes or improper brake adjustment (36% of the accidents).
- Indications of driver impairment such as the use of alcohol or fatigue due to excessive driving time (21% of the accidents).

The study recommended a solution for factors 1, 2, and 3, which involved the development of an effective GSRS and appropriate warning signs to aid drivers in choosing the correct speed and gear with special emphasis on the inexperienced driver. This recommendation led to the development of the current Federal Highway Administration (FHWA) GSRS model and the Weight Specific Speed (WSS) sign.

Studies were carried out that included some field experiments to develop the FHWA model (Burr, 2015; Lill, 1975). The FHWA GSRS model recognized that the brake heat generated is higher for heavier trucks traveling at higher speeds on longer and steeper slopes. Bowman et al. indicated that at high temperatures of about 375 °F (190.6 °C), brake fade begins to occur as the brake drums begin to deform, and the contact surface between the brake pads and the drums reduce. The reduction in the contact surface reduces the braking capacity of the truck. At a higher temperature of 500 °F (260 °F), the contact surface reduces to the extent where the brakes fail completely and the driver loses control of the vehicle. Thus the aim of the FHWA GSRS model was to predict the maximum speed of a truck descending a specific downgrade and length of grade which will not result in brake temperatures approaching and exceeding 500 °F (26 °F). The outcome of the GSRS was the WSS signs. The signs have a column for truck gross weights (maximum 80,000lbs) on the left side and corresponding speeds on the right side.

A MS-DOS computer program was developed for the model that enabled its implementation to determine maximum safe downgrade speeds (VanOstrand, 2014). Inputs of the program are information pertaining to truck weight (lb.), posted speed (mph), percent of grade, and length (mi.) of downgrade. The program uses this information to generate the outputs of maximum safe downgrade speeds for different truck weights (see Fig. 3). The maximum safe descent speeds produced by the program are then utilized in WSS signs as advisory signs for various truck weight category drivers.

Ruhl et al. (2006) compared the brake fade temperature predicted by four temperature models (GSRS, UMTRI, Limpert, and HVE-SIMON™) by analyzing data from a real world accident involving a

MAXIMUM TRUCK WEIGHT (POUNDS)	MAXIMUM SAFE SPEED (MPH)	BRAKE TEMP. FROM DECLINE (F)	BRAKE TEMP. FROM EMERGENCY STOP (F)	TOTAL BRAKE TEMP. (F)	TOTAL TRAVEL TIME (MIN.)
70000	13	480	3	483	13.8
65000	17	488	5	493	10.6
60000	24	488	10	498	7.5
55000	32	482	17	499	5.6
50000	55	442	47	489	3.3

NOTE : INITIAL BRAKE TEMPERATURE = 150

Press 'C' to continue or 'B' for speeds with brake temperature between 500 °F and 530 °F :

Fig. 3. FHWA GSRS MS-DOS program output.

tractor-semitrailer that lost its brakes on a steep downgrade. The analysis showed that the brake temperatures predicted by the GSRS model were relatively low compared to the other models. The difference in measurement was attributed to the differences in diffusivity constant.

After the development of the FHWA GSRS model and the WSS signs, tests were conducted to determine the feasibility of utilizing the WSS signs to reduce truck runaway incidents (Hanscom, 1985). Before-after sign effects were evaluated in terms of speed differences and the incidences of smoking brakes for trucks in different categories. These tests indicated that the WSS signs were effective in reducing mean speed and smoking brakes at 66% of the high-downgrade locations they were installed and consequently downgrade truck crashes since they simplified the driving task and emphasized the severity of the downgrade.

A simulation was carried out to determine the effectiveness of WSS signs in comparison to minimal (no sign at all, or a sign saying "HILL, TRUCKS USE LOW GEAR") and good standard signing (Johnson et al., 1981). This was done by obtaining performance and driver opinion data to provide valid comparisons of the road signs using a simulator. Brake temperature at the bottom of a virtual hill from the simulation exercise was the primary performance measure used to evaluate the various signs. The results showed that, drivers tended to underestimate or overestimate the severity of downgrades with minimal and standard signing. This resulted in high brake temperatures at the end of the downgrades or a significantly slower than necessary descent speed. The WSS signs on the other hand enabled drivers to accurately assess the severity of grades and selected speeds compatible with safe and expeditious descents.

To make recommendations for improving on the safety of advance warning system for mountain passes, it is necessary to understand the factors that affect crash frequencies on the mountain passes. Previous researches have modeled crash occurrence to gain an understanding of why the crashes occur. Abdel-Aty and Radwan undertook a study that also modeled crash occurrence; the study determined that annual average daily traffic (AADT), speed, lane width, number of lanes, land use, shoulder width, and median width have a statistical significant effect on crash occurrence (Abdel-Aty and Radwan, 2000). Other studies that modeled crash prediction include studies by Tegge et al. (2010), Khattak and Knapp (2001), Andrey and Yagar (1993), Kalokoata and Seneviratne (1994), Saha et al. (2015), and Cafisco et al. (2010).

Poisson, negative binomial (NB), and zero-inflated negative binomial regression methods are the predominant techniques used for modeling crash data (Miaou and Lord, 2003; Saha and Young, 2014). This is because most crash data are count data with a distribution that is often not normal; using ordinary least squares (OLS) regression for modeling count data may result in coefficients that are very unstable

with large standard errors (Cohen et al., 2003). The Poisson regression method overcomes the OLS requirements for constant variance and normal distribution and is most suitable for modeling count data.

Poisson regression, the most common count-data modeling approach, restricts the mean to be equal to the variance and this makes it unsuitable for modeling crash frequency. In the presence of over-dispersed data, estimating a common Poisson model can result in biased and inconsistent parameter estimates and could produce erroneous inferences (Park et al., 2009). An improvement to the Poisson regression model is the NB model. An over-dispersion parameter is introduced to account for dispersion in the data. However, the NB model is unable to handle under-dispersed data, and has dispersion-parameter estimation problems when the data have low sample mean values and small sample sizes (Lord et al., 2010).

Another challenge of crash data is that a significant number of zeros often characterizes them; more than would be expected in a traditional Poisson or NB model. In such a situation, one state is considered a zero-crash state with no crashes, and the other assumed to be the non-zero crash state, in which the crash frequencies are presumed to follow the Poisson or NB distribution. Simply applying the Poisson or NB distribution to model the crashes will result in an incorrectly specified model (Huang and Hong, 2010). This dual system is modeled using the zero-inflated Poisson regression. It can determine the probability of a roadway entity being in a zero or non-zero state using a binary logit or probit model (Washington et al., 2010). Despite its numerous advantages, the zero-inflated Poisson regression is unable to handle crash data characterized by large zero densities and has been criticized for its application in highway safety (Lord and Bonneson, 2007).

The zero-inflated NB method has proven to be an improvement to the conventional zero-inflated Poisson model in accounting for outcomes with numerous zeros. In the use of standard Poisson regression models, over-dispersion has little effect on the parameter estimates but results in underestimation of standard errors (Cox, 1983). Zero-inflated models depend very much on the probability of a zero count in the underlying distribution. If the underlying distribution is erroneously assumed to be Poisson while it is in fact negative binomial, inconsistent parameter estimates will be obtained due to a misspecification of the functional form (Ridout et al., 2001). It has also been established that the zero-inflated Poisson parameter estimates can be severely biased if over-dispersion of the zero counts occur in relation to the Poisson distribution (Yau et al., 2003). The zero-inflated NB operates just like the conventional zero-inflated models by a splitting regime that models a crash-free versus a crash-prone section of a roadway entity (Dong et al., 2014). The crash free section is always assumed to have zero crashes, whereas the crash prone section may be zero, but not always and has a Poisson-distributed count (Cox, 1983). The underlying distribution of the zero-inflated NB is specified as (Garay et al., 2011):

$$\Pr(Y_i = y_i) = p_i + (1 - p_i) \left(\frac{\phi}{\mu_i + \phi} \right)^\phi, \quad y_i = 0, \tag{1}$$

$$\Pr(Y_i = y_i) = (1 - p_i) \frac{\Gamma(\phi + y_i)}{\Gamma(y_i + 1)\Gamma(\phi)} \left(\frac{\mu_i}{\mu_i + \phi} \right)^{y_i} \left(\frac{\phi}{\mu_i + \phi} \right)^\phi, \quad y_i = 1, 2, \dots, \tag{2}$$

where $0 \leq p_i \leq 1$, $\mu_i \geq 1$, ϕ^{-1} is the dispersion parameter with $\phi > 0$ and $\Gamma(\cdot)$ is the gamma function. The mean and variance of the model are $E(Y_i) = (1 - p_i)\mu_i$, $\text{Var}(Y_i) = (1 - p_i)\mu_i(1 + \mu_i\phi^{-1} + p_i\mu_i)$. When $p_i = 0$, the random variable Y_i has a NB distribution with mean μ_i and dispersion parameter ϕ .

2. Material and methods

Due to the over-dispersion inherent in most crash data, a NB distribution is commonly used to develop a safety performance function (SPF). The SPF uses traffic volume and roadway characteristics to predict crashes. An example of an SPF is the Highway Safety Manual (HSM) basic SPF for predicting crashes on various road types (AASHTO,

2010). The basic HSM SPF accounts for the contributing effects of average annual daily traffic (AADT), and the length of roadway segment on crash frequency. In this study, an SPF is developed to aid in understanding the impact of various road elements on crash frequency. The functional form of NB regression SPF model is shown in Eq. (3).

$$N_{predicted,i} = \exp(\beta_0 + \beta_1 X_1 + \dots + \beta_k X_{ki}) \tag{3}$$

where, $N_{predicted,i}$ = Expected crash frequency on segment i , β_k = coefficients for the variable k , X_{ki} = linear predictor k of segment i .

To identify the best subset model(s) that predict crashes, Akaike Information Criterion (AIC), Bayesian information criterion, and deviance information criterion have been used in previous studies. In this study, the maximum likelihood utilized in computing AIC was used to determine the model complexity and fit. The AIC is defined as:

$$AIC = -2 \times \ln(\text{maximum likelihood}) + 2 \times k \tag{4}$$

where, k is the number of estimated parameters.

The Stata statistical software utilized in developing this study's model includes the maximum likelihood value in each subset model output. Smaller AIC, and by extension, smaller maximum likelihoods indicate better models.

To achieve the research objective of assessing the safety effectiveness of advance warning systems on Wyoming's mountain passes, the following research process was followed in this study. The research study began by collecting data on the locations of advance warning signs, and the vertical geometric data on all rural two-way two-lane highways in the State of Wyoming. These data were collected from WYDOT. The vertical geometric dataset was analyzed to identify locations that require special precautions by a road user as defined by the MUTCD. Thereafter, crash data, and geometric features of the identified locations were collected in a database.

An analysis of the descriptive statistics of the crash dataset was carried out to determine an appropriate statistical technique to implement for modeling the crashes. A model was built with presence of an advance warning sign, and other features of the roadway as explanatory variables.

All subset models from the identified predictors were generated using the Stata statistical software and the significant models with the lowest maximum likelihood were reported. The significant predictors of the model(s) were assessed to determine variables and factors that influence the crash risks of trucks on the mountain passes. Some recommendations for reducing the crash frequency on those mountain passes were then made from the result of the assessment.

3. Data preparation and analysis

3.1. Data description

Mountain passes are identified by the MUTCD description of vertical alignments that require some road signs to warn road users about the presence of a steep descent (FHWA, 2009). This made it necessary to obtain data on the grade and vertical alignments of all rural two-way two-lane highways in Wyoming. A dataset was collected from WYDOT that contained milepost (MP) information for each road with their associated elevations. The gradient between any two locations with information on their MP and elevation was computed using Eq. (5)

$$\text{Gradient} = \frac{\text{Elevation}_{(i)} - \text{Elevation}_{(i-1)}}{\text{MP}_{(i)} - \text{MP}_{(i-1)}} \times 100 \tag{5}$$

Where, $\text{Elevation}_{(i)}$ and $\text{MP}_{(i)}$ refers to the elevation and milepost at point i ;

$\text{Elevation}_{(i-1)}$ and $\text{MP}_{(i-1)}$ refers to the recorded elevation at the station prior to i .

A graphical plot was generated of the gradient at each MP. The plots

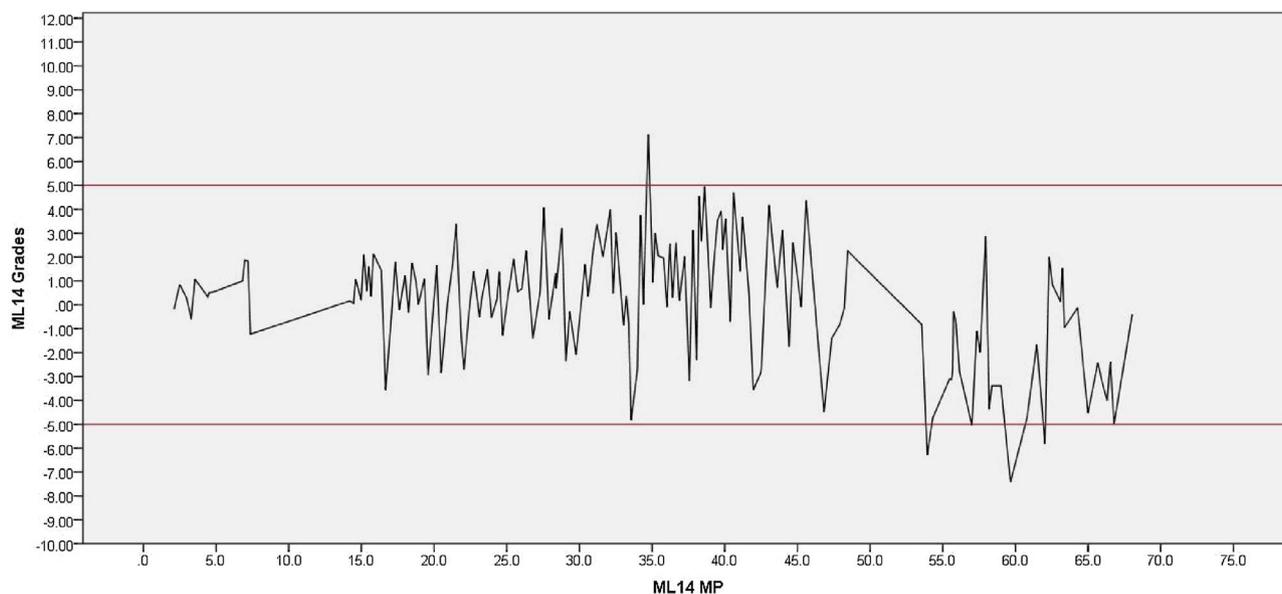


Fig. 4. Identifying Mountain passes from a road grade profile.

helped identify grades that exceeded the minimum grade of five (5) percent at which an advance warning sign may be required. A plot of the grades on Route ML14 is shown in Fig. 4 as a typical example. Locations of the route where the absolute grade exceeded 5 were selected. The length of each section was then examined to determine if they meet the MUTCD criteria for a steep grade advance warning system.

When a downhill section was identified to meet the mountain pass criteria, the section was extended by one mile beyond the base of the slope. The inclusion of the additional mile downstream of the hill was to account for runaway truck crashes occurring beyond the actual grade.

A ten-year crash data (from 2006 to 2015) for each of the routes with mountain passes were extracted from the Critical Analysis Reporting Environment (CARE) software package provided by WYDOT. The CARE package is a statistical analysis software used by many departments of transportation to analyze and present crash data. It was used to generate all the crashes for each route with associated information such as types of vehicles involved, circumstances that led to the crash, severity of crash, location (by MP), and the time of the crash. The data enabled identification of truck crashes and their locations. Fig. 5 shows the frequency of crashes by MP for Route ML14 (WY 28) determined from the CARE Package.

Plots for the grade profile and the crash profile of individual routes were compared. The comparison of the crash frequency with the grade profile for the selected routes indicated generally higher truck crashes at the vicinity of mountain passes compared to other sections of the routes.

Crash data for each mountain pass segment was compiled from the CARE Package. Data on the number of vertical curves, presence or absence of advance warning signs, length of the grade, AADT, average daily truck traffic (ADTT), horizontal curve radius, and the number of horizontal curves were also collected for each segment. These data were checked visually by means of an online video log from automated road and pavement conditions survey (<http://pathweb.pathwayservices.com/wyoming/>). The video logs also included information on the grades at each location; this was used to verify the grades computed from the elevation data provided by WYDOT.

3.2. Preliminary analysis

One hundred and twenty-two (122) sections were identified from

the dataset as mountain passes. Approximately 54% (65 sections) of the 122 sections were hotspot locations with one or more crashes. The average crash per identified mountain pass was 1.31 with the highest number on a section being 13 crashes. For the segments identified, the crashes per mile was determined to be 0.64. Fig. 6 shows the distribution of the crash data. The distribution is a Poisson distribution with a large number of zeroes within the dataset and a variance that is greater than the mean. A zero-inflated NB was therefore identified as a suitable modeling technique.

A preliminary analysis was carried out to examine the potential explanatory variables at the hotspot locations. The explanatory variables included the grade, length of the grade, AADT, ADTT, horizontal curve radius, and the number of horizontal and vertical curves. Based on the results from previous studies, increasing grade, length of grade, AADT, and ADTT were expected to increase the risk of crashes. Sharper curves (short horizontal curve radii) and increasing number of horizontal and vertical curves were also expected to increase the risk of crashes since those conditions will require the driver to be more cautious to maintain control of the vehicle on the roadway. Table 1 compares the descriptive statistics for crashes on the mountain passes with advance warning signs versus those without them and other potential variables.

4. Results

The effects of geometric features and mountain pass advance warning systems was investigated by developing a SPF. Two subset models (models A and B) were identified as significant predictors of truck crash frequency on the mountain passes ($p < 0.001$). Using an alpha level of 1% (0.01), a third model (Model C) with a higher p-value of 0.05 was determined as not statistically significant. However, using an alpha value of 5% (0.05) finds Model C significant. These significant models provide some insights concerning the factors that are likely to impact incidents of runaway crashes. The models and their parameter estimates are presented in Table 2.

The first significant model (Model A) indicated an interaction between the number of vertical curves and the length of the grades (grade and length) on the mountain passes. This meant a higher likelihood of runaway trucks on mountain passes with compound vertical curves and/or longer grades. Bowman identified the effects of compound vertical curves as potential issues that had to be addressed in future attempts to improve the FHWA GSRS model. To determine the actual

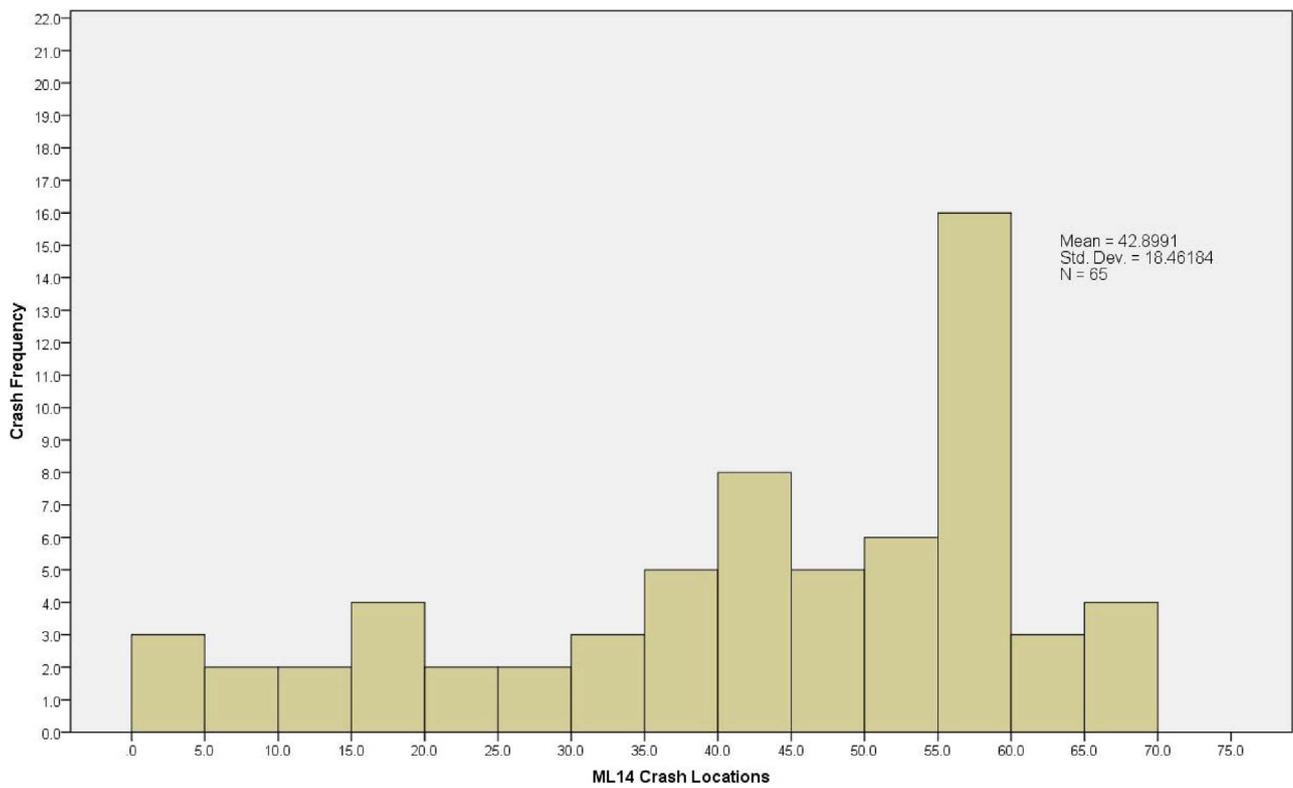


Fig. 5. Truck crash frequency by MP for Route ML14 (WY 28).

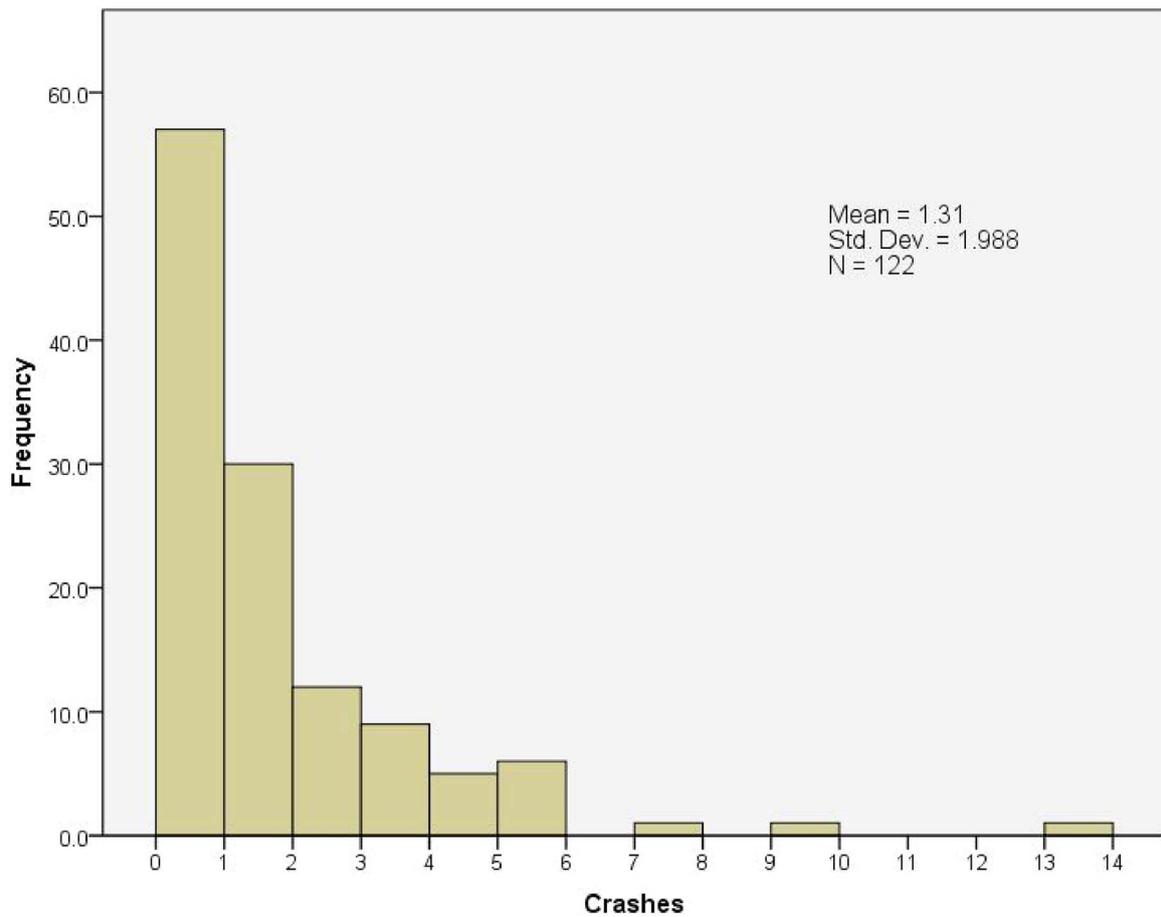


Fig. 6. Wyoming mountain passes crash distribution.

Table 1
Descriptive statistics of the independent variables.

Variables	N	Minimum	Maximum	Mean	Std. Deviation
Roads with advance warning signs (crashes per mile)	43	0.00	0.26	0.74	0.67
Roads without advance warning signs (crashes per mile)	22	0.00	0.13	0.43	0.44
AADT	65	124	5345	962	779
ADTT	65	19	597	106	95
Horizontal curve radius, ft.	65	60.5	11,333	1222	1934
No. of horizontal curves	65	1	58	9.02	9.58
No of vertical curves	65	0	38	8.52	6.61
Grade, %	65	5	10	6.46	1.16
Length of grade, mile	65	0.25	6.90	1.54	1.34

Table 2
Parameter estimates for predicting truck crashes.

	Model A	Model B	Model C
Zero-inflated Negative Binomial Models			
Intercept	-6.117*	-6.305*	-5.7615**
Vertical Curves × Length	0.008*		
Grade × Length		0.034*	
horizontal curve radii x Length			-0.00009**
Ln(AADT)	1 (exposure)	1 (exposure)	
Goodness of Fit			
Number of Observations	122	122	122
Zero Observation	56	56	56
Pearson Chi-Square	13.97*	16.23*	3.90
Log likelihood	-115.22	-114.09	-118.61

* p < 0.001.

** p = 0.05.

effect of the interaction of number of vertical curves and length of grades, the exponent of 0.008 was computed to obtain a value of 1.008. Model B identified the interaction between the steepness and length of grades as having a significant impact on runaway crashes. This agrees with the MUTCD’s recommendation that identified both the steepness of grade and its length as a criterion for classifying a hill as risky. The interaction effects of grade steepness and the length of grade was also computed as 1.035. Model C found grades with increased horizontal curve radii reduced the likelihood of runaway truck crashes. This can be explained by the fact that trucks experiencing brake failure on a descent are more likely to safely negotiate horizontal curves with longer radii compared to descents on grades with sharp horizontal curves. Traffic volume was included in the model as an exposure variable to account for the varying traffic volumes for the various routes. The log likelihood values for both models were low. Individually, grade, length of the grade, AADT, ADTT, horizontal curve radius, and the number of horizontal and vertical curves were not found to be significant predictors of truck crashes.

5. Discussion

The coefficients gave an indication of the effect of each interaction term. The value of 1.035 for the grade and grade length interaction means for each unit increase in either grade length or grade while the other variable is constant, truck crashes increase by 0.35%. Thus a 5% grade with a length of 6 mi. (9.7 km) will experience 0.35% more crashes over a ten-year period compared to a similar road with a 5% grade with a length of 5 mi. (1.6 km). For the number of vertical curves and grade interaction, the coefficient value of 1.008 indicates that a compound downgrade slope has a higher crash risk. In this instance, a unit increase in one of the two variables while the other variable is held constant will result in an increase in the risk of crashes by 0.08%.

The resulting models indicate that mountain passes that have a combination of steep grades and longer lengths, or long grades with multiple vertical curves require special remediation measures beyond what is being implemented with the current advance warning signs. Some measures to consider include implementing improved advanced warning systems based on the FHWA GSRS model, using more visible advance warning signs, or increasing the frequency of advance warning signs before the steep descent. Such measures at locations with the identified high truck crash risk features may improve safety on the mountain passes and effectively address the needs of inexperienced drivers and/or drivers unfamiliar with the terrain.

6. Conclusions and recommendations

The aim of this study is to assess the safety of mountain passes for heavy trucks in Wyoming. Variables such as the presence of advance warning systems, geometric characteristics, and traffic volumes were considered in developing a truck crash prediction model. The geometric factors were grades, length of grades, number of vertical and horizontal curves, and horizontal curve radii.

Three zero-inflated negative binomial models were developed that best predicted crash occurrence. The choice of the zero-inflated NB regression method was due to the count nature of the crash data and the presence of a large number of zeroes in the dataset. The first zero-inflated NB model found the interaction of number of vertical curves and the length of curves to be significant predictors; the second significant model is the interaction effects of steep grade and the length of grade. The third model is the interaction of horizontal curve radii and length of the grade.

The three models identified features associated with high truck crash risks regardless of current advance warning systems. Mountain passes that have steep and long grades, long grades combined with multiple vertical curves, or long grades on sharp horizontal curves were identified as high truck crash risk locations.

Based on the results of this study, the following recommendations are suggested for improving safety on Wyoming Mountain passes with regards to runaway truck crashes:

1. The locations with a high likelihood for runaway truck crashes identified in this study require additional safety improvements beyond the current advance warning systems. Future studies are recommended to analyze individual mountain passes to assess the impacts on crash occurrence by the frequency of signs at a segment, their locations, sizing, and the kind of information displayed for road users.
2. The percentage grade information displayed by the advance warning signs may not be adequate for truck drivers resulting in the selection of wrong speeds or gears during descent that leads to brake failure. Subsequent studies are recommended that will examine the inclusion of more information such as the recommended descent speeds based on different truck weight categories as recommended by the FHWA GSRS based weight specific speed (WSS) signs.
3. The future study will also examine the impact of human and environmental factors such as weather on runaway truck crashes.
4. Even though the WSS signs provide explicit information to truck drivers on the appropriate speeds at which they can descend steep grades safely, changes in truck design and braking systems since the 1970s require a review and update of the current FHWA GSRS model for current trucks. This paper recommends a review and update of the current model to ensure the prediction of appropriate safe speeds that will not be considered too low by truck drivers, and that will ensure high compliance. Installing WSS signs with advisories from an updated GSRS model will ensure improved safety on Wyoming mountain passes.

Funding

This work is supported by the Wyoming Department of Transportation (WYDOT) grant number 1003151.

Acknowledgements

The authors wish to acknowledge James Evensen, Joel Meena, Matt Carlson, and other staff of WYDOT who provided critical insights and data that were instrumental to the success of the study.

References

- AASHTO, 1997. Highway Safety Design and Operations Guide. American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO, 2010. Highway Safety Manual, 1st edition. American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO, 2011. A Policy on Geometric Design of Highways and Streets, 6th edition. Association of State Highway and Transportation Officials, Washington, D.C.
- Abdel-Aty, M.A., Radwan, E.A., 2000. Modeling traffic accident occurrence and involvement. *Accid. Anal. Prev.* 32, 633–642.
- Ahmed, M., Huang, H., Abdel-Aty, M., 2011. Exploring a bayesian hierarchical approach for developing safety performance functions for a mountainous freeway. *Accid. Anal. Prev.* 43 (4), 1581–1589.
- Andrey, J., Yagar, S., 1993. A temporal analysis of rain related crash risk. *Accid. Anal. Prev.* 25.
- Bowman, B.L., 1989. Grade Severity Rating System (GSRS). Federal Highway Administration, Mclean, VA.
- Burr, R., Fatal Crash West of Dayton. Big Horn Mountain Radio Network <http://www.bighornmountainradio.com/pages/22298157.php?> (Accessed 21 December 2015).
- Cafisco, S., Di Graziano, A., Di Silvestro, G., La Cava, G., Persaud, B., 2010. Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables. *Accid. Anal. Prev.* 42.
- Cohen, J., Cohen, P., West, S.G., Aiken, L.S., 2003. *Applied Multiple Regression/Correlation Analysis for the Behavioral Science*. Lawrence Erlbaum Associates, Mahwah, NJ.
- Cox, D.R., 1983. Some remarks on over-dispersion. *Biometrika* 70, 269–274.
- Dong, C., Clarke, D.B., Yan, X., Khattak, A., 2014. Multivariate random-parameters zero-inflated negative binomial regression model: an application to estimate crash frequencies at intersections. *Accid. Anal. Prev.* 70, 320–329.
- FHWA, 2009. Manual on Uniform Traffic Control Devices for Streets and Highways, 2009 edition. U.S. Department of Transportation Federal Highway Administration.
- Fancher, P., Winkler, C., Campbell, M., 1992. The Influence of Braking Strategy on Brake Temperatures in Mountain Descents. U.S. Department of Transportation Report No. PB93-137032.
- Fisher, P.D., 1961. The Why and How of Combination Vehicle Braking. Society of Automotive Engineers.
- Garay, A.M., Hashimoto, E.M., Ortega, E.M., Lachos, V.H., 2011. On estimation and influence diagnostics for zero-inflated negative binomial regression models. *Comput. Stat. Data Anal.* 55, 1304–1318.
- Hanscom, F.R., 1985. Field Tests of the Grade Severity Rating System. Federal Highway Administration, Washington, D.C Report No. FHWA-RD-86-011.
- Huang, H., Hong, C.C., 2010. Modeling road traffic crashes with zero-inflation and site-specific random effects. *Stat. Methods Appl.* 3445–3462.
- Hykes, P.G., 1963. Truck Downhill Control Prediction Procedure. Society of Automotive Engineers Paper No. 630A.
- Johnson, W.A., Myers, T.T., DiMarco, R.J., Allen, R.W., 1981. A Downhill Grade Severity Rating System. Society of Automotive Engineers Paper 811263.
- Johnson, W.A., DiMarco, R.J., Allen, R.W., 1982. The Development and Evaluation of a Prototype Grade Severity Rating System. U.S. Department of Transportation Report No. FHWA/RD/81/185.
- Kalokoata, K., Seneviratne, P., 1994. Accident Prediction Models for Two-Lane Rural Highways. Utah Transportation Center, Logan.
- Khattak, A.J., Knapp, K.K., 2001. Snow event effects on interstate highway crashes. *J. Cold Reg. Eng.* 15 (4).
- Lill, R.A., 1975. Development of Grade Severity Rating System. American Trucking Association.
- Lill, R.A., 1977. Review of BMCS Analysis and Summary of Accident Investigations, 1973–1976 With Respect to Downgrade Runaway Type Accidents. American Trucking Association, Inc., Memorandum 13 Sept.
- Limpert, R., Andrews, D.F., 1987. Analysis of Truck Braking Accidents. Society of Automotive Engineers Paper 870504.
- Lord, D., Bonneson, J.A., 2007. Development of accident modification factors for rural frontage road segments in Texas. *Transp. Res. Rec.* 2023 Washington, D.C.
- Lord, D., Geedipally, S.R., Guikema, S., 2010. Extension of the application of Conway Maxwell-Poisson models: analyzing traffic crash data exhibiting under-dispersion. *Risk Anal.* 30 (8).
- Miaou, S., Lord, D., 2003. Modeling traffic crash-flow relationships for intersections: dispersion parameter, functional form, and Bayes versus empirical Bayes methods. *Transp. Res. Rec.* J. Transp. Res. Board.
- Park, B.J., Lord, D., Hart, J.D., 2009. Bias properties of Bayesian statistics in finite mixture of negative binomial regression models in crash data analysis. *Accid. Anal. Prev.* 43 (8), 741–749.
- Ridout, M., Hinde, J., Demetrio, C.G., 2001. A score test for testing a zero-inflated poisson regression model against zero-inflated negative binomial alternatives. *Biometrics* 57, 219–223.
- Ruhl, R.A., Ruhl, R.L., Inendino, L.V., Southcombe, E.J., Fittano, D.A., 2006. Comparison of Established Heavy Brake/Cooling Models for HVE Brake Designer in a Real Mountain Descent Accident. Society of Automotive Engineers Paper 2006-01-3556.
- Saha, P., Young, R.K., 2014. Weather-based safety analysis for the effectiveness of rural VSL corridors. In: Presented at 93rd Annual Meeting of the Transportation Research Board. Washington, D.C..
- Saha, P., Anmed, M., Young, R.K., 2015. Safety effectiveness of variable speed limit system in adverse weather conditions on challenging roadway geometry. *Transp. Res. Rec.* J. Transp. Res. Board Washington, D.C.
- Scott, John, Fay, Richard, Hoover, Norris, Robinette, Ric, Deering, Darrell, 2003. Brake Performance Testing and Truck Runaway Analysis. No. 2003-01-3396. SAE Technical Paper.
- Tegge, R.A., Jo, J., Ouyang, Y., 2010. Development and Application of Safety Performance Functions for Illinois. Illinois Center of Transportation, Rantoul IL.
- VanOstrand, M., Rush of Truck Rollovers Prompts WYDOT to Take Action. *Kotatv.* <http://www.kotatv.com/news/wyoming-news/rash-of-truck-rollovers-prompts-wydot-to-take-action/27846600> (Accessed 02 September 2014).
- WYDOT, Updating and Implementing the Grade Severity Rating System (GSRS) for Wyoming Mountain Passes. <http://www.dot.state.wy.us/files/live/sites/wydot/files/shared/Planning/Research/RS09126%20GSRS.pdf> (Accessed 15 July 2016).
- Washington, S.P., Karlaftis, M.G., Mannering, F.L., 2010. *Statistical and Econometric Methods for Transportation Data Analysis*, second edition. Chapman Hall/CRC, Boca Raton, FL.
- Yau, K.W., Wang, K., Lee, A.H., 2003. Zero-inflated negative binomial mixed regression modeling of over-dispersed count data with extra zeros. *Biomed. J.* 45, 437–452.