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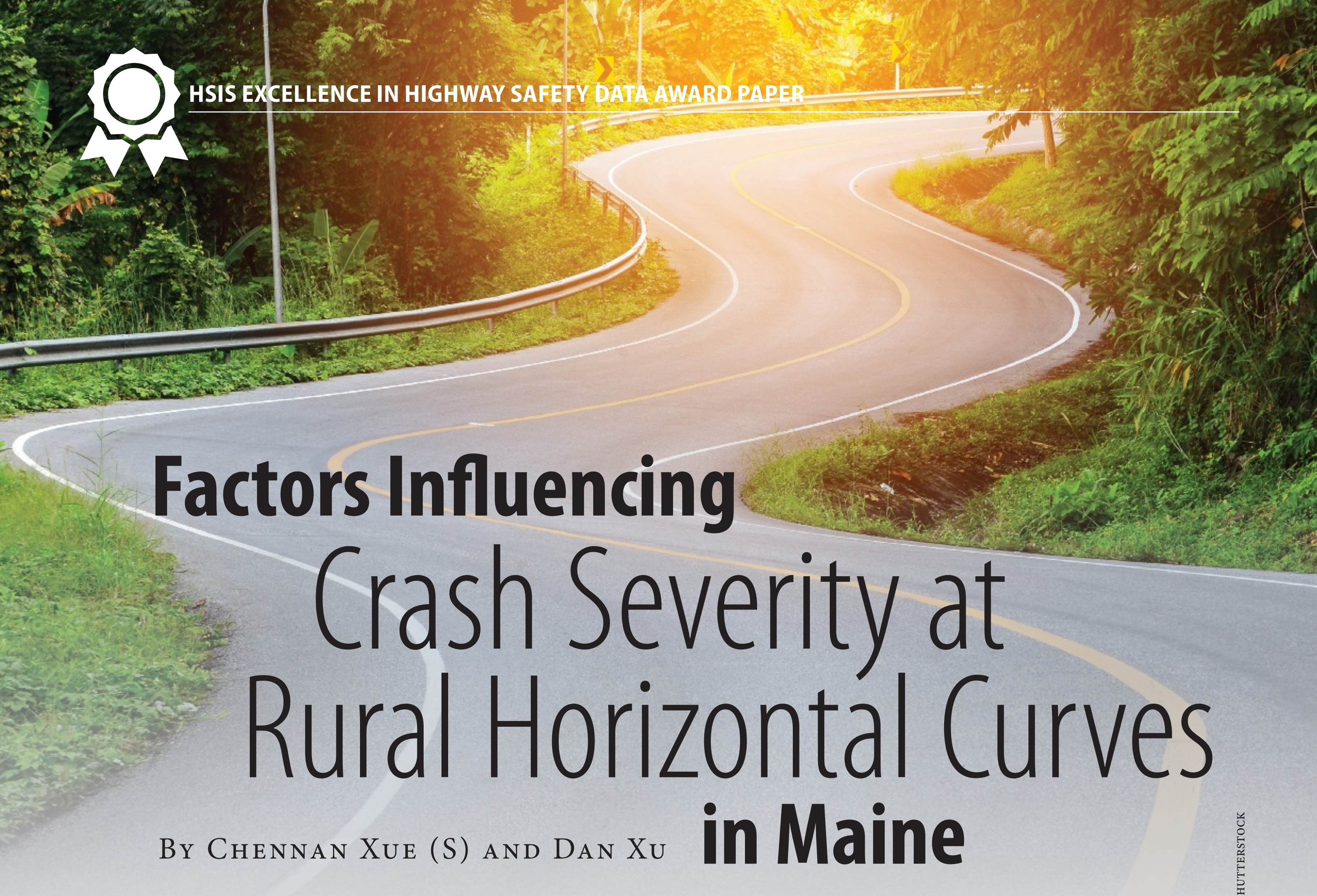

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Factors Influencing Crash Severity at Rural Horizontal Curves in Maine

By Chennan Xue (S) and Dan Xu

According to the Federal Highway Administration (FHWA), in 2008 nearly one-fourth of the fatalities occurred at horizontal curves.[1] Particularly, fatality rates at rural horizontal curves are more than twice than that at urban horizontal curves. Fatal-and-injury (FI) (i.e., incapacitating injury crash, non-incapacitating crash, and possible injury crash) crashes accommodate roughly half the number of total crashes. Hence, addressing the safety problem at horizontal curves is one of FHWA's three focus areas.[2] The *Strategic Highway Safety Plan* prepared by the American Association of State Highway and Transportation Officials (AASHTO) also counts crashes at horizontal curves as one of 22 emphasis areas.[3]

THIRD PLACE PAPER of the Federal Highway Administration's (FHWA) 2018 Excellence in Highway Safety Data Award, which is designed to encourage university students to use Highway Safety Information System (HSIS) data to investigate a topic that advances highway safety and to develop a paper to document the original research. The HSIS Highway Safety Data Awards Program is jointly administered by FHWA and the Institute of Transportation Engineers.

HSIS
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As stated in a study of the economic and societal impact of motor vehicle crashes published by FHWA,[4] the estimated comprehensive unit cost of an FI crash, approximately, ranges from 0.1 to 1.4 million based on the severity of the crash. Turning to the property-damage-only (PDO) crash, the comprehensive unit cost is valuated around $40,000. Given these circumstances of the crash severity at rural horizontal curves and economic and societal impacts of FI crashes, there is an urgent need to identify factors that influence the crash severity at rural horizontal curves.

To the best of the authors' knowledge, while plenty of studies focused on the correlation between crashes and geometric variables (e.g., curve radius and grade), few studies put effort on other factors, including the presence of a traffic control device due to limited data. According to a study conducted by the American Traffic Safety Services Association,[5] Maine, USA is ranked sixth in terms of percentage of average annual roadway departure fatalities (71 percent) in the nation from 2007–2012. The Maine Highway Safety Improvement Program also lists 19 areas with the purpose of achieving a significant reduction in FI crashes, including seven that relate to rural horizontal curve safety.[6] These are, horizontal curve, roadway departure, rural state highways, sign replacement and improvement, shoulder improvement, skid hazard, and low-cost spot improvements. Therefore, crash and inventory data of Maine from the Highway Safety Information System (HSIS), which include various crash-related variables, were used in this study. More specifically, Maine is the only state whose data contain information on the traffic control device at horizontal curves (i.e., curve warning signs in this study).

The objective of this study is to identify contributing factors that influence the crash severity at rural horizontal curves and to provide practical recommendations to reduce the crash severity based on results that are specific to Maine.

Literature Review

Numerous studies were conducted in the past that concentrated on developing prediction models for horizontal curves principally generalized linear models. However, several studies have been more specific in the methodology developed to examine potential factors that may influence horizontal curve safety.

Bauer and Harwood[7] developed Crash Modification Factors (CMFs) and Safety Performance Functions (SPFs) for fatal-and-injury and PDO crashes at horizontal curves. The prediction models include a main effect for annual average daily traffic (AADT) and an interaction between horizontal curve radii and the change in grade. Zegeer and Stewart summarized the effects of several curve improvements based on a predictive model.[8] Widening lanes and shoulders were two options found that can significantly reduce crashes at horizontal curves. Fitzpatrick et al.[9] employed negative binomial regression models to the impact of driveway density on horizontal curve safety. Results showed no significant difference in crash rates on curves and tangents with respect to the same driveway density.

Additionally, a driving simulator-based study compared combinations of advance warning signs, delineations, and road marking treatments in New Zealand.[10] Montella performed an empirical Bayes observational before-and-after study to evaluate the safety effectiveness of treatments aimed at improving horizontal curve safety.[11] The outcomes of these two studies are consistent in that the advance curve warning sign is the most effective treatment to counter potential crashes at rural horizontal curves.

The literature review showed that recent studies concentrated on either estimating crashes at rural horizontal curves through developing SPFs and CMFs or further explore the correlation of safety effects and curve alignment. Few have focused on comparing FI crashes with PDO crashes to test the significance of all confounding contributing factors, which can be conducted using logistic regression models. In this paper, a new logistic method generalized from the maximum likelihood estimate (MLE) model—the Firth's penalized-likelihood logistic regression—is used to identify factors that affect the crash severity at rural horizontal curves. Compared to MLE methods, this method is capable of addressing issues of separability, small sample sizes, and bias of parameter estimates. Recently, this logistic approach has been satisfactorily applied in the field of traffic safety.

Data

Though road alignment data are not available in Maine's inventory data, it is important to note that Maine is the only state whose data contain the information of the traffic control device (i.e., curve warning signs in this study) at horizontal curves. In view of a number of studies having already investigated the correlation between the road alignment (e.g., curve radius) and crashes at horizontal curves, HSIS crash and inventory data in rural highways from 2001 to 2010 in Maine were used to extract crashes at horizontal curves for the final analysis with the special consideration of variables which were barely studied before such as the traffic control device. A total number of 2,427 crashes remained for model development after filtering incomplete crash records. These crashes contained 20 (0.8 percent) fatal crashes, 88 (3.6 percent) incapacitating injury crashes, 277 (11.4 percent) non-incapacitating injury crashes, 303 (12.5 percent) possible injury crashes, and 1,739 (71.7 percent) PDO crashes. As shown in Figure 1, the total number of crashes has presented a downward trend after the year 2006. However, it is worthy to mention that the percentage of FI crashes demonstrated an increased trend from 2007 to 2010. Due to a substantial proportion (71.7 percent) of PDO crashes, data were split into FI crashes and PDO crashes to identify factors that influence the crash severity at rural horizontal curves. After filtering out the Unknown/Not Coded categories for variables, the independent variables in this study include time information (i.e., time of day, day of week, and month of year), weather, lighting condition, road surface condition, presence of curve warning signs, vehicle type (e.g., heavy vehicle), crash type (e.g., run off road), contributing factor (e.g., oversize load), roadway characteristics (i.e., AADT, number of lanes, and shoulder width), and driver characteristics (i.e., gender, age, physical condition, and usage of seatbelt).

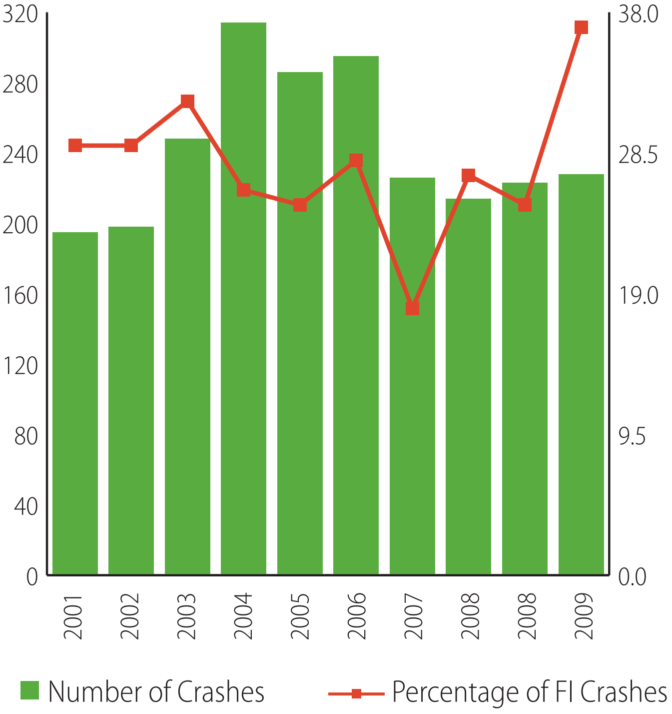

Figure 1. Number of Crashes and Percentage of FI Crashes at Rural Horizontal Curves in Maine

Methodology

In this paper, the dependent variable is the probability of FI versus PDO crashes at rural horizontal curves, which represents a binary outcome warranting the use of binary logistic regression. While standard binary logistic regression works well for a large-size and balanced sample, the Firth's logistic regression model has the capability to handle unbalanced data (i.e., 28 percent FI crashes and 72 percent PDO crashes in this study) and precisely estimate coefficients.

To develop the model, the dependent variable was assigned a binary indicator with a value of 1 if it was an FI crash at the horizontal curve and 0 if PDO crash. The categorical explanatory variables were also assigned a binary indicator of 1 or 0. Therefore, the fitted logistic regression model can be expressed as follows:

$$logit(p) = \beta_0+\beta_1x_1+\beta_2x_2+\ldots+\beta_nx_n \qquad n=1,2,\ldots,k \tag{1}$$

where p is the probability of an FI crash at horizontal curves (the dependent variable will be assigned a binary indicator of 1 if p is greater than 50 percent; otherwise, 0); $x_1, x_2, \ldots, x_n$ are the explanatory variables; β_0 is the intercept; $\beta_1, \beta_2, \ldots, \beta_n$ are the regression coefficients; and k is the number of variables estimated.

After developing the full model initially utilizing all the variables, a backward elimination procedure based on the penalized-likelihood ratio test was employed to produce a final model that best explains the dependent variable. As a rule of thumb, Akaike information criteria (AIC) was calculated to eliminate the insignificant variables and determine the subset of variables that precisely predict the probability of having an FI crash at horizontal curves compared to PDO crashes. The process continues by eliminating one variable at a time and comparing the corresponding AIC values until a model with a minimum AIC value is found. In this study, the AIC was calculated as follows:

$$AIC = 2k - 2L_\beta \tag{2}$$

where k is the number of explanatory variables in the model, and L_β is the maximum log-likelihood of the model.

Finally, the odds ratio (OR) corresponding to the estimated coefficient, as a relative measure of the effect, was calculated as shown in Equation 3. OR can be used to determine whether a variable is a risk factor for a particular outcome. In other words, when OR is greater than one, the dependent variable (i.e., FI crashes on horizontal curves) is more likely to have the specific characteristics than the reference categories.

$$OR_n = \exp(\beta_n) \qquad n = 1,2,\ldots, k \tag{3}$$

Results and Discussions

A Wald test was conducted to determine whether the entire model or a certain explanatory variable is significant or not. Subsequently, a Firth's logistic regression model was developed. Based on the test results, the Wald Chi-square statistic of 449.35 with 20 degrees of freedom, which is substantially larger than the respective Chi-square values at any reasonable confidence interval level, demonstrates that the alternative hypothesis (i.e., "This model is reliable.") can be accepted. Therefore, the model with explanatory variables is statistically better than the model with only the intercept (the null model). Moreover, 19 explanatory variables were found that significantly influence the crash severity at rural horizontal curves at a 95 percent confidence level. Seven explanatory variables (i.e., crash type, number of injuries, seat position, left shoulder type, right shoulder type, median type, and road surface type) were determined to have no significant impacts on the crash severity with p-values exceeding 0.05.

Temporal Variables

Variables in this category describe the temporal information at rural horizontal curves in terms of hour, day, and month. The results showed statistically significant differences in terms of time of day between FI crashes and PDO crashes. Considering the lighting condition, daytime was defined from 6:00 a.m. to 6:00 p.m. (otherwise, nighttime). Crashes that occurred at rural horizontal curves during nighttime were 1.13 times more probable to be FI crashes, respectively.

Crashes that happened during the weekend account for about 30 percent of the total crashes. For weekends, the likelihood of having injuring crashes increases to 1.10 times compared with PDO crashes. The reason could be driving under the influence (DUI) which is in line with the results of driver characteristics and other studies.[12, 13]

Further, crashes at rural horizontal curves were observed to be more frequent (more than 60 percent) during winter (November, December, January, and February). The results showed that crashes that happened during the winter were 1.17 times more likely to be a result of FI crashes, which is consistent with findings of the weather and the road surface condition.

Crash Variables

Estimation results of weather condition, road surface condition, lighting condition, vehicle type, the presence of the traffic control device, contributing factors, and roadway characteristics were found to have significant impacts on crash severity at rural horizontal curves in this category.

For weather conditions, rain or snow is found to increase the likelihood of FI crashes by 19 percent (OR=1.19) compared with clear or cloudy weather. Likewise, a wet road surface or having snow/ice on the road surface is 1.52 times more likely to experience FI crashes, with reference to dry road surface conditions. The findings are consistent with a study by Morgan and Mannering that the likelihood of FI crashes increased when crashes occurred on wet or snow/ice road surfaces.[14] Darkness is found to increase the likelihood of FI crashes by 32 percent (OR=1.32) due to negative impacts on the sight distance of drivers. Better illumination would result in greater visibility to reduce the risk during nighttime or harsh weather, such as rain and snow.[15]

In consideration of vehicle type, FI crashes at rural horizontal curves tend to be 1.19 times more likely to have heavy vehicles involved compare with PDO crashes. In addition to vehicle type, overloading is even more dangerous regarding the crash severity at rural horizontal curves. Based on the estimation results, oversize-loading is almost three times more probable (OR=2.91) to result in FI crashes than PDO crashes. Therefore, heavy or oversize-load vehicles shall drive with extra caution at rural horizontal curves. A previous study stated that drivers of large trucks also need to face the additional challenge of negotiating rural horizontal curves to prevent cargo shift or rollover due to the vehicle size and length.[16] Moreover, speeding (OR=1.51) and distracted driving (OR=1.47) were identified as the other two significant contributing factors that increase the driver's likelihood of experiencing FI crashes in comparison with PDO crashes. A previous study also illustrated the significance of these two factors on the frequency of crash occurrence at horizontal curves.[17]

As stated in Section 2C.06 and 2C.07 of the *Manual on Uniform Traffic Control Devices* (MUTCD), a horizontal alignment warning sign advises motorists of a change in the roadway alignment. The curve warning sign is required to be installed in advance of the curve if the difference between speed limit and advisory speed exceeds 10 miles per hour. When comparing FI crashes and PDO crashes, the presence of a traffic control device (i.e., curve warning signs in this study) was found to be a statistically significant factor. Crashes occurring at rural horizontal curves are 1.69 times more likely to be an FI crash without the installation of curve warning signs. In other words, the presence of curve warning signs could effectively reduce the crash severity at rural horizontal curves. Though curve warning signs may increase the potential hazard at horizontal curves in rural two-lane situations, studies revealed that the installation of curve warning signs is the most effective treatment to slow down vehicles and lower the crash frequency at horizontal curves.[10, 11, 18]

Turning to roadway characteristics in the estimation results, four variables were found to be significant. The first is the AADT at curves. The hypothesis is that the increase in AADT will result in the increase of crash severity. From the results, it is more probable to have FI crashes than PDO crashes when the AADT is more than 15,000, considering data on average AADT at curves is 14,817. Moreover, factors such as more lanes and narrow left/right shoulders at rural horizontal curves increase the likelihood of FI crashes. It was found that crashes are more likely to be classified as FI with a smaller number of lanes (i.e., less than or equal to two lanes in this study). Shoulders increase safety by providing a stable, clear recovery area for drivers who have left the travel lane. As expected, crashes occurred at rural horizontal curves when the shoulder width was less than 4 feet (ft.), i.e. 1.40 (left shoulder) and 1.34 (right shoulder) times, respectively, more likely to experience FI crashes than PDO crashes.

Driver Characteristics

According to estimated results, driver's gender, age, physical condition, and seatbelt usage are found to significantly differentiate between FI crashes and PDO crashes. Female drivers are 1.3 times more likely to get involved in FI crashes at rural horizontal curves. Additionally, elderly drivers (age 65 and over) are 1.18 times more likely to experience FI crashes, though they account for a small proportion of drivers involved in this type of crash. These findings are perhaps related to the physical or behavioral difference between either males and females or elderly and younger drivers. In addition, these findings are also in line with findings that female and elderly drivers are more likely to have injuries when a crash occurred.[19]

Being statistically significant, DUI drivers are 2.34 times more probable to experience FI crashes at rural horizontal curves. Previous studies have found considerable impacts on alcohol consumption that causes difficulties for drivers in perceiving roadway information.[20] Failure of using the seatbelt is 1.15 times more likely in FI crashes at rural horizontal curves. The safety effects of the seatbelt have been investigated in previous studies[21, 22] implying that seatbelt usage can significantly lower the severity of crashes.

Conclusions and Recommendations

This study identifies influencing factors that can be considered to relieve the severity of crashes occurring at rural horizontal curves in Maine. Temporal variables of nighttime, weekend, and winter; crash variables of harsh weather, icy road surface, dusk, heavy vehicle, absence of curve warning signs, oversize load, speeding, distracted driving, larger AADT, reducing number of lanes, narrow shoulders; and driver characteristics of female, elderly, DUI driving, and failure of seatbelt usage are factors that are more likely to increase the crash severity. The method and calculated OR provide an opportunity for the state department of transportation (DOT) and traffic agencies to proactively identify locations that are prone to such issues. Meanwhile, results can help them prioritize critical factors, providing safety treatments or education programs so that the crash severity can be reduced.

The first recommended low-cost countermeasure is to install or enhance traffic control devices (TCDs). As listed in the *Low-Cost Treatments for Horizontal Curve Safety 2016*,[24] some TCDs have received promising results in speed and crash reductions at rural horizontal curves. For example, Pennsylvania DOT placed an orange flag supplementing the reverse curve warning sign and speed advisory plaque to enhance the visibility of curve warning signs. Ohio DOT provided the advance curve warning sign on both sides of the road at some locations with horizontal curve crash history. In this study, absence of curve warning signs (OR=1.69) is one of the top three factors with relative higher likelihood that increase the crash severity. However, it is important to note that the implementation rate of this low-cost traffic control device is less frequent based on the descriptive statistics. Therefore, installing curve warning signs is recommended as the first priority to reduce the crash severity at rural horizontal curves.

Rumble strips is another effective TCD that can alert drivers via noise and vibration. Minnesota DOT has recommended several countermeasures including edgeline and centerline rumble strips, advanced signs and Safety Edge^{SM} as the systemic program. Furthermore, an innovative design of directional rumble strips[25] with the double number of strips on the inside of curve segments on ramps, which was developed as a low-cost countermeasure for wrong-way driving, has shown great potential in providing visual and acoustic information and slowing down vehicles at rural horizontal curves. However, rumble strips may not be as effective in northern states than in southern states due to snow or ice on the pavement. In this case, chevron signs may have improved performance compared to rumble strips due to better visibility. Sequential Dynamic Curve Warning Systems (SDCWS) are horizontal curve chevron signs with solar powered flashing lights embedded in the sign. With regards to safety, it was found that the total number of crashes per year declined by 17 to 91 percent at seven locations after the SDCWS were installed in the states of Missouri, USA; Texas, USA; Washington, USA; and Wisconsin, USA.

The second recommended countermeasure is widening the shoulders. Shoulder width that is less than 4 ft. has been identified to be another influencing factor that increases crash severity (left: OR=1.40; right: OR=1.33). According to the highway design guide published by Maine DOT,[23] it recommends that flatter horizontal curvatures and widening of the travel way (inside of horizontal curves only) shall be considered on a case-by-case basis with additional thoughts of curve length, superelevation, and sight distance. Additionally, extra clear zones on the outside of the horizontal curves should be considered based on the crash history and engineering judgment. However, shoulder width and number of lanes may not easily be modified due to the cost of the reconstruction.

Regarding weather patterns in Maine (e.g., snow), regular maintenance on pavement condition and road surface condition is considered as the third practical countermeasure. As evidence, the winter season, rain or snow, and icy road surface were identified as contributing factors that increase crash severity at rural horizontal curves in this study. Therefore, snow removal and anti-icing are essential for either preventing the occurrence of curve-related crashes or lowering the crash severity. To increase the friction of the pavement, the high friction surface treatment has helped reduce 70–75 percent in crash reduction at treated sites in Kentucky, USA.[24]

Similar to the other studies, safety concerns that are associated with the other factors needs further investigation on human factors and policies. Factors found in this study such as DUI, distracted driving, and speeding also provide an opportunity to change driver's behavior through education (e.g., education program, safety campaign) and enforcement (e.g., policy, law enforcement). **itej**

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Chennan Xue (S) *is a Ph.D. student in the department of civil engineering at Auburn University since August 2016. He received his master's degree in biosystems engineering at Auburn University in 2016 and mechanical engineering at Shanghai Ocean University in 2017. He is now majoring in transportation engineering focusing on traffic safety and operation, especially traffic control device and signal timing optimization. Chennan is now working on the projects of implementing directional rumble strips to deter wrong-way entries and optimizing signal timing plans.*

Dan Xu *is a Ph.D. student in civil engineering with a focus in transportation engineering at Auburn University. She graduated from the People's Public Security University of China, with a bachelor of science degree in traffic management engineering. Her research interests are safety impacts related to freeway deceleration lane design and driver behavior by exploring the Naturalistic Driving Study.*