Empirical Analysis of Crash Injury Severity on Mountainous and Nonmountainous Interstate Highways

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Received 24 October 2014, Accepted 19 January 2015

Objective: Mountainous (MT) highways usually exhibit complex geometry features such as steep gradients or sharp curves, which can cause considerably different driver behavior and vehicle performance compared to nonmountainous (NM) ones. In addition, MT highways experience adverse weather conditions more often than NM counterparts. We examine different characteristics of crash injury severity from an MT highway and an NM highway.

Methods: One major interstate highway with typical MT terrain and another one with NM terrain in Colorado were selected for this study. A comparative investigation about the impact on injury severity from MT and NM highways is conducted. Separate mixed logit models are estimated for both highways with 4-year detailed crash data.

Results: Incorporating 2 major interstate highways from the same region into the comparative study offers some unique strength on investigating the impacts from different causes. As a result, the study provides better insights about contributing factors and associated mechanism for injury severity on MT highways. Substantial differences in the magnitude and direction of the influence of some contributing factors between MT and NM models are observed. Some new findings about injury severity on MT highways are made possible for the first time.

Conclusion: The findings in this study provide scientific guidance to potentially improve the current highway design and traffic management policy on thousands of miles of MT highways in the country.

Keywords: mountainous highways, injury severity, mixed logit, crashes

Introduction

Traffic safety on highways is a major concern to both transportation agencies and researchers (Christoforou et al. 2010; Yasmin and Eluru 2013). In order to implement more effective and customized injury mitigation strategy, it is crucial to investigate injury severity and associated risk factors of crashes on a specific highway. Mountainous (MT) highways, where steep gradients and sharp curves are usually present, can cause considerably different driver behavior and vehicle performance compared to nonmountainous (NM) counterparts. In addition to geometric complexity, MT highways are usually more susceptible to harsh weather conditions. Despite sharing a lot of similarities, such as traffic volume, driver population, and vehicle composition, different highways in the same area may exhibit varying traffic injury risks with different contributing factors. This is particularly true for those areas with both MT and NM highways where a uniformed traffic safety performance function across the region may not be sufficient.

Considerable research efforts have been made to analyze injury severity on typical highways during the past decades in terms of different categories of crashes, such as different vehicle types and crash types (Chang and Mannering 1999; Islam and Hernandez 2013a), different numbers of vehicles involved in crashes (Chen and Chen 2011; Savolainen and Mannering 2007; Xie et al. 2012), and different driver demographic and road surface conditions (Morgan and Mannering 2011; Ulfarsson and Mannering 2004). Based on these studies, transportation practitioners and researchers have gained good knowledge about crash severity on common NM highways. There are limited studies focusing on crash severity on MT highways. Yu and Abdel-Aty (2014b) studied crash injury severity for 2 roads, a MT freeway and an urban expressway, using real-time traffic and weather data. In their subsequent study, Yu and Abdel-Aty (2014a) examined crash severity using 3 different models for a MT freeway. These studies offered some good insights about severity based on separate investigations on NM and MT highways in different regions. However, little study has been reported about comparative research focusing on the unique contribution from MT nature on crash injury risk.
This study aims at investigating the injury severity characteristics on MT interstate highways through a comparative investigation. Two major interstate highways in Colorado, one NM and the other MT, were selected. Studying both MT and NM highways in the same region can offer some unique advantages on investigating the impacts specifically contributed by MT nature through excluding influences from many other factors including driver population and so on. In addition, different from some existing studies on MT highways (e.g., Yu and Abdel-Aty 2014a, 2014b), detailed police-reported data are used in this study to consider as many critical factors as possible (Christoforou et al. 2010). Although criticized as possibly suffering from underreporting (Savolainen et al. 2011), police-reported crash data are believed to provide more insights than non-crash-specific data, avoid small sample problems, and maintain statistical inferences from detailed crash data (Anastasopoulos and Mannering 2011). With some new findings for the first time, the present study can provide better insights about contributing factors and associated mechanisms related to MT nature, which can add to the state-of-the-art of understanding injury severity risks and potential mitigation efforts. The findings of this study will provide scientific guidance to improve the current highway design and traffic management policy and propose next-generation safety initiatives for MT highways in order to reduce the injury severity and life and financial losses caused by crashes.

Data and Empirical Setting

Colorado State Patrol (CSP) has detailed traffic crash data of Colorado highways, which contains crash, driver, vehicle, roadway design, and environmental information. To study different characteristics of crash injury severity on MT and NM interstate highways, 2 major interstate highways that both cross Colorado were selected: I70 and I25. The I70 Mountain Corridor, ranging from Denver to Grand Junction through the Rocky Mountains, is a typical MT highway segment. Along the corridor, steep grades and sharp curves, accompanied by fast changing weather conditions, pose considerable safety threats on passing vehicles. I25 in Colorado goes through the Great Plains and shares a lot of common features with other NM highways in the United States. Therefore, in the following comparative study, MT highway crashes refers to those happening on the I70 Mountain Corridor, and NM highway crashes refers to those happening on I25 with plain terrain.

Four-year (2007–2010) detailed crash data on the I70 Mountain Corridor and I25 are utilized herein. After removing the crash records without crash location information, there are 16,057 crash data records during the 4-year time period in the CSP database, with 7,467 records on MT highway and 8,590 records on NM highway. The selected MT highway has a total length of 259.94 miles with an average 27,859 annual average daily traffic (AADT), and the selected NM highway has a total length of 298.879 miles with an average 69,664 AADT. In the CSP database, the variable “Highest Inj Level” means the highest level of injury in a crash with a scale from 0 to 4, representing no injury, possible injury, nonincapacitating injury, incapacitating injury, and fatality, respectively. To ensure that each category has a decent number of observations, they are regrouped into 3 categories (1) no injury (NI), (2) possible injury/nonincapacitating injury (PI/NII), and (3) incapacitating injury/fatal (II/F). To simplify the following presentation, incapacitating injury/fatal is referred to as severe injury, and possible injury/nonincapacitating injury is referred to as moderate injury. Among 7,467 crashes on the MT highway, 5,739 (76.9%) crashes had no injury, 1,465 (19.6%) crashes had moderate injury; and 263 (3.5%) crashes had severe injury. Among 8,590 crashes on the NM highway, 6,089 (70.9%) crashes had no injury, 2,194 (25.5%) crashes had moderate injury, and 307 (3.6%) crashes had severe injury.

Detailed crash characteristics in the CSP data are categorized into 5 groups: (1) roadway characteristics, (2) temporal and environmental characteristics, (3) driver characteristics, (4) crash characteristics, and (5) vehicle characteristics. In the remainder of this article, the driver characteristics, vehicle characteristics, and accident characteristics refer to the characteristics of the at-fault driver or at-fault vehicle. In order to limit potential estimation biases, all explanatory variables are carefully screened and some are redefined. For example, snowy and icy road surface indicators are combined together, because it is possible that a crash reported to occur on a snowy surface was actually caused by icy road surface (Morgan and Mannering 2011). Additionally, the driver had no insurance indicator and the driver had no proof of insurance indicator are combined. Tables 1 and 2 give the number of observations and the percentage distribution across injury severity for MT and NM data sets, respectively.

Methodology

In the present study, we focus on the differences in crash injury severities between crashes on MT and NM highways. Three crash injury severity outcomes are considered: severe injury (incapacitating injury/fatal); moderate injury (possible injury/nonincapacitating injury); and no injury. Over the years, researchers have adopted a variety of discrete outcome models to analyze crash severity data, such as ordered logit or probit models, multinomial logit models, Markov switching multinomial logit models, nested logit models, random parameter logit (mixed logit) models, and latent class models (see Mannering and Bhat [2014] and Savolainen et al. [2011] for complete reviews on those methodological approaches). Among the most frequently used methodological approaches, the mixed logit model is a well-developed approach that relaxes independence of irrelevant alternatives (IIA) assumption and independent and identically distributed (IID) errors assumption and allows for unobserved heterogeneity compared to the multinomial logit model (Jones and Hensher 2007). In addition, random parameter models (e.g., mixed logit model) and latent class logit models have gained popularity recently (Cerwick et al. 2014; Eluru et al. 2012). Differing from mixed logit models, latent class models can accommodate group specific
unobserved heterogeneity and relax continuous distributional assumptions for random parameters. However, latent class logit models do not deal with individual unobserved heterogeneity as mixed logit models can. No consensus has yet been made in terms of which approach is superior given the fact that both approaches have both strengths and limitations (Xiong and Mannering 2013). Given that latent class models and random parameter models may not adequately accommodate the unobserved heterogeneity in some cases, Xiong and Mannering (2013) proposed a finite-mixture (latent class) random parameter model to accommodate both the group-specific heterogeneity and individual heterogeneity within each group, which results in a complex model structure. Following recent work (Chen and Chen 2011; McFadden and Train 2000; Milton et al. 2008), the current article adopts a mixed logit model approach.

Let \( P_n(i) \) be the probability of crash \( n \) causing injury severity category \( I \) (Ulfarsson and Mannering 2004):

\[
P_n(i) = P(\beta_i X_n + \epsilon_{ni} \geq \beta_j X_{nj} + \epsilon_{nj}) \quad \forall j \in I, \quad j \neq i,
\]

where \( I \) is a set of all possible discrete injury outcomes—that is, severe injury, moderate injury, and no injury in the present study. \( \beta_i \) and \( \beta_j \) are the vectors of estimable coefficients corresponding to different injury severity alternatives \( i \) and \( j \) respectively, and \( X_{ni} \) and \( X_{nj} \) are the vectors of explanatory variables for crash \( n \) that determine the injury severity alternatives \( i \) and \( j \), respectively. \( \epsilon_{ni} \) and \( \epsilon_{nj} \) are error terms that are assumed to be generalized extreme value distributed (McFadden 1981). The mixed logit model formation is derived when parameter \( \beta_i \) is allowed to vary across observations as follows (Train 2003):

\[
P_n(i|\varphi) = \int e^{\beta_i X_n} \sum_{j \neq i} f(\beta_j|\varphi) d\beta_j,
\]

where \( P_n(i|\varphi) \) is the probability of injury severity alternative \( i \) conditioned on \( f(\beta_i|\varphi) \). and \( f(\beta_j|\varphi) \) is the density function of \( \beta_i \) with a vector of parameters \( \varphi \) of the density function (mean and variance).

A simulation-based likelihood method is adopted to estimate mixed logit models using Halton sequence, which has been found to be a more efficient way of drawing values than purely random draws (Bhat 2003; Train 2003). Methods with 200 Halton draws are used in the forthcoming model estimations (Bhat 2003; Gkritza and Mannering 2008; Milton et al. 2008). With a sample size of 7,467 for MT highway crashes and a sample size of 8,590 for NM highway crashes, both data sets are much larger than the sample size requirements suggested by Ye and Lord (2014).

Elasticity is calculated to measure the effect of explanatory variables on injury severity probability. Because all of the explanatory variables in this study are indicator variables, direct pseudo-elasticity is calculated to assess percentage effect on severity probability \( P_n(i|\varphi) \) when a particular indicator changes from 0 to 1 or reverse as follows (Ulfarsson and Mannering 2004):

\[
E_{X_{nk}}^{P(i)} = \left[ e^{\beta_{nk}} \sum_{k \neq n} \left[ e^{\beta_{nk}} \right] \right] - 1 \times 100,
\]

where \( E_{X_{nk}}^{P(i)} \) is the direct pseudo-elasticity of the \( k \)-th variable from the vector \( X_n \) for observation \( n \). \( X_{nk} \) is the value of the variable \( k \) for the outcome \( n \). \( \beta_{nk} \) is the \( k \)-th component of the vector \( \beta_i \) of injury severity outcome \( i \). \( e^{\beta_{nk}} \) is the value of \( e^{\beta_{nk}} \) with \( X_{nk} = 0 \), and \( e^{\beta_{nk}} \) is the value of \( e^{\beta_{nk}} \) with \( X_{nk} = 1 \). Average pseudo-elasticity is reported by taking the average of the elasticity across all observations.

### Table 1. Descriptive statistics for the MT model

| Variable | No injury | Moderate injury | Severe injury | Total |
|----------|-----------|-----------------|---------------|-------|
| Roadway characteristics | | | | |
| Wide median (median width ≥ 50 ft) | 2,005 | 74.23% | 557 | 21.36% | 119 | 4.41% | 2,701 |
| No rut indicator (rut index = 100) | 967 | 72.22% | 303 | 22.63% | 69 | 5.15% | 1,339 |
| Heavy traffic (AADT/number of lanes ≥ 7.5k) | 1,579 | 78.79% | 362 | 18.06% | 63 | 3.14% | 2,004 |
| Highway interchange | 149 | 73.04% | 42 | 20.59% | 13 | 6.37% | 204 |
| Low truck percentage (≤4%) | 122 | 68.93% | 49 | 27.68% | 6 | 3.39% | 177 |

*Please refer to Appendix for a complete version of Table 1.*

### Table 2. Descriptive statistics for the NM model

| Variable | No injury | Moderate injury | Severe injury | Total |
|----------|-----------|-----------------|---------------|-------|
| Roadway characteristics | | | | |
| Wide median (median width ≥ 50 ft) | 3,010 | 71.91% | 1,005 | 24.01% | 171 | 4.09% | 4,186 |
| Deep rut indicator (rut index ≥ 88) | 2,140 | 72.30% | 714 | 24.12% | 60 | 3.58% | 2,960 |
| High speed limit (speed limit ≥ 75 mph) | 4,762 | 70.42% | 1,736 | 25.67% | 264 | 3.90% | 6,762 |
| Depressed median | 2,828 | 69.42% | 1,066 | 26.17% | 180 | 4.22% | 4,074 |
| Heavy traffic (AADT/number of lanes ≥ 7.5 k) | 4,880 | 71.22% | 1,771 | 25.85% | 201 | 2.93% | 6,852 |

*Please refer to Appendix for a complete version of Table 2.*
In order to determine that separate developments of MT and NM models are statistically justified, a likelihood ratio test is performed. The all data model is estimated using combined MT and NM data sets. The test statistic adopted in the likelihood ratio test is (Ulfransson and Mannerings 2004):

$$X^2 = -2 [LL_N(\beta) - LL_{M_{\text{mt}}}(\beta^{m}) - LL_{M_{\text{nm}}}(\beta^{mn})],$$  

(4)

where $LL_N(\beta)$ is the log-likelihood at convergence of the all data model, with a parameter vector $\beta$. $LL_{M_{\text{mt}}}(\beta^{m})$ and $LL_{M_{\text{nm}}}(\beta^{mn})$ are the log-likelihood at convergence of the model estimated on the MT data subset and the NM data subset, respectively. The $\chi^2$ test statistic follows a $\chi^2$ distribution with degrees of freedom equal to the number of the parameters estimated in the MT and NM models minus the number of the parameters estimated in all data set models. Based on the test result with $P < .001$, we can conclude that the choice of modeling MT and NM crashes separately in the present study is warranted.

**Table 3. MT crash injury severity model estimation results**

| Variable                        | Injury outcome | Estimates | $t$ Statistics |
|---------------------------------|---------------|-----------|----------------|
| Snowy/icy road surface          | PI/NII        | −0.943    | −3.26          |
| SD of parameter distribution—normal |               | 1.775     | 3.98           |
| Young driver (age ≥ 25)         | PI/NII        | −0.796    | −2.95          |
| SD of parameter distribution—uniform |           | 1.398     | 3.26           |
| Pickup truck/utility            | PI/NII        | −0.646    | −2.84          |
| Pickup truck/utility            | II/F          | −0.389    | −2.31          |
| SD of parameter distribution—triangular |         | 2.229     | 2.58           |

Model statistics
- Number of observations: 7,467
- Log likelihood at zero: 9,437.08
- Log likelihood at convergence: 8,203.34
- McFadden pseudo $R^2$: 0.4886

*Please refer to Appendix for a complete version of Table 3.*

**Model Comparison**

We also conduct a likelihood ratio test to compare the differences between the random parameter models (i.e., mixed logit models) and their fixed parameter counterparts (i.e., base multinomial models) using the test statistic (Washington et al. 2011)

$$X^2 = -2 [LL(\beta_{\text{random}}) - LL(\beta_{\text{fixed}})].$$  

(5)

where $LL(\beta_{\text{random}})$ and $LL(\beta_{\text{fixed}})$ are the log-likelihood at convergence of mixed logit model and fixed parameter model estimated using the same data set (e.g., MT or NM data set), respectively. The test statistic is $\chi^2$ distributed with degrees of freedom equal to the difference in the number of estimated parameters between the 2 models. The $\chi^2$ value of the test is 16.08 with 3 degrees of freedom for the MT model. The $\chi^2$ value is 10.82 with 2 degrees of freedom for the NM model. Thus, the corresponding $P$ value is .0045 for the MT model and .001 for the NM model. Therefore, we are more than 99.5% confident that the mixed logit models are statistically superior.

**Empirical Results**

The estimated model results for MT and NM crashes are given in Tables 3 and 4, respectively. The results reveal substantial differences in contributing factors toward crash injury severity between MN and NM crashes. No injury outcome is chosen to be the base alternative among the 3 predefined injury outcomes. All estimated coefficients included in the MT and NM models are statistically significant at a 95% confidence level. Tables 3 and 4 show that both severity models have an overall good fit with McFadden pseudo-$\rho^2$ equal to 0.4886 for the MT model and 0.4253 for the NM model.

With regard to the random parameter density function, 4 types of distributions are considered: normal, lognormal, triangular, and uniform. Three variables are found to produce statistically significant random parameters in the MT model, and 2 random parameters are significant in the NM model. In the MT model, it is found that the snowy/icy road surface indicator variable is normally distributed for moderate injury with the mean and standard deviation being 0.943 and 1.775, respectively. This indicates that 70.2% of the MT crashes that happened on snowy/icy road surface increase the probability of moderate injury, and 29.8% of the MT crashes that happened on snowy/icy road surface decrease the probability of moderate injury. Such phenomena reflect the complex tradeoff between more cautious driving behavior and the increased difficulties on operating the vehicles on snowy/icy roads. Young driver indicator is uniformly distributed for moderate injury and the mean and standard deviation are −0.796 and 1.398, respectively. This suggests that the probability of moderate injury increases for 30.6% of MT crashes involving young drivers but decreases for the rest (69.4%). This phenomenon is perhaps due to mixed effects from relatively imprudent driving behavior and less driving experience yet shorter reaction time of young drivers. Pickup truck/utility indicator of having severe injury crashes is triangularly distributed with a mean and

**Table 4. NM Crash injury severity model estimation results**

| Variable                        | Injury outcome | Coefficient | $t$ Statistic |
|---------------------------------|---------------|-------------|--------------|
| Wide median (median width ≥ 50 ft) | PI/NII        | −0.372      | −2.98        |
| SD of parameter distribution—normal |               | 0.976       | 3.08         |
| Snowy/icy road surface          | PI/NII        | −0.806      | −2.98        |
| SD of parameter distribution—uniform |           | 1.570       | 3.6          |
| Snowy/icy road surface          | II/F          | −0.806      | −4.56        |

Model statistics
- Number of observations: 8,590
- Log likelihood at zero: −5,423.15
- Log likelihood at convergence: 4,886.20
- McFadden pseudo $R^2$: 0.4253

*Please refer to Appendix for a complete version of Table 4.*
standard deviation of $-2.825$ and $2.229$, respectively. This indicates that the effect of pickup truck/utility is not the same across observations. One possible explanation is that it captures unobserved heterogeneity such as safety features, dynamic characteristics of pickup truck/utility, and different pickup truck/utility driver behaviors.

In the NM model, the snowy/icy road surface indicator in moderate injury outcome is also found uniformly distributed with the mean of $-0.806$ and standard deviation of $1.570$. This implies that $30.3\%$ of the NM crashes on snowy/icy road surface result in an increase in the probability of moderate injury and $69.7\%$ of the NM crashes on snowy/icy road surface result in a decrease in the probability of moderate injury. Additionally, wide median indicator, which is defined for moderate injury outcome, is found normally distributed and the mean and standard deviation are, respectively, $-0.372$ and $0.976$. For $64.8\%$ of the crashes, a wide median decreases the probability of moderate injury, whereas for $35.2\%$ of the crashes, a wide median increases the probability of moderate injury. This is probably the outcome from the tradeoff between the improved physical protection and the affected driving behavior due to either “safer” or “more dangerous” interpretations by different drivers.

Average direct pseudo-elasticity results for MT and NM models are presented in Table 5. In the following section, detailed observations from Table 5 will be discussed.

### Roadway Characteristics

With regard to roadway characteristics, large disparities are found between the MT and NM models. Although wide median indicator and heavy traffic indicator are found to be significant in both models, their effects on crash injury severity are opposite. For the MT model, a wide median decreases the probability of severe injury by $2.7\%$ but increases the probability of moderate injury by $16.3\%$. For the NM model, however, a wide median increases severe injury probability by $8.9\%$ and decreases moderate injury probability by $24.9\%$. Such findings suggest that complex interactions between crash injury severity and wide median may exist. On NM highways, a wide median may provoke more aggressive driving behavior but provide more physical protection (Chen and Chen 2011). The heavy traffic indicator increases severe injury (5%) and decreases moderate injury (24.8%) in the MT model. On the contrary, it decreases the probability of severe injury (34.5%) and increases the probability of moderate injury (1.8%) in the NM model. This result may reflect some effects caused by different traffic patterns between MT corridor I70 and NM interstate highway I25 on crash injury severity. Some specific mitigation strategies of severe injury on heavy traffic road sections of MT highways may be needed in the future by considering the unique characteristics of MT crashes.

Some variables are found to be only significant in the MT crash model. For instance, no rut indicator and low truck percentage increase the probability of moderate injury by $18.3$ and $79.4\%$, respectively, and they both slightly decrease the probability of severe injury in MT crashes. If a crash happens on an MT highway interchange, the probability of a severe injury is significantly increased by $132.9\%$. Traffic agencies and the research community therefore need to put more efforts toward MT highway safety by focusing on these unique contributing variables. Some variables are found only significant in the NM crash model. For example, deep rut indicator and high speed limit indicator increase the probability of severe injury (4.0 vs. 64.4%) but decrease the probability of moderate injury (12.7 vs. 1.6%). Depressed median, however, decreases severe injury by $5.1\%$ and increases moderate injury by $19.6\%$.

### Table 5. Average direct pseudo-elasticity for MT and NM models

| Variable                                      | MT elasticity (%) | NM elasticity (%) |
|-----------------------------------------------|-------------------|-------------------|
|                                               | NI    | PI/NII | II/F | NI    | PI/NII | II/F |
| Roadway characteristics                       |       |        |      |       |        |      |
| Wide median (median width $\geq$ 50 ft)       | $-2.7$ | 16.3   | $-2.7$ | 8.9   | $-24.9$ | 8.9   |
| Heavy traffic (AADT/number of lanes $\geq$ 7.5k) | 5.0   | $-24.8$ | 5.0   | 1.8   | 1.8    | $-34.5$ |
| Driver characteristics                        |       |        |      |       |        |      |
| Young driver (age $\leq$ 25)                 | 13.5  | $-48.8$ | $-23.1$ | 3.7   | $-11.8$ | 3.7   |
| Driving under the influence of alcohol/drug use | $-15.0$ | 57.9   | 216.9b | $-25.1$ | 58.6   | 278.8b |
| Careless/reckless driving                    | $-8.7$ | 33.9   | 108.2b | $-4.6$ | 16.5   | $-4.6$ |
| Driver was fatigued                          | $-3.3$ | $-3.3$ | 121.6b | $-3.7$ | $-3.7$ | 106.4b |
| Driver had no insurance/no proof of insurance| $-13.0$ | 57.9   | 151.2b | $-6.2$ | 12.7   | 59.1   |
| Crash characteristics                        |       |        |      |       |        |      |
| More than 2 vehicles involved                | $-26.6$ | 133.2b | 321.1b | $-34.0$ | 120.5b | 156.1b |
| Exceeded legal speed                        | $-22.1$ | 98.1   | 271.9b | $-15.0$ | $-15.0$ | 531.0b |
| Overturn                                     | $-29.0$ | 168.4b | 402.9b | $-43.3$ | 173.3b | 217.9b |
| Front-to-rear collision                      | 1.8   | 1.8    | $-48.2$ | 4.3   | 4.3    | $-74.1$ |
| Collision with cable rail                   | 11.4  | $-57.7$ | 11.4  | 14.3  | $-32.8$ | $-54.9$ |
| Collision with embankment                    | $-4.6$ | $-4.6$ | 180.5b | $-15.3$ | 56.5   | $-15.3$ |
| Vehicle characteristics                      |       |        |      |       |        |      |
| Pickup truck/utility                         | 17.1  | $-38.6$ | $-93.1$ | 2.1   | 2.1    | $-46.4$ |
| SUV                                          | 10.8  | $-33.7$ | $-52.6$ | 1.5   | 1.5    | $-34.9$ |

*Please refer to Appendix for a complete version of Table 5.

bSignificant increase in injury severity probability (elasticity $\geq 100\%$).
**Temporal and Environmental Characteristics**

Although a variety of temporal indicators are considered, including different hours of the day and different days of the week, only Monday indicator is significant. If a crash happens on Monday, it is 44.1 and 58.9% more likely to result in severe injury for the MT and NM models, respectively.

As discussed above, snowy/icy road surface condition has been found randomly distributed in both the MT and NM models. According to the elasticity results from Table 5, snowy/icy road surface reduces the probability of severe injury by 59.0 and 45.9% and reduces the probability of moderate injury by 53.8 and 45.9% for MT and NM crashes, respectively. Wet road surface condition is also found to reduce the probability of severe injury by 57.1% for the NM model. These findings are consistent with several previous research (Chen and Chen 2011; Christoforou et al. 2010; Malyshkina and Mannering 2010; Xie et al. 2009; Yamamoto and Shankar 2004). Such an effect can be partly explained by the fact that drivers tend to drive more cautiously on snowy/icy road surface or wet road surface than on normal surface condition. In addition to road surface conditions, the inclement weather indicator (snow/sleet/hail) is found to be only significant for MT highway crashes. To be specific, it alleviates the probability of severe injury by 55.3% but slightly aggravates that of moderate injury. Xie et al. (2009) and Paleti et al. (2010) also reported similar findings. The darkness-road lighted indicator also significantly affects the injury severity for MT highway crashes (decreases the severe injury likelihood by 65.1%). This finding highlights the importance of lighting on MT highways, which may be considered in future mitigation efforts at some crash hot spots.

**Driver Characteristics**

Different effects on injury severity are observed for crashes caused by young drivers. For MT highway crashes, it is found that young drivers are less likely to cause severe injury (by 23.1%) and moderate injury (48.8%). For NM highway crashes, however, Table 5 shows that there is a 3.7% increase and 11.8% decrease, respectively, in the probabilities of causing severe injury and moderate injury by young drivers. Careless/reckless driving is usually believed to considerably increase the probability of causing traffic crashes. Nevertheless, its effect on injury severity has not been fully studied. Based on Table 5, on the one hand, it is found that careless/reckless driving increases the chance of moderate injury for crashes on both MT and NM highways with varying magnitudes (33.9 vs. 16.5%). On the other hand, careless/reckless driving shows a 108.2% increase and 4.6% decrease in causing severe injury on MT and NM highways, respectively. To the authors’ knowledge, such differences were not observed before, especially for the tremendous influence of careless/reckless driving behavior on severe injury on MT highways.

Although differences in driver characteristics’ effects between the MT and NM models are observed, some variables related to driver characteristics have a similar influence on crash injury severity in both MT and NM crashes. For example, older drivers are more prone to experience severe injury (68.4 and 51.9% in MT and NM models). Such a finding echoes those of previous studies (Xie et al. 2009; Yasmin and Eluru 2013) and is perhaps due to longer reaction time compared to other drivers. For female drivers, on the one hand, moderate injury increases for MT and NM highway crashes (44.9 vs. 29.2%); on the other hand, severe injury decreases on both types of highways. This finding is in accordance with several studies (for example, Weiss et al. [2014] for young drivers, Malyshkina and Mannering [2010] on design exceptions, and Islam and Hernandez [2013b] on heavy vehicles) but different from others (Xie et al. 2009). In addition to driver age and gender, if a driver was asleep, there is a 94.0 and 78.5% greater chance of severe injury for MT crashes and NM crashes, respectively. Fatigued driving has long been recognized as a hazardous factor in causing crashes. In the present study, it is discovered that fatigued driving substantially increases the chance of causing severe injury. Anastasopoulos and Mannering (2011) reported similar findings in their individual crash data models. This observation may be partly attributable to slow reaction time, decreased awareness, and impaired judgment from driver fatigue. In addition, if a driver was under the influence of alcohol or drugs or the driver was asleep, the MT and NM models result in increases in both severe injury and moderate injury. Note that under the influence of alcohol or drugs, the probability of severe injury increases considerably in both models. This result is supported by several studies (Chimba and Sando 2009; Chiou et al. 2013; Xie et al. 2009; Yasmin and Eluru 2013) and confirms the common belief about higher risk of driving under the influence. In addition, drivers with no insurance or no proof of insurance are more likely to trigger crashes with severe injury and moderate injury on both highways. This implies the need for state patrol to pay more attention to those more vulnerable drivers.

Moreover, 2 variables are found to only significantly affect NM crash injury severity. For all drivers, severe injury is decreased by 19.2%. For a driver distracted by passenger, there is a 245.8% greater chance severe injury.

The above-mentioned observations have significant implications in driving education, training, and police enforcement. These observations highlight similarities and disparities of hazardous factors in MT and NM crashes and thus can be potentially useful in training professional/commercial drivers and helping police departments allocate enforcement resources more efficiently.

**Crash Characteristics**

Many variables of crash characteristics show similar influences on MT and NM crashes. For single-vehicle crashes, a reduction in the probability of both the severe injury and moderate injury is observed. Other variables, which are significant in both the MT and NM models, also show plausible trends of influence on the probability of severe injury and moderate injury. For example, animal-caused crashes are less inclined to result in severe injury and moderate injury, and the probability of severe injury decreases while the probability of moderate injury increases if vehicles collide with guardrail in both models.
Two variables are noteworthy: more than 2 vehicles involved indicator (multivehicle crash with 3 or more vehicles involved) and overturn indicator. The effects from both indicators on crash injury severity differ greatly in magnitudes for MT and NM crashes. For multivehicle crashes, it is found that the probability of severe injury increases by 321.1% in MT crashes and 156.1% in NM crashes. When a vehicle overturns, it is 402.9% more likely to result in severe injury in MT crashes and 217.9% more likely to result in severe injury in NM crashes. These results are consistent with previous studies (e.g., Shankar et al. 1996). Both multivehicle crash and overturn crash exhibit a more critical influence on crash injury severity in MT crashes. This result may be related to the interactions between complex terrain and driver maneuver difficulties on MT highways, and further analysis is needed to fully uncover the mechanism behind this phenomenon.

Except for those indicators that have similar effects on MT and NM crashes, other indicators show substantial differences. One major difference between MT and NM crashes is that the impacts of exceed legal speed indicator on moderate injury are opposite (98.1 vs. −15.0%). It is worth mentioning that exceeding legal speed indicator significantly increases the likelihood of severe injury (271.9 and 531% for MT and NM crashes, respectively) as expected on both types of highways. Christoforou et al. (2010) also found that higher speed is more susceptible to severe injury. This phenomenon emphasizes the importance of speed law enforcement on both MT and NM highways. When a vehicle collides with a cable rail, it results in an 11.4% increase and a 54.9% decrease in severe injury for MT and NM crashes, respectively. Collision with an embankment increases severe injury by 180.5% and slightly decreases moderate injury in MT crashes, though it decreases the severe injury by 15.3% and increases moderate injury by 56.5% in NM crashes. This probably reflects different effects of roadside design features on crash injury severity in MN crashes as opposed to NM crashes, leading to some potential improvements in the design of roadside infrastructure on MT highways.

Two indicators are found to be exclusively significant in the MT model. Collision with a parked motor vehicle increases the severe injury probability substantially (166.8%) in MT crashes. Collision with a delineator post is inclined to increase both the probability of severe injury and moderate injury (177.5 vs. 75.7%). Similar to the 2 variables that are only significant in the MT model, 5 indicators are found to be only significant in the NM model. For example, improper passing and front-to-front collision are found to substantially increase severe injury probability by 294.1 and 142.1% in NM crashes, respectively. In addition, if a vehicle stops in traffic, the probability of severe injury increases considerably by 260.8% and the probability of moderate injury increases by 75.2% in the NM model.

**Vehicle Characteristics**

If the at-fault vehicle is a pickup truck/utility or sport utility vehicle (SUV), there is a substantial difference in moderate injury probability between MT and NM models (−38.6 vs. −37.5% for pickup truck/utility, −33.7 vs. 1.5% for SUV). Passenger car/van and pickup truck/utility with trailer are found to decrease severe injury and moderate injury in both models. Moreover, trucks are found to reduce severe injury and moderate injury in MT crashes. These findings indicate that heavy vehicle occupants are far less likely to sustain severe injury in contrast to light vehicles (for example, motorcycles). Similar conclusions were also drawn by other studies (e.g., Christoforou et al. 2010). One explanation may be that lighter vehicles absorb much more kinetic energy from a collision than heavy vehicles (Christoforou et al. 2010). Note that Abdel-Aty (2003) found that van and pickup occupants suffer less severe injury than passenger car occupants, and Yamamoto and Shankar (2004) found that motorcycle riders and truck drivers are less likely to suffer from severe injury in urban areas. These different findings may reflect the different driver behaviors in different regions and on different terrains. For SUV with trailer, there is a 17.6% increase in severe injury probability and an 84.6% decrease in moderate injury in the MT model. Comparatively, defective tires indicator is found to be only significant in the NM model. It decreases severe injury probability by 18.0% and increases moderate injury probability by 67.5%.

**Results Summary**

Based on the above discussions, critical contributing factors with different directions of influence in both models and those only significant in one model are summarized in Table 6.

As shown in Table 6, there are contributing factors that significantly affect injury severity on both types of highways but with different directions of influence: wide median (width ≥ 50 ft), heavy traffic (AADT/number of lanes ≥ 7.5 k), young driver, careless/reckless driving, exceeded legal speed, collision with cable rail, collision with embankment, and pickup truck/utility and SUV.

Moreover, there are 9 important contributing factors that are only significant in the MT model: no rut indicator (rut index = 100), highway interchange, low truck percentage (≤4%), snow/sleet/hail, darkness-road lighted, collision with parked motor vehicle, collision with delineator post, truck,
and SUV with trailer. Comparatively, there are 13 important contributing factors that are only significant in the NM model: deep rut indicator (rut index ≥ 88), high speed limit (speed limit ≥ 75 mph), depressed median, wet road surface, illness/medical, distracted by passenger, driver’s license had been denied, stopped in traffic, backing, improper passing, front-to-front collision, front-to-side collision, and defective tires.

With 4-year detailed crash injury severity data, separate mixed logit models were estimated for one MT and one NM interstate highway in Colorado. To provide scientific insights about potential mitigation efforts, critical contributing factors were comprehensively investigated. Substantial differences in the magnitude and direction of the influence of contributing factors were observed. Of the factors that significantly affect injury severity, 9 are exclusive to MT crashes and 13 to NM crashes. Additionally, there are 9 contributing factors that have opposite effects on injury severity between the MT and NM models. Those factors that lead to more severe injury are (elasticity greater than 100%): highway interchange (MT crashes), driving under the influence of alcohol/drug use (both MT and NM crashes), careless/reckless driving (MT crashes), driver was fatigued (both MT and NM crashes), no insurance/no proof of insurance (MT crashes), driver’s license had been denied (NM crashes), more than 2 vehicles involved (both MT and NM crashes), exceeded legal speed (both MT and NM crashes), stopped in traffic (NM crashes), overtaken (both MT and NM crashes), improper passing (NM crashes), front-to-front collision (NM crashes), collision with parked motor vehicle (MT crashes), collision with embankment (MT crashes), and collision with delineator post (MT crashes).

Those factors that lead to less severe injury are (elasticity greater than 50%): snowy/icy road surface (both MT and NM crashes), snow/sleet/hail (MT crashes), wet road surface (NM crashes), darkness-road lighted (MT crashes), only one vehicle involved (both MT and NM crashes), animal caused (both MT and NM crashes), followed too closely (both MT and NM crashes), front-to-rear collision (NM crashes), side-to-side collision with vehicles in the same direction (both MT and NM crashes), collision with cable rail (NM crashes), collision with vehicle debris or cargo (both MT and NM crashes), passing car/van (both MT and NM crashes), pickup truck/utility (MT crashes), pickup truck/utility with trailer (both MT and NM crashes), and SUV (MT crashes).

This study is explorative in nature in terms of investigating both MT and NM highways from the same region side by side. Rather than offering generic findings with the mixed model in most existing studies, it is helpful in identifying and understanding specific critical factors affecting injury severity in MT and NM crashes. There are, however, some limitations of this study that offer room for future improvements. For example, real-time traffic and weather data were not included in the model due to the incompleteness of the data. Although the adoption of a mixed logit model is helpful in capturing heterogeneity in this regard, future work should incorporate real-time data when it becomes widely available to form a decent sample size. Findings based on the comparative study of 2 typical interstate highways in Colorado can offer valuable information about MT highways in general. However, further comparative studies on more highways from various states are still desired to provide more comprehensive insights.

Acknowledgment

The crash, traffic, and environmental data obtained from the Colorado State Patrol and Colorado Department of Transportation for this study are greatly appreciated.

Funding

This study was partially sponsored by the U.S. Department of Transportation (through the Mountain Plains Consortium).

Supplemental Materials

Supplemental data for this article can be accessed on the publisher’s website.

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