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The effects of road-surface conditions, age, and gender on driver-injury severities

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ABSTRACT

Drivers' adaptation to weather-induced changes in roadway-surface conditions is a complex process that can potentially be influenced by many factors including age and gender. Using a mixed logit analysis, this research assesses the effects that age, gender, and other factors have on crash severities by considering single-vehicle crashes that occurred on dry, wet, and snow/ice-covered roadway surfaces. With an extensive database of single-vehicle crashes from Indiana in 2007 and 2008, estimation results showed that there were substantial differences across age/gender groups under different roadway-surface conditions. For example, for all females and older males, the likelihood of severe injuries increased when crashes occurred on wet or snow/ice surfaces–but for male drivers under 45 years of age, the probability of severe injuries decreased on wet and snow/ice surfaces – relative to dry-surface crashes. This and many other significant differences among age and gender groups suggest that drivers perceive and react to pavement-surface conditions in very different ways, and this has important safety implications. Furthermore, the empirical findings of this study highlight the value of considering subsets of data to unravel the complex relationships within crash-injury severity analysis.

1. Introduction

Weather conditions and resulting changes in roadway-surface conditions have long been known to be contributing factors to the frequencies and severities of roadway crashes. The effect that adverse roadway-surface conditions have on the likelihood and severity of crashes depends on many factors. Perhaps the most important of these is the ability of drivers to observe and appropriately adjust for weather-generated changes in roadway-surface conditions. Past work has provided some insight into this process. For example, a review by Andrey et al. (2003) found that almost all research has shown an increase in the frequency and severity of crashes during adverse surface conditions, but that the magnitude of the increase has varied widely across studies. They speculated that this variation could be a result of the statistical methods used and/or the result of different drivers' recognition of and reactions to perceived deteriorations in road-surface conditions. In other work, Eisenberg (2004) found lagged effects to be important during precipitation events (e.g., if it rained yesterday and today, the number of rain-related crashes would be lower today than it would be if had not rained yesterday), suggesting that drivers gather information that allows them to adjust to changes in surface conditions. The temporal elements of this inclement-weather adjustment process have been observed by numerous researchers (see for example Andrey and Yagar, 1993) and countless other studies have shown that drivers' speed and headway change substantially during inclement weather as drivers seek to compensate for adverse conditions and maintain an acceptable level of safety (see Martchouk et al., 2011).

Overall, past research suggests that drivers respond to changing surface conditions and that this response is likely a function of a wide variety of factors including experience, visual acuity, perception/reaction times, attentiveness, and potentially a variety of other human-factor related elements. However, in determining resulting crash-injury severities, the problem is further complicated by the fact that differences in roadway friction under various conditions can have a significant impact on how crash forces are dissipated. This suggests a complex interaction among the various human-factor related elements (which are likely to be associated with driver age and other factors, for example) and the physics of the crash. This can result in interesting aggregate effects. For example, Eisenberg and Warner (2005) found that snowy days resulted in fewer fatal crashes than dry days but that there were more non-fatal injury crashes. They also found the first snowy day to be substantially more dangerous than subsequent snowy days, particularly for elderly drivers, supporting the lagged effects mentioned above as well as suggesting adaptation differences, by age, across the driving population.

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Virtually every research effort that has studied the severity of occupant injuries in highway crashes has found roadway-surface conditions to be a significant determining factor. Furthermore, a number of studies have focused specifically on surface/weather conditions in an effort to provide new insights into the complex process that determines occupant injuries under varying surface/weather conditions (Norrman et al., 2000; Carson and Mannering, 2001; Malyshkina and Mannering, 2009; Jung et al., 2010). However, much of the existing research that has considered weather/surface conditions has been somewhat limited in that consideration is often only given to one or two conditions, or the data are analyzed at a more aggregate level and not at the level of individual crashes. Efforts that have assessed individual crash-injury severities have developed statistical models that most often use indicator variables to account for weather and/or roadway surface conditions. These indicators can capture the general effect of weather/surface conditions on crash-injury severities, but they are limited in terms of uncovering the effects that driver characteristics (such as age and weather) may have on the process of perceiving and adjusting to changes in roadway-surface conditions. The more general alternative to using indicator variables is to estimate models with subsets of the data (defined by specific weather/surface conditions) which allow all parameters to vary from one data subset to the next.

With regard to the impact of roadway-surface conditions on crash-injury severities, the effects of age and gender merit special consideration because both age and gender are known to have a significant impact on resulting crash-injury severities (Richardson et al., 1996; Awadzi et al., 2008). However, as with weather/surface effects, the majority of crash-severity research has accounted for age/gender effects by using indicator variables which again, due to the complexity of interrelated factors, potentially limits inferences that can be drawn. There are some notable exceptions. For example, Ulfarsson and Mannering (2004) estimated separate models for male and female crash severities in different vehicle types (sport-utility, minivan, pickup, and passenger cars) and concluded that behavioral and physiological differences between male and female drivers were the cause of dramatic male-female differences in the determinants of injury severities across vehicle types. In other work, Islam and Mannering (2006) estimated separate models by age (for drivers 16–24, 25–64, and over 65 years old) and gender, finding highly significant differences in the determinants of crash-injury severities across the various age/gender groupings. In addition to behavioral differences, they speculated that the differences may again be the result of physiological differences (weight, height, muscle mass, etc.) and the way vehicle structural design and safety features interact with these differences.

Based on the findings of these earlier research efforts, one might expect injury severities under different weather-related roadway-surface conditions to also interact in complex ways with age and gender because of the behavioral differences (in terms of detecting surface conditions, adjusting to surface conditions, etc.) and physiological differences among age/gender groups.[1] To assess this possibility, the current paper moves away from the simple indicator-variable approach previously used to capture the effects of weather-surface conditions by developing completely separate models based on weather-surface condition, age, and gender. In addition, random parameters are estimated to account for potential unobserved heterogeneity that is likely to be present in many of these models. The findings will show that there are many interesting interactions among roadway-surface conditions, age, and gender effects and that there is strong statistical justification for separate models as opposed to the more common indicator-variable approach of accounting for weather-related effects on injury severity.

2. Methodology

In the forthcoming empirical analysis, we study the driver-injury severities in single-vehicle passenger-car crashes.[2] Three discrete driver-injury severity outcomes are considered: severe injury (fatal or incapacitating); minor injury (non-incapacitating or possible injury); and no injury. To address this type of discrete outcome data, over the years researchers have used a variety of methodological approaches including ordered probit models, multinomial logit models, nested logit models, mixed (random parameters) logit models, and dual-state multinomial logit models (Shankar et al., 1996; Duncan et al., 1998; Chang and Mannering, 1999; Carson and Mannering, 2001; Khattak, 2001; Khattak et al., 2002; Kockelman and Kweon, 2002; Lee and Mannering, 2002; Abdel-Aty, 2003; Kweon and Kockelman, 2003; Ulfarsson and Mannering, 2004; Yamamoto and Shankar, 2004; Khorashadi et al., 2005; Lee and Abdel-Aty, 2005; Islam and Mannering, 2006; Hill and Boyle, 2006; Eluru et al., 2008; Savolainen and Mannering, 2007; Milton et al., 2008; Malyshkina and Mannering, 2009; Malyshkina and Mannering, 2010; Christoforou et al., 2010; Anastasopoulos and Mannering, 2011). A complete review of crash-injury severity models and methodological approaches can be found in Savolainen et al. (2011).

Herein, to study driver-injury severity we follow Milton et al. (2008) and Washington et al. (2011), and start with a function that determines driver-injury severity,

$$S_{in} = \beta_i X_{in} + \varepsilon_{in} \tag{1}$$

where, S_{in} is a severity function determining the driver-injury severity category i in crash n, $\boldsymbol{X}_{in}$ is a vector of explanatory variables that affect driver-injury severity category i in crash n, $\boldsymbol{\beta}_i$ is a vector of estimable parameters for driver-injury severity category i, and ε_{in} is an error term which is assumed to be generalized extreme value distributed (McFadden, 1981). To arrive at the mixed logit model, random parameters are introduced with $f\left(\beta_i|\varphi\right)$, where φ is a vector of parameters of the chosen density function (mean and variance). The resulting mixed-logit injury-severity probabilities are (see McFadden and Train, 2000; Train, 2003):

$$P_n\left(i|\varphi\right) = \int \frac{e^{\beta_i X_{in}}}{\sum\limits_{\forall I} e^{\beta_i X_{in}}} f\left(\beta_i|\varphi\right) d\beta_i \tag{2}$$

where, $P_n\left(i|\varphi\right)$ is the probability of injury severity i conditional on $f\left(\beta_i|\varphi\right)$. If the variance in φ is determined to be significantly different from zero, there will be crash-specific variations of the effect of $\boldsymbol{X}$ on injury severity across each crash observation n, with the density function $f\left(\beta_i|\varphi\right)$ used to determine the values of $\boldsymbol{\beta}_i$ across crashes (see Train, 2003).

Simulated maximum likelihood is used to estimate mixed logit models with logit probabilities approximated by drawing values of $\boldsymbol{\beta}_i$ from $f\left(\beta_i|\varphi\right)$ for given values of φ. Research by Bhat (2003) has shown that an efficient way of drawing values of $\boldsymbol{\beta}_i$ from $f\left(\beta_i|\varphi\right)$ to compute logit probabilities is to use a Halton sequence approach (for more on this technique, see Halton, 1960; Bhat, 2003; Train,

[1] There is also the possibility that age, gender, and road-surface conditions could interact with other factors such as geometric variables (horizontal curves). Unfortunately, due to the limited number of severe-injury crashes in some surface/age/gender categories we are not able explore such further data classifications.

[2] In Indiana, single-vehicle passenger-car accidents account for over half of all fatal and incapacitating-injury accidents, a third of all minor-injury accidents, and a quarter of all reported no-injury accidents.

Table 1
Driver injury frequency and percentage distribution by roadway surface condition and gender.

Surface and driver groups	Severe injury		Minor injury		No injury		Total
Dry surface crashes	109	1.36%	952	11.90%	6,843	85.54%	7,904
Male drivers	67	1.69%	425	10.75%	3,463	87.56%	3,955
Female drivers	42	1.06%	527	13.35%	3,380	85.59%	3,949
Wet surface crashes	75	1.26%	816	13.74%	5,049	85.00%	5,940
Male drivers	50	1.37%	451	12.39%	3,138	86.23%	3,639
Female drivers	25	1.09%	365	15.86%	1,911	83.05%	2,301
Snow/ice surface crashes	77	0.80%	1389	14.49%	8,121	84.71%	9,587
Male drivers	39	0.73%	612	11.38%	4,725	87.89%	5,376
Female drivers	38	0.90%	777	18.45%	3,396	80.65%	4,211
Total	261	1.11%	3,157	13.47%	20,013	85.41%	23,431

2003). Bhat (2003) and others have shown that 200 Halton draws is usually sufficient for accurate parameter estimation (this number of Halton draws will be used in forthcoming model estimations). In this paper, for the functional form of the parameter density functions, consideration is given to normal, lognormal, triangular, uniform, and Weibull distributions. With the functional forms of the parameter density functions specified, values of $\boldsymbol{\beta_i}$ are drawn from $f\left(\beta_i|\varphi\right)$, logit probabilities are computed, and the simulated likelihood function is maximized.

To assess the effect of individual parameter estimates on injury-severity outcome probabilities, elasticities can be computed (see Washington et al., 2011) from the partial derivative for each observation n (n subscripting omitted) as:

$$E_{x_{ki}}^{P(i|\varphi)} = \frac{\partial P(i|\varphi)}{\partial x_{ki}} \times \frac{x_{ki}}{P(i|\varphi)} \tag{3}$$

where, $P(i|\varphi)$ is the probability of injury-severity outcome i and x_k is the value of variable k. Elasticity values can be roughly interpreted as the percent effect that a 1% change in x_{ki} has on the injury-severity outcome probability $P(i|\varphi)$. For indicator variables, a pseudo elasticity can be calculated which gives the percent effect on the injury-severity outcome probability of the variable going from a value of zero to one (see Washington et al., 2011). Finally, cross elasticities give the effect that a variable defined for injury outcome i has on a non-i injury-severity outcome j. This differs from the "direct" elasticity (the effect that a variable defined for injury outcome i has on injury outcome i) as shown in Eq. (3).[3]

3. Data and empirical setting

In terms of weather conditions, a primary focus of this work, we concentrate on the effects of roadway-surface conditions and use police-reported crash data from Indiana as a basis for the empirical analysis. The crash data include information from all police-reported crashes over the years 2007 and 2008 (the two most recent years that had completed data at the time of the study).[4] Indiana police crash reports categorize possible roadway surface conditions as dry, wet, muddy, snow/slush, ice, loose material on road, and water (standing or moving). For the forthcoming empirical analysis, crashes were removed if the surface condition was not reported or was miscoded. Also, due to the small number of observations available for the muddy, loose material, and water conditions, these crashes were not considered for this study. The remaining crashes were initially divided into four groups based on roadway-surface condition (dry, wet, snow, and ice). However, it was decided that snow and ice conditions should be combined into one group because it could not be determined with certainty if some vehicles reportedly involved in snow-condition crashes came to rest on a snow-covered surface but were actually caused by an ice-surface condition.

Only Interstates, US Routes, and State Roads were considered because the maintenance on these roads is controlled by the Indiana Department of Transportation; therefore, the variability in winter maintenance practices (salting, de-icing, and plowing) among highway agencies could be minimized.

To further focus the large crash database available, only the driver-injury severities in single-vehicle passenger-car crashes were considered. This avoids the complexities of the interaction between vehicle types in multi-vehicle crashes and vehicle occupancies which can play a significant role in the severity outcome of a crash, especially in crashes involving two vehicles of different vehicle sizes (see Ulfarsson and Mannering, 2004, and Islam and Mannering, 2006, for an example of others who have done this). Table 1 shows the frequency and percentage distribution of crashes for each of the three weather-related roadway surface conditions.[5]

4. Model estimation results

A series of likelihood ratio tests were conducted to determine if separate models by gender, age, and surface condition were warranted. The test statistics used were (see Washington et al., 2011):

$$X^2 = -2[\mathrm{LL}(\beta_T) - \sum_{k=1}^{K} \mathrm{LL}(\beta_k)] \tag{4}$$

where $\mathrm{LL}(\boldsymbol{\beta}_T)$ is the log-likelihood at convergence of the model estimated with all data, $\mathrm{LL}(\boldsymbol{\beta}_k)$ is the log-likelihood at convergence of the model using subset k data (gender, age, and road-surface combinations) and K is the total number of data subsets used. This X^2 statistic is χ^2 distributed with degrees of freedom equal to the summation of the number of estimated parameters in all subset K models minus the number of estimated parameters in the total-data model. The resulting X^2 statistic provides the confidence level that the null hypothesis (that the parameters are the same) can be rejected. We also conducted a series of individual tests using,

$$X^2 = -2\left[\mathrm{LL}\left(\beta_{k_1 k_2}\right) - \mathrm{LL}\left(\beta_{k_2}\right)\right] \tag{5}$$

where, $\mathrm{LL}\left(\beta_{k_1 k_2}\right)$ is the log-likelihood at convergence of a model using the converged parameters from data subset k_1 (using only subset k_1's data) on subset k_2's data (restricting the parameters to

[3] It is possible that an explanatory variable x_{ki} may appear in more than one injury-severity function. In such cases, the net effect of the variable can be determined by considering both the direct and cross elasticities associated with all x_k variables in the model.

[4] It is well known that minor crashes tend to be under-reported in all crash databases which can potentially lead to estimation biases. Savolainen et al. (2011) provide a detailed discussion of this problem.

[5] The frequency of crashes that were considered on dry surfaces was more than twice that of any other surface condition. To make the computing time of model estimations reasonable, a random sample of dry-surface crashes was taken. This random sample was checked against the overall sample to ensure that it was an accurate representation of the total sample.

Table 2
Mixed logit severity model results for male drivers under 45 years old on dry surfaces.

Variable	Coefficient	*t*-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−6.160	−15.08			
Minivan (1 if driving a minivan; 0 otherwise)	1.728	3.35	10.2%	−0.5%	−0.5%
Curved and graded (1 if collision on curved and graded roadway segment; 0 otherwise)	1.318	2.93	7.9%	−0.5%	−0.6%
Dark and unlit (1 if dark and unlit roadway; 0 otherwise)	0.751	2.12	40.8%	−0.7%	−0.9%
Off roadway/runoff (1 if collision type; 0 otherwise)	1.842	4.60	20.8%	−1.2%	−1.5%
Tree (1 if collision with; 0 otherwise)	2.411	4.84	7.9%	−0.8%	−1.0%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	−1.209	−2.88	2.3%	−1.9%	2.0%
Sport utility vehicle (SUV) (1 if driving an SUV; 0 otherwise)	−0.624	−2.17	1.2%	−6.6%	1.2%
Single occupant (1 if driver was only vehicle occupant; 0 otherwise)	−2.237	−7.91	21.2%	−122.2%	17.0%
Urban (1 if crash on urban road; 0 otherwise)	−0.413	−2.00	1.1%	−5.6%	0.9%
Dark (1 if dark; 0 otherwise)	−0.486	−2.84	3.2%	−24.9%	2.5%
AM or PM peak period (1 if collision occurred 6:00–9:00 AM or 4:00–7:00 PM; 0 otherwise)	−0.656	−2.56	1.0%	−9.9%	0.7%
Off roadway/runoff (1 if collision type; 0 otherwise)	1.466	5.87	−4.9%	10.1%	−4.1%
Tree (1 if collision with; 0 otherwise)	1.978	5.46	−2.7%	3.4%	−2.3%
Guardrail face or end (1 if collision with; 0 otherwise)	1.084	4.16	−2.6%	6.0%	−2.2%
Passenger car (1 if driving a passenger car; 0 otherwise)	−1.341	−3.73	2.9%	6.5%	2.9%
Standard deviation of passenger car (normally distributed)	1.507	3.57			
Defined for no injury					
Not belted (1 if seat belt was not used; 0 otherwise)	−3.926	−8.89	5.3%	4.0%	−9.8%
Multiple occupants (1 if vehicle had 2–7 occupants including driver; 0 otherwise)	2.053	7.32	−50.9%	−44.1%	6.5%
Curved (1 if collision on curved roadway segment; 0 otherwise)	−0.415	−2.18	5.6%	4.5%	−1.7%
Weather Cloudy (1 if true; 0 otherwise)	0.422	2.11	−8.8%	−7.9%	1.0%
Embankment (1 if collision with; 0 otherwise)	−1.739	−4.31	2.6%	1.8%	−1.6%
Ditch (1 if collision with; 0 otherwise)	−1.062	−3.65	3.7%	2.8%	−1.4%
Pole (1 if collision with light/luminary support, utility pole, or other post/pole/support; 0 otherwise)	−1.324	−4.48	4.1%	3.2%	−1.9%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	−1.692	−7.56	26.4%	20.0%	−9.9%
Pickup truck (1 if driving a pickup truck; 0 otherwise)	1.655	4.07	−7.6%	−7.6%	2.6%
Standard deviation of pickup truck (normally distributed)	1.343	2.86			
Model statistics					
Number of observations	2394				
Log-likelihood at constants	−2630.08				
Log-likelihood at convergence	−858.85				
McFadden ρ^2	0.673				

be k_1's estimated parameters), and $LL\left(\beta_{k_2}\right)$ is the log-likelihood at convergence of the model using subset k_2's data. This test was also run using the reverse $LL\left(\beta_{k_2k_1}\right)$ and $LL\left(\beta_{k_1}\right)$. In Eq. (5), the statistic is again χ^2 distributed with the degrees of freedom equal to the number of estimated parameters in $\beta_{k_1k_2}$, and the resulting X^2 statistic provides the probability that the models have different parameters. For Eq. (5), a large number of subset pairings were tested using different age and gender combinations on the three road-surface conditions identified. The combination of these two tests yields an excellent assessment of the statistical differences among various gender, age, and road-surface combinations.

Based on these likelihood ratio tests, it was determined that 12 separate severity models were statistically justified (with confidence levels exceeding 97%) under various gender, age, and road-surface combinations:[6]

1. Male drivers under 45 years old on dry surfaces,
2. Male drivers 45 years old and older on dry surfaces,
3. Female drivers under 45 years old on dry surfaces,
4. Female drivers 45 years old and older on dry surfaces,
5. Male drivers under 45 years old on wet surfaces,
6. Male drivers 45 years old and older on wet surfaces,
7. Female drivers under 45 years old on wet surfaces,
8. Female drivers 45 years old and older on wet surfaces,
9. Male drivers under 45 years old on snow- or ice-covered surfaces,
10. Male drivers 45 years old and older on snow- or ice-covered surfaces,
11. Female drivers under 45 years old on snow- or ice-covered surfaces, and
12. Female drivers 45 years old and older on snow- or ice-covered surfaces.

Detailed model estimation results are presented in Tables 2–13. For models that produced statistically significant random parameters, 200 Halton draws were used (see previous methodological discussion). As can be seen from the detailed results provided in these tables, there are marked differences among the various gender, age, and road-surface condition categories in terms of the number of variables found to be significant and the magnitude of the variables' effects as measured by elasticities. There were significant differences across models with regard to road-surface

[6] It is important to note that many other studies have been able to find finer male/female age distributions to be significant, particularly at the younger and older limits. For example, in their use of indicator variables for age, Hill and Boyle (2006) found significant differences in age categories 16–34 years, 35–54 years, 55–74 years, and 75 years and older for females. Using separate models (subsamples) for age, Islam and Mannering (2006) found that models should be segmented with ages from 16 to 24 years, 25 to 64 years, and from 65 years or more. In the current paper, very extensive testing of alternate data subsets by age could only uncover a statistical distinction at 45 years old. Some of the 12 models estimated herein, however, do contain age indicator variables that allow for some further age variation within the age subset.

Table 3
Mixed logit model results for male drivers 45 years old and older on dry surfaces.

Variable	Coefficient	t-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−9.778	−5.96			
Not belted (1 if seat belt was not used; 0 otherwise)	5.083	4.99	9.1%	−2.9%	−1.0%
Vehicle 5–10 years old (1 if true; 0 otherwise)	4.630	2.99	142.8%	−3.7%	−1.0%
Vehicle 10–20 years old (1 if true; 0 otherwise)	3.389	2.30	63.3%	−1.6%	−0.6%
Interstate (1 if collision on interstate; 0 otherwise)	3.017	3.10	47.1%	−1.3%	−0.3%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	6.367	4.93	3.9%	−1.8%	−0.7%
Off roadway/runoff (1 if collision type; 0 otherwise)	−0.646	−0.35	15.8%	−1.1%	−0.8%
Standard deviation of off roadway/runoff (normally distributed)	4.818	2.80			
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	3.080	4.20	−3.4%	4.1%	−1.6%
Pickup truck (1 if driving a pickup truck; 0 otherwise)	−1.732	−4.84	6.2%	−40.9%	1.9%
Urban (1 if crash on urban road; 0 otherwise)	−0.804	−1.98	2.9%	−9.0%	0.7%
State road (1 if collision on state road; 0 otherwise)	−2.060	−7.53	13.6%	−96.0%	4.4%
Non-collision crash (1 if vehicle did not collide with another object; 0 otherwise)	2.766	4.63	−4.6%	4.2%	−1.9%
Head-On collision (1 if collision type; 0 otherwise)	−1.448	−4.68	3.7%	−60.3%	1.5%
Tree (1 if collision with; 0 otherwise)	3.316	4.38	−4.2%	2.2%	−1.6%
Defined for no injury					
Age 65–74 years (1 if true; 0 otherwise)	1.339	2.38	−14.6%	−14.7%	0.6%
Minivan (1 if driving a minivan; 0 otherwise)	1.318	2.22	−11.5%	−11.6%	0.6%
Vehicle less than 2 years old (1 if true; 0 otherwise)	2.425	3.81	−32.6%	−32.7%	0.7%
Vehicle 5–10 years old (1 if true; 0 otherwise)	1.765	4.68	−48.7%	−49.3%	2.3%
70 mph speed limit (1 if posted speed limit was 70 mph; 0 otherwise)	1.423	2.10	−13.1%	−13.3%	0.7%
Divided roadway (1 if collision on divided roadway segment; 0 otherwise)	1.854	4.22	−37.2%	−37.5%	1.8%
Late night (1 if collision occurred 12:00–6:00 AM; 0 otherwise)	1.059	2.58	−17.7%	−17.8%	0.8%
Driver-related factor (1 if contributing factor; 0 otherwise)	−0.646	−1.37	15.7%	19.9%	−4.3%
Standard deviation of driver-related factor (normally distributed)	3.797	4.99			
Model statistics					
Number of observations	1561				
Log-likelihood at constants	−1714.93				
Log-likelihood at convergence	−386.18				
McFadden ρ^2	0.775				

Table 4
Mixed logit model results for female drivers under 45 years old on dry surfaces.

Variable	Coefficient	t-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−6.003	−14.54			
Not belted (1 if seat belt was not used; 0 otherwise)	4.840	7.42	11.1%	−1.8%	−2.4%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	6.387	6.84	7.5%	−1.8%	−2.7%
Pole (1 if collision with light/luminary support, utility pole, or other post/pole/support; 0 otherwise)	2.507	3.47	8.1%	−0.5%	−0.5%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	2.996	5.89	−4.5%	2.5%	-3.9%
Age 25–44 years (1 if true; 0 otherwise)	−2.835	−13.98	22.2%	−139.7%	15.2%
Passenger car (1 if driving a passenger car; 0 otherwise)	−0.698	−3.40	8.0%	−35.7%	5.3%
Vehicle 5–10 years old (1 if true; 0 otherwise)	−0.619	−2.94	4.2%	−19.6%	2.8%
Dark and lighted (1 if dark and lighted roadway; 0 otherwise)	−1.050	−2.63	1.2%	−4.8%	0.7%
Overturn/rollover (1 if collision type; 0 otherwise)	2.158	3.89	−1.9%	1.2%	−1.4%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	4.615	5.66	−4.6%	1.7%	−4.4%
Tree (1 if collision with; 0 otherwise)	2.875	6.19	−4.0%	2.3%	−3.3%
Utility pole (1 if collision with; 0 otherwise)	2.199	4.70	−2.4%	2.1%	−1.8%
Guardrail face or end (1 if collision with; 0 otherwise)	1.000	3.59	−3.8%	5.4%	−2.1%
Embankment (1 if collision with; 0 otherwise)	1.910	4.15	−2.1%	1.6%	−1.5%
Ditch (1 if collision with; 0 otherwise)	1.597	4.65	−3.3%	3.5%	−2.3%
Tire failure or defective (1 if contributing factor; 0 otherwise)	1.336	2.66	−0.4%	1.3%	−0.4%
Vehicle 10–20 years old (1 if true; 0 otherwise)	−0.557	−1.46	1.7%	6.5%	0.4%
Standard deviation of vehicle 10–20 years old (normally distributed)	1.519	2.74			
Off roadway/runoff (1 if collision type; 0 otherwise)	1.116	3.22	−3.4%	10.0%	−3.4%
Standard deviation of off roadway/runoff (normally distributed)	2.204	3.29			
No injury/PDO equation					
Age 16–24 years (1 if true; 0 otherwise)	2.147	8.96	−66.6%	−57.8%	13.7%
Vehicle less than 2 years old (1 if true; 0 otherwise)	0.836	2.37	−8.4%	−8.1%	0.7%
Curved and dark (1 if collision on curved roadway segment and dark light conditions; 0 otherwise)	0.853	2.17	−5.1%	−4.6%	0.7%
Aggressive behavior or speeding (1 if contributing factor; 0 otherwise)	−1.339	−3.38	2.3%	2.0%	−1.4%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	−1.468	−5.46	22.8%	19.9%	−8.3%
Standard deviation of Other driver-related factor (normally distributed)	1.842	3.10			
Model statistics					
Number of observations	2487				
Log-likelihood at constants	−2732.25				
Log-likelihood at convergence	−827.07				
McFadden ρ^2	0.697				

Table 5
Mixed logit model results for female drivers 45 years old and older on dry surfaces.

Variable	Coefficient	*t*-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−3.865	−5.33			
Not belted (1 if seat belt was not used; 0 otherwise)	3.673	3.22	3.8%	−0.8%	−0.8%
Divided roadway (1 if collision on divided roadway segment; 0 otherwise)	−2.562	−2.98	−54.8%	0.6%	1.6%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	6.440	5.23	6.3%	−3.2%	−4.8%
Driver-related factor (1 if contributing factor; 0 otherwise)	2.859	3.44	56.8%	−3.5%	−3.4%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	3.232	3.28	−2.3%	1.6%	−1.6%
Multiple occupants (1 if vehicle had 2–7 occupants including driver; 0 otherwise)	−0.922	−3.16	3.9%	−18.2%	1.6%
Grade (1 if collision on graded roadway segment; 0 otherwise)	−0.816	−2.74	3.7%	−14.6%	1.3%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	4.299	3.59	−3.5%	2.7%	−2.9%
Non-collision crash (1 if vehicle did not collide with another object; 0 otherwise)	1.603	3.32	−2.9%	2.6%	−1.9%
Driver-related factor (1 if contributing factor; 0 otherwise)	1.605	5.74	−13.4%	16.7%	−7.8%
Divided roadway (1 if collision on divided roadway segment; 0 otherwise)	−2.802	−3.73	2.4%	6.9%	1.6%
Standard deviation of divided roadway (normally distributed)	2.886	3.62			
Defined for no injury					
Vehicle less than 2 years old (1 if true; 0 otherwise)	1.279	2.90	−16.5%	−14.6%	0.9%
One-way road (1 if collision on one-way road segment; 0 otherwise)	2.116	3.95	−10.6%	−10.6%	1.2%
Intersection (1 if crash at intersection; 0 otherwise)	1.186	2.19	−7.2%	−6.9%	0.6%
Weather cloudy (1 if true; 0 otherwise)	1.100	3.30	−21.2%	−19.5%	1.9%
AM or PM peak period (1 if collision occurred 6:00–9:00 AM or 4:00–7:00 PM; 0 otherwise)	1.102	3.04	−21.5%	−20.1%	1.1%
Late night (1 if collision occurred 12:00–6:00 AM; 0 otherwise)	1.596	2.88	−22.2%	−20.7%	1.0%
Head-on collision (1 if collision type; 0 otherwise)	1.780	5.56	−61.5%	−57.5%	2.6%
Illness (1 if contributing factor; 0 otherwise)	−1.777	−2.18	0.8%	0.7%	−1.1%
State road (1 if collision on state road; 0 otherwise)	2.932	5.21	2.0%	−1.9%	6.5%
Standard deviation of state road (normally distributed)	2.204	3.66			
Model statistics					
Number of observations	1462				
Log-likelihood at constants	−1606.17				
Log-likelihood at convergence	−434.83				
McFadden ρ^2	0.729				

Table 6
Mixed logit severity model results for male drivers under 45 years old on wet surfaces.

Variable	Coefficient	*t*-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−4.867	−15.66			
Not belted (1 if seat belt was not used; 0 otherwise)	1.440	3.12	4.6%	−0.8%	−1.0%
Off roadway/runoff (1 if collision type; 0 otherwise)	1.166	2.91	16.7%	−0.8%	−0.8%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	5.808	7.92	5.5%	−2.8%	−3.6%
Defined for minor injury					
Two-lane, two-way road (1 if collision on two-lane, two-way road segment; 0 otherwise)	−1.897	−15.86	15.0%	−75.7%	12.3%
Divided roadway (1 if collision on divided roadway segment; 0 otherwise)	−1.928	−13.24	11.9%	−44.2%	5.7%
Overturn/rollover (1 if collision type; 0 otherwise)	2.054	5.69	−2.0%	1.6%	−1.9%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	3.497	5.06	−2.8%	2.1%	−2.7%
Tree or utility pole (1 if collision with; 0 otherwise)	1.035	5.73	−3.6%	6.9%	−3.0%
Alcoholic beverages (1 if contributing factor; 0 otherwise)	0.774	2.40	−1.6%	1.3%	−0.8%
Pickup truck (1 if driving a pickup truck; 0 otherwise)	−1.031	−2.62	1.5%	6.3%	0.1%
Standard deviation of pickup truck (normally distributed)	1.740	3.48			
Defined for no injury					
Not belted (1 if seat belt was not used; 0 otherwise)	−2.122	−6.20	3.4%	2.5%	−4.0%
Weather sleet/hail/freezing rain (1 if true; 0 otherwise)	2.185	2.69	−4.6%	−4.5%	0.2%
Vehicle less than 2 years old (1 if true; 0 otherwise)	1.022	3.28	−7.4%	−7.2%	0.6%
One-way road (1 if collision on one-way road segment; 0 otherwise)	1.972	7.59	−13.7%	−13.1%	1.7%
Crest (1 if collision on crest of roadway; 0 otherwise)	0.755	2.14	−3.2%	−3.1%	0.4%
Head-On collision (1 if collision type; 0 otherwise)	0.987	5.43	−23.4%	−22.2%	2.0%
Highway traffic sign post (1 if collision with; 0 otherwise)	1.697	2.59	−3.9%	−3.9%	0.2%
Dark and lighted (1 if dark and lighted roadway; 0 otherwise)	3.916	1.93	4.7%	3.8%	−0.4%
Standard deviation of dark-lighted (normally distributed)	5.264	2.47			
Model statistics					
Number of observations	2478				
Log-likelihood at constants	−2722.36				
Log-likelihood at convergence	−1019.11				
McFadden ρ^2	0.626				

Table 7
Mixed logit model results for male drivers 45 years old and older on wet surfaces.

Variable	Coefficient	t-Statistic	Elasticity		
			Severe Injury	Minor Injury	No Injury
Defined for severe injury					
Constant	−7.380	−5.82			
Not belted (1 if seat belt was not used; 0 otherwise)	5.125	4.16	7.9%	−1.6%	−1.9%
Dark and lighted (1 if dark and lighted roadway; 0 otherwise)	2.863	2.81	21.8%	−0.9%	−1.0%
Off roadway/runoff (1 if collision type; 0 otherwise)	2.132	2.01	18.2%	−0.9%	−0.9%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	3.908	4.03	7.0%	−1.9%	−2.1%
Tree (1 if collision with; 0 otherwise)	3.185	2.95	14.2%	−1.1%	−1.1%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	2.454	2.30	34.2%	−0.9%	−1.2%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	3.230	4.25	−2.8%	2.6%	−2.1%
Weather clear (1 if true; 0 otherwise)	−1.674	−3.07	1.8%	−8.2%	0.9%
Urban (1 if crash on urban road; 0 otherwise)	−1.042	−3.16	2.6%	−15.2%	1.7%
Multiple occupants (1 if vehicle had 2–7 occupants including driver; 0 otherwise)	−0.854	−2.76	2.1%	−18.5%	1.5%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	1.220	4.17	−4.6%	10.3%	−3.8%
Weather rain (1 if true; 0 otherwise)	−2.185	−3.73	8.7%	−5.1%	2.5%
Standard deviation of rain (normally distributed)	1.988	2.79			
Defined for no injury					
Weather Cloudy (1 if true; 0 otherwise)	1.444	5.05	−28.9%	−28.9%	3.5%
Dark and unlit (1 if dark and unlit roadway; 0 otherwise)	1.560	5.00	−68.8%	−58.7%	3.8%
Head-on collision (1 if collision type; 0 otherwise)	1.022	3.17	−33.0%	−28.4%	1.8%
AM or PM peak period (1 if collision occurred 6:00–9:00 AM or 4:00–7:00 PM; 0 otherwise)	2.538	1.89	28.8%	12.5%	−0.3%
Standard deviation of AM or PM peak (normally distributed)	2.998	2.54			
Model statistics					
Number of observations	1161				
Log-likelihood at constants	−1275.49				
Log-likelihood at convergence	−370.73				
McFadden ρ^2	0.709				

Table 8
Mixed logit model results for female drivers under 45 years old on wet surfaces.

Variable	Coefficient	t-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−5.877	−9.37			
Not belted (1 if seat belt was not used; 0 otherwise)	4.228	5.71	6.1%	−1.3%	−2.4%
Interstate (1 if collision on interstate; 0 otherwise)	1.771	2.73	43.5%	−0.5%	−0.7%
Off roadway/runoff (1 if collision type; 0 otherwise)	1.394	2.22	19.8%	−0.5%	−0.7%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	4.184	5.70	4.3%	−1.4%	−1.9%
Tree (1 if collision with; 0 otherwise)	2.124	3.01	13.3%	−0.6%	−1.0%
Alcoholic beverages (1 if contributing factor; 0 otherwise)	2.715	2.82	4.8%	−0.2%	−0.4%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	2.118	3.14	−1.3%	1.4%	−1.3%
Two-lane, two-way road (1 if collision on two-lane, two-way road segment; 0 otherwise)	−1.505	−7.05	9.1%	−51.3%	9.1%
Divided roadway (1 if collision on divided roadway segment; 0 otherwise)	−0.772	−2.88	2.4%	−15.1%	2.4%
Interstate (1 if collision on interstate; 0 otherwise)	−0.612	−2.18	1.7%	−10.4%	1.7%
Curved (1 if collision on curved roadway segment; 0 otherwise)	0.557	2.80	−3.1%	8.9%	−3.1%
Multiple occupants (1 if vehicle had 2–7 occupants including driver; 0 otherwise)	−0.528	−2.48	1.8%	−12.3%	1.8%
AM peak period (1 if collision occurred 6:00–9:00 AM; 0 otherwise)	−0.690	−2.63	1.3%	−7.3%	1.3%
Overturn/rollover (1 if collision type; 0 otherwise)	1.789	3.05	−0.8%	1.3%	−0.8%
Head-On Collision (1 if collision type; 0 otherwise)	−1.081	−3.85	1.6%	−20.6%	1.6%
Pole (1 if collision with light/luminary support, utility pole, or other post/pole/support; 0 otherwise)	1.243	3.54	−1.8%	3.7%	−1.8%
Tree (1 if collision with; 0 otherwise)	1.077	2.93	−1.4%	3.4%	−1.4%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	0.792	3.30	−2.7%	6.7%	−2.7%
Age 16–24 years (1 if true; 0 otherwise)	−1.425	−2.72	−0.6%	16.6%	−0.6%
Standard deviation of age 16–24 years old (normally distributed)	2.681	3.65			
Vehicle 10–20 years old (1 if true; 0 otherwise)	−0.043	−0.07	−2.1%	9.5%	−2.1%
Standard deviation of vehicle 10–20 years old (normally distributed)	2.627	2.11			
Defined for no injury					
Weather clear (1 if true; 0 otherwise)	1.824	2.50	−8.5%	−6.8%	0.4%
60–70 mph speed limit (1 if posted speed limit was 60–70 mph; 0 otherwise)	0.943	3.02	−16.6%	−13.0%	1.5%
Crest (1 if collision on crest of roadway; 0 otherwise)	1.272	2.25	−5.1%	−4.2%	0.4%
Dark (1 if dark; 0 otherwise)	1.076	5.72	−53.0%	−41.3%	5.5%
Ditch (1 if collision with; 0 otherwise)	−0.810	−2.72	6.2%	3.7%	−1.6%
Model Statistics					
Number of observations	1592				
Log-likelihood at constants	−1748.99				
Log-likelihood at convergence	−692.28				
McFadden ρ^2	0.604				

Table 9
Mixed logit model results for female drivers 45 years old and older on wet surfaces.

Variable	Coefficient	t-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−3.578	−8.20			
Defined for minor injury					
Weather clear (1 if true; 0 otherwise)	−1.859	−3.16	1.8%	−11.0%	1.8%
55–60 mph speed limit (1 if posted speed limit was 55 or 60 mph; 0 otherwise)	−0.744	−2.47	4.0%	−33.8%	4.0%
Off roadway/runoff (1 if collision type; 0 otherwise)	2.077	4.42	−5.3%	9.7%	−5.3%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	2.763	3.06	−4.2%	1.5%	−4.2%
Aggressive behavior or speeding (1 if contributing factor; 0 otherwise)	1.167	2.57	−2.6%	6.4%	−2.6%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	2.053	4.76	−8.1%	15.5%	−8.1%
Weather rain (1 if true; 0 otherwise)	−2.636	−3.95	8.1%	−19.2%	8.1%
Standard deviation of rain (normally distributed)	2.152	2.63			
Defined for no injury					
Weather cloudy (1 if true; 0 otherwise)	1.798	4.96	−37.0%	−37.0%	5.8%
Weather snowing or blowing snow (1 if true; 0 otherwise)	2.162	3.39	−11.6%	−11.6%	1.5%
AM or PM peak period (1 if collision occurred 6:00–9:00 AM or 4:00–7:00 PM; 0 otherwise)	1.081	2.59	−21.8%	−18.9%	1.5%
Dark and lighted (1 if dark and lighted roadway; 0 otherwise)	1.517	2.78	−9.5%	−7.5%	1.6%
Dark and unlit (1 if dark and unlit roadway; 0 otherwise)	0.935	3.00	−45.7%	−37.0%	3.7%
Model statistics					
Number of observations	709				
Log-likelihood at constants	−778.92				
Log-likelihood at convergence	−274.85				
McFadden ρ^2	0.647				

Table 10
Mixed logit severity model results for male drivers under 45 years old on snow/ice surfaces.

Variable	Coefficient	t-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−4.403	−11.74			
Not belted (1 if seat belt was not used; 0 otherwise)	2.885	4.31	6.1%	−0.2%	−0.5%
State road (1 if collision on state road; 0 otherwise)	−1.671	−2.79	−55.0%	0.1%	0.3%
Curved and runoff (1 if vehicle ran off roadway on curved segment; 0 otherwise)	1.718	2.14	3.5%	−0.1%	−0.1%
Late night (1 if collision occurred 12:00–6:00 AM; 0 otherwise)	1.463	3.15	27.1%	−0.3%	−0.5%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	5.159	7.50	3.9%	−0.6%	−1.3%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	2.899	7.01	−2.0%	2.1%	−2.0%
Weather clear (1 if true; 0 otherwise)	−1.194	−4.89	1.3%	−8.1%	1.3%
Weather cloudy (1 if true; 0 otherwise)	−1.292	−4.91	1.2%	−8.7%	1.2%
Weather sleet/hail/freezing rain (1 if true; 0 otherwise)	−1.520	−7.82	3.2%	−26.1%	3.2%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	4.351	5.81	−1.7%	1.0%	−1.7%
Driver-related factor other than speeding or runoff (1 if contributing factor; 0 otherwise)	0.608	2.43	−0.5%	2.9%	−0.5%
Probationary driver's license (1 if true; 0 otherwise)	1.426	2.53	−0.3%	0.9%	−0.3%
Two-lane, two-way road (1 if collision on two-lane, two-way road segment; 0 otherwise)	−1.625	−2.56	−0.1%	5.4%	−0.1%
Standard deviation of two-lane, two-way road (normally distributed)	2.366	3.16			
Dark and unlit (1 if dark and unlit roadway; 0 otherwise)	−1.868	−2.27	−0.8%	11.8%	−0.8%
Standard deviation of dark-unlit (normally distributed)	2.554	3.00			
Snow on roadway surface (1 if present; 0 otherwise)	−0.760	−1.91	0.3%	0.3%	0.3%
Standard deviation of snow on roadway (normally distributed)	1.290	2.30			
Defined for no injury					
Weather snowing or blowing snow (1 if true; 0 otherwise)	1.463	7.93	−70.2%	−54.3%	6.0%
Urban (1 if crash on urban road; 0 otherwise)	0.400	2.40	−9.3%	−8.0%	0.8%
Divided roadway (1 if collision on divided roadway segment; 0 otherwise)	0.361	2.22	−15.9%	−13.7%	1.5%
Vehicle 5–10 years old (1 if true; 0 otherwise)	0.481	3.44	−19.9%	−15.8%	1.6%
Guardrail face or end (1 if collision with; 0 otherwise)	0.507	3.16	−15.6%	−13.2%	1.2%
Highway traffic sign post (1 if collision with; 0 otherwise)	1.500	2.49	−4.2%	−3.5%	0.2%
Model statistics					
Number of observations	3765				
Log-likelihood at constants	−4136.28				
Log-likelihood at convergence	−1296.05				
McFadden ρ^2	0.687				

Table 11
Mixed logit model results for male drivers 45 years old and older on snow/ice surfaces.

Variable	Coefficient	*t*-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−4.764	−9.29			
Not belted (1 if seat belt was not used; 0 otherwise)	3.428	4.82	4.5%	−1.1%	−1.1%
Pickup truck (1 if driving a pickup truck; 0 otherwise)	2.029	3.48	81.2%	−1.1%	−1.1%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	3.210	4.59	7.4%	−1.0%	−1.0%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	1.712	3.46	−1.3%	1.5%	−1.3%
Minivan (1 if driving a minivan; 0 otherwise)	−1.641	−6.81	2.7%	−11.7%	2.7%
Sport utility vehicle (SUV) (1 if driving an SUV; 0 otherwise)	−1.727	−9.55	5.0%	−24.8%	5.0%
Age 65–90 years (1 if true; 0 otherwise)	0.422	2.26	−1.3%	5.9%	−1.3%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	2.238	5.99	−3.5%	2.4%	−3.5%
Defined for no injury					
Passenger car (1 if driving a passenger car; 0 otherwise)	2.374	13.94	−71.3%	−71.3%	7.8%
Pickup truck (1 if driving a pickup truck; 0 otherwise)	2.002	14.19	−68.6%	−68.6%	12.7%
Vehicle 10–20 years old (1 if true; 0 otherwise)	−0.438	−2.38	5.9%	5.9%	−1.5%
Guardrail face (1 if collision with; 0 otherwise)	0.544	2.01	−7.2%	−7.2%	0.6%
Embankment (1 if collision with; 0 otherwise)	−0.854	−3.34	3.4%	3.4%	−1.5%
Head-on collision (1 if collision type; 0 otherwise)	0.859	3.30	−14.7%	−14.7%	1.0%
Model statistics					
Number of observations	1611				
Log-likelihood at constants	−1769.86				
Log-likelihood at convergence	−642.99				
McFadden ρ^2	0.637				

Table 12
Mixed logit model results for female drivers under 45 years old on snow/ice surfaces.

Variable	Parameter estimate	*t*-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−5.106	−10.15			
Not belted (1 if seat belt was not used; 0 otherwise)	4.201	6.41	6.7%	−0.7%	−0.9%
US route (1 if collision on US route; 0 otherwise)	1.152	2.28	26.9%	−0.3%	−0.3%
Multiple occupants (1 if vehicle had 2–7 occupants including driver; 0 otherwise)	0.987	2.03	28.1%	−0.3%	−0.3%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	4.483	7.01	6.9%	−0.8%	−1.0%
Tree (1 if collision with; 0 otherwise)	2.312	3.75	11.5%	−0.3%	−0.4%
Defined for minor injury					
Not belted (1 if seat belt was not used; 0 otherwise)	2.489	5.66	−2.5%	1.4%	−2.2%
Weather clear (1 if true; 0 otherwise)	−1.035	−4.36	3.2%	−6.1%	1.9%
Two-lane, two-way road (1 if collision on two-lane, two-way road segment; 0 otherwise)	−0.270	−2.05	2.5%	−7.5%	1.7%
Minivan (1 if driving a minivan; 0 otherwise)	0.675	2.66	−0.9%	2.3%	−0.7%
Sport utility vehicle (SUV) (1 if driving an SUV; 0 otherwise)	0.626	4.09	−3.9%	9.5%	−2.8%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	2.548	6.04	−2.6%	1.4%	−2.3%
Overturn/rollover (1 if collision type; 0 otherwise)	0.723	2.49	−0.9%	1.4%	−0.7%
Utility pole (1 if collision with; 0 otherwise)	0.746	3.07	−1.2%	2.6%	−0.9%
Tree (1 if collision with; 0 otherwise)	1.315	5.17	−2.1%	3.6%	−1.6%
Daylight (1 if daylight; 0 otherwise)	−0.895	−2.58	2.3%	6.2%	−0.2%
Standard deviation of daylight (normally distributed)	1.620	3.02			
Defined for No Injury					
Weather cloudy (1 if true; 0 otherwise)	1.568	5.85	−10.9%	−9.1%	2.3%
Weather snowing or blowing snow (1 if true; 0 otherwise)	1.788	9.41	−79.8%	−67.8%	13.2%
Weather sleet/hail/freezing rain (1 if true; 0 otherwise)	1.762	8.09	−32.7%	−27.5%	5.8%
Pickup truck (1 if driving a pickup truck; 0 otherwise)	−0.581	−2.77	3.6%	3.0%	−1.0%
One-way road (1 if collision on one-way road segment; 0 otherwise)	0.551	2.23	−4.1%	−3.4%	0.5%
Dark (1 if dark; 0 otherwise)	0.365	2.16	−11.1%	−11.1%	2.4%
Embankment (1 if collision with; 0 otherwise)	−0.750	−2.99	2.7%	2.1%	−0.8%
Weather cloudy (1 if true; 0 otherwise)	1.568	5.85	−10.9%	−9.1%	2.3%
AM or PM peak period (1 if collision occurred 6:00–9:00 AM or 4:00–7:00 PM; 0 otherwise)	0.871	2.51	10.9%	4.6%	0.0%
Standard deviation of AM or PM peak (normally distributed)	1.769	3.39			
Model statistics					
Number of observations	3135				
Log-likelihood at constants	−3444.15				
Log-likelihood at convergence	−1447.11				
McFadden ρ^2	0.580				

Table 13
Mixed logit model results for female drivers 45 years old and older on snow/ice surfaces.

Variable	Coefficient	*t*-Statistic	Elasticity		
			Severe injury	Minor injury	No injury
Defined for severe injury					
Constant	−5.522	−11.61			
AM peak period (1 if collision occurred 6:00–9:00 AM; 0 otherwise)	1.163	2.24	26.5%	−0.9%	−0.9%
Overturn/rollover (1 if collision type; 0 otherwise)	2.197	2.79	7.3%	−0.6%	−0.6%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	4.450	6.75	16.5%	−2.9%	−2.9%
Tree (1 if collision with; 0 otherwise)	2.253	3.47	13.6%	−0.8%	−0.8%
Defined for minor injury					
Weather clear or cloudy (1 if true; 0 otherwise)	−1.688	−8.66	8.9%	−26.4%	8.9%
Weather snowing or blowing snow (1 if true; 0 otherwise)	−2.007	−10.72	19.2%	−87.5%	19.2%
Weather sleet/hail/freezing rain (1 if true; 0 otherwise)	−1.846	−9.60	10.3%	−33.5%	10.3%
Overturn/rollover (1 if collision type; 0 otherwise)	1.457	3.80	−2.4%	2.8%	−2.4%
Trapped in or pinned under vehicle (1 if trapped in or pinned under vehicle; 0 otherwise)	2.940	6.71	−9.0%	3.8%	−9.0%
Utility pole (1 if collision with; 0 otherwise)	0.804	2.31	−1.1%	2.8%	−1.1%
Tree (1 if collision with; 0 otherwise)	1.168	4.00	−2.6%	4.9%	−2.6%
Ditch (1 if collision with; 0 otherwise)	1.019	4.58	−4.4%	8.4%	−4.4%
Snow on roadway surface (1 if present; 0 otherwise)	−0.367	−2.09	2.9%	−14.1%	2.9%
Defined for no injury					
Vehicle 10–20 years old (1 if true; 0 otherwise)	−0.479	−2.41	5.5%	5.5%	−2.5%
Multiple occupants (1 if vehicle had 2–7 occupants including driver; 0 otherwise)	−0.402	−2.25	6.5%	6.5%	−2.7%
Median barrier (1 if collision with; 0 otherwise)	−0.521	−2.02	4.3%	4.3%	−1.2%
Model statistics					
Number of observations	1076				
Log-likelihood at constants	−1182.11				
Log-likelihood at convergence	−554.43				
McFadden ρ^2	0.531				

condition. As shown in Tables 2-13, only five factors were found to affect the injury severities of specific driver groups regardless of the roadway-surface condition: not wearing a seatbelt, being trapped in or pinned under the vehicle, overturn/rollover collisions, head-on collisions, and collisions with a tree. Many more variables were found to affect injury severities on only one or two of the three road-surface conditions.

From a methodological point of view and the application of the mixed logit model, 26 parameter estimates were found to be statistically significant as random parameters across the 12 injury-severity models (although a variety of distributions were tried, the normal distribution provided the best statistical fit for all random parameters). While random parameters were found to be significant for most models, the effects of all factors were found to be fixed across the populations of older male and female drivers for snow- or ice-related crashes.

Of the 26 random parameters in the severity models, seven of these parameters were observed to have means that were not significantly different from zero (less than 95% confidence). Most notably, the mean of the indicator for off-roadway/runoff collisions in the model for male drivers 45 years old and older on dry-surface conditions and the mean of the indicator for vehicles 10–20 years old in the model of female drivers under 45 years old on wet-surface conditions were determined to be statistically different from zero with only 5.4% and 27.4% confidence. As a result, the effects of these random parameters would be nearly evenly split around zero in terms of these variables positively or negatively influencing injury-severity categories, thus having an increasing effect on the appropriate injury-severity probability for about 50% of the relevant drivers and a decreasing effect on the other half of those drivers.

5. Assessment of driver-injury severity probabilities

For each of the 12 models, the estimated model parameters were used to compute the predicted injury-severity probabilities by enumerating through the data sample and averaging the predicted injury-severity probabilities. Table 14 provides a summary of the average predicted injury-severity probabilities for each driver group and the percent difference of the adverse weather probabilities compared to the dry-surface probabilities. Figs. 1–3 illustrate the average effect that surface conditions had on the three injury-severity probabilities for the four gender/age groups.

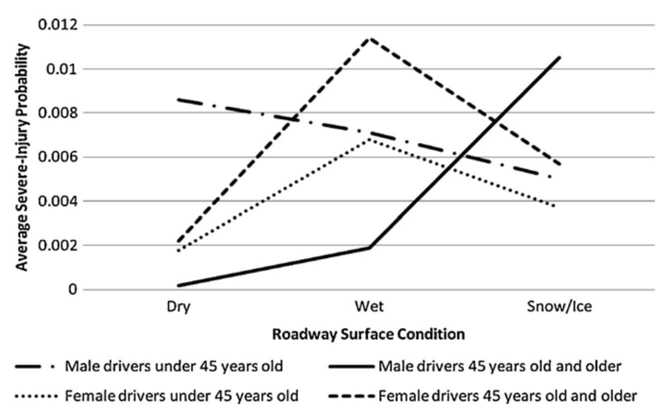

Fig. 1. Change in severe-injury probabilities by driver group and roadway surface.

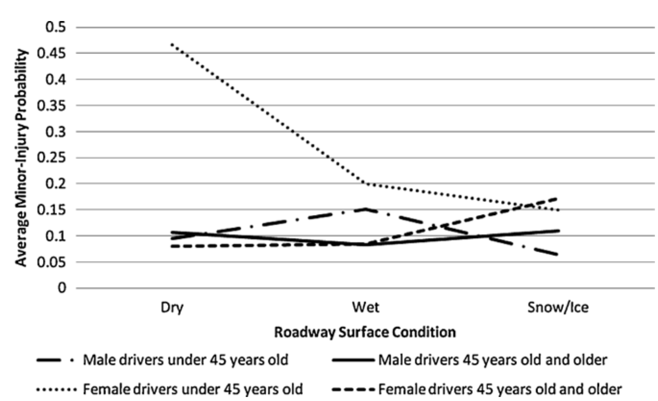

Fig. 2. Change in minor-injury probabilities by driver group and roadway surface.

Table 14
Average predicted probability summary for driver groups (calculated through sample enumeration).

Driver group	Injury	Average predicted probability			Percent difference in average predicted probability relative to dry surface crashes	
		Dry	Wet	Snow/ice	Wet	Snow/ice
Average of all four driver groups	Severe	0.0032	0.0068	0.0062	113%	94%
	Minor	0.1871	0.1295	0.1236	−31%	−34%
	No injury	0.8097	0.8638	0.8702	7%	7%
Male drivers under 45 years old	Severe	0.0086	0.0071	0.0050	−17%	−42%
	Minor	0.0955	0.1512	0.0633	58%	−34%
	No injury	0.8958	0.8417	0.9317	−6%	4%
Male drivers 45 years old and older	Severe	0.0002	0.0019	0.0105	850%	5150%
	Minor	0.1066	0.0828	0.1095	−22%	3%
	No injury	0.8932	0.9153	0.8801	2%	−1%
Female drivers under 45 years old	Severe	0.0018	0.0068	0.0037	277%	106%
	Minor	0.4658	0.1994	0.1501	−57%	−68%
	No injury	0.5323	0.7939	0.8462	49%	59%
Female drivers 45 years old and older	Severe	0.0022	0.0114	0.0057	418%	159%
	Minor	0.0803	0.0845	0.1716	5%	113%
	No injury	0.9175	0.9041	0.8227	−1%	−10%

Table 14 shows that the average severe-injury probabilities of most driver groups increased by more than 100% under adverse-surface conditions relative to dry-surface conditions. The exception is male drivers under 45 years old, which actually had their severe-injury probabilities decrease by 17% on wet surfaces and 42% on snow/ice surfaces relative to dry-surface severe-injury probabilities. The results show surprising differences across male and female driver age categories in terms of both the magnitude of movement and direction.

For minor-injury probabilities, male drivers under 45 years old had higher probabilities on wet surfaces and lower probabilities on snow/ice surfaces relative to dry surfaces. In contrast, male drivers 45 years old and older had lower minor-injury probabilities on wet surfaces and slightly higher minor-injury probabilities on snow/ice surfaces. Female drivers under 45 years old had lower minor-injury probabilities on both wet and snow/ice surfaces relative to dry surfaces. And, female drivers 45 years old and older had the opposite results with higher minor-injury probabilities on wet and snow/ice surfaces relative to dry surfaces. Again, the results show dramatic differences among the groups in terms of the direction and magnitude of the surface effects.

With regard to no-injury probabilities, male drivers under 45 years old had lower probabilities on wet surfaces and higher probabilities minor-injury on snow/ice surfaces relative to dry surfaces. In contrast, male drivers 45 years old and older were the exact opposite with higher no-injury probabilities on wet surfaces and lower probabilities on snow/ice surfaces relative to dry surfaces. However, it should be noted that the changes in no-injury probabilities were somewhat small for both male driver age groups. Female drivers under 45 years old had substantially higher no-injury probabilities on wet and snow/ice surfaces relative to dry surfaces. The shift here is coming from their substantial reduction in minor-injury probabilities on wet and snow/ice surfaces relative to dry surfaces. Finally, in contrast to their younger counterparts, female drivers 45 years old and older had slightly lower probabilities on both wet and snow/ice surfaces relative to dry surfaces.

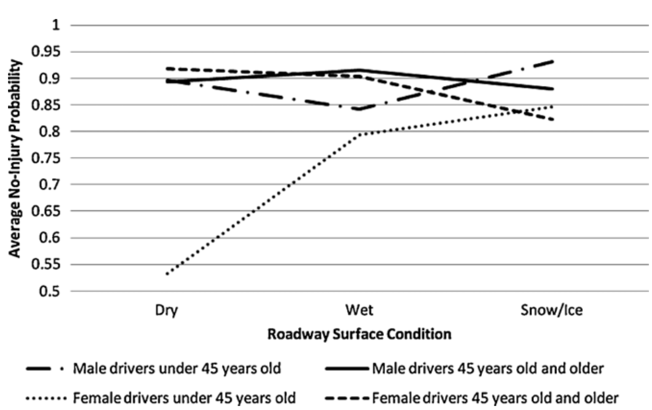

Fig. 3. Change in no-injury probabilities by driver group and roadway surface.

6. Summary and conclusions

Using 2007–2008 police-reported crash data from single-vehicle crashes in Indiana, driver-injury severities are defined as: severe injury (fatal or incapacitating); minor injury (non-incapacitating or possible injury); and no injury are considered. Separate mixed logit models are estimated for young and older, male and female drivers on three weather-related roadway surface conditions, for a total of 12 different models.

Estimations results show striking and significant differences among the 12 models. The results show differences in driver-injury severities from one roadway-surface condition to the next as expected given the physics involved. However, the significant differences among age and gender groups suggest that drivers perceive and react to different pavement-surface conditions in very different ways. Individual parameter estimates in the various models confirm this, as the magnitude and sometimes direction of the influence of crash-specific variables vary widely from one age/gender/surface-condition model to the next. In addition, there are large differences in the average driver-injury severity probabilities from one age/gender/surface-condition group to the next.

The results of this study suggest the need to look more carefully at the process by which drivers assess and react to weather-induced road-surface changes. Additional research along these lines (which would have a strong human-factors component) could result in educational/licensing efforts that are aimed at improving the safety of specific sub-groups of the driving population.

Without doubt, the police-reported crash data used in this study are limited. For example, we do not have detailed information on weather/surface conditions before (which may affect how drivers have adjusted) or at the time of the crash, nor do we have information on how drivers may have reacted before and during the crash, their reaction times, visual acuity, weather-related experience, and so on. The use of a random parameter model helps in this regard, but still, the collection and use of more detailed data could provide important additional insights and we view this avenue as the most fruitful for future research.

On a more fundamental level, this research provides some basis for more generally considering subsets of data. The traditional approach for modeling crash-injury severities has assumed that the influence of explanatory variables can be handled by carefully constructed variables. For example, in a crash-injury severity model, an indicator variable that is equal to one if the driver is male, aged 45 and above, and driving on a wet pavement and zero otherwise may be used. However, the empirical findings contained herein suggest that the relationship is indeed more complex as indicated by the findings of the likelihood ratio tests and the large differences in estimated model parameters.

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