Driver Injury Severity Resulting from Single-Vehicle Crashes Along Horizontal Curves on Rural Two-Lane Highways

William H. Schneider IV, Peter T. Savolainen, and Karl Zimmerman

Horizontal curves have been identified as a target area for improving safety on rural two-lane highways in Texas. This study involved the development of multinomial logit models to assess driver injury severity resulting from single-vehicle crashes on such roads. Likelihood ratio tests warranted the development of separate injury severity models for curves of small, medium, and large radius. Various driver, vehicle, roadway, and environmental characteristics were found to affect injury severity among the 10,029 crashes analyzed. Run-off-the-road crashes, particularly those resulting in collisions with roadside objects, were found to increase injury severity significantly. Females were more likely to sustain injury and older drivers to be critically injured, particularly on curves of smaller radius. Various driver actions and behaviors were also significant determinants of injury severity. Unbelted drivers were up to 10 times more likely to suffer fatal injuries, and drivers who were uninsured, fatigued, or under the influence of drugs or alcohol were more likely to be seriously injured. Several of these behavioral factors were more pronounced on sharper curves.

Nearly 50,000 centerline miles of paved roadways in Texas are rural two-lane roads that, on average, serve fewer than 2,000 vehicles per day (*1*). Because of the low traffic volumes and frequencies of crashes on such roads, safety improvements may not be viewed as cost-effective, although crashes may be overrepresented at these locations. To address this issue, research was previously conducted to identify causal factors and develop a series of economical countermeasures aimed at mitigating crashes on rural two-lane highways (*1–6*). Among the recommended improvements are treatments that decrease the frequency of run-off-the-road crashes on horizontal curves and improve driver awareness of the presence of such curves.

The safety of motorists traveling on two-lane highways and the influence of horizontal curvature on the frequency and severity of crashes have long been areas of concern within the transportation community. Several national initiatives, including the *AASHTO Strategic Highway Safety Plan* (*7*) and the forthcoming *Highway Safety Manual*, emphasize the influence of horizontal curves on safety. Research was conducted for FHWA in the early 1990s that focused on the safety of and potential improvements to horizontal curves on two-lane highways (*8, 9*). The findings suggest that a curve with a radius of 500 ft is twice as likely to experience a crash and that a curve with a radius of 1,000 ft is 50% more likely to experience a crash than an equivalent tangent section. Harwood et al. found that when the length and radius of the horizontal curve were both 100 ft, the crash rate was more than 28 times higher than for a similar tangent section on the same roadway (*10*). Other researchers have found similar results for crashes on horizontal curves (*11, 12*). Two possible reasons, as described by Pratt and Bonneson, for the increased number of crashes on horizontal curves include a lack of driver awareness of the curve and an underestimation of the sharpness of the curve (*13*).

Other research has focused on the relationships between horizontal curves and driver speed (*14–16*) and comfort (*17*), the development of crash modification factors (*18*), and the use of statistical techniques to improve crash prediction model estimation (*19, 20*). Additional research (*21–24*) has shown that as horizontal curves become sharper, the potential for crashes increases, while some studies have examined the general impacts of curvature on crash occurrence by using categorical curve indicator variables (*25, 26*) or classification schemes based on ranges of degree of curvature (*27*).

Another recommendation from the aforementioned Texas research was to minimize the severity of crashes occurring on horizontal curves, which often result in vehicles running off the road. In addition to roadway and environmental characteristics, numerous driver-related factors may contribute to injury severity. Previous studies have explored the relationships between driver behaviors, such as speeding (*28, 29*) and alcohol use (*30, 31*), and driver characteristics, such as age and gender (*32–35*), on injury severity. The objective of this paper is to examine the impacts of a coalescence of driver, vehicle, roadway, and environmental factors on the degree of driver injury severity sustained in crashes occurring on rural two-lane horizontal curves in the state of Texas. To achieve this objective, multinomial logit (MNL) models are developed to assess the relative impacts of factors associated with injury severity in two-lane curve-related crashes.

The roadway geometry data used in this study were developed from the Texas Geometric Roadway Inventory (RI) File, while the crash data were extracted from the Texas Roadway Inventory Accident and Driver Vehicle Files, which are based on police crash reports.

The RI file is maintained in the Texas Reference Marker System developed by the Texas Department of Transportation (TxDOT). The RI file provides information about the state-maintained highway cross section, including roadway surface widths, shoulder widths, number of lanes, average annual daily traffic, urban and rural classification, and district notation. Also provided within this data set are horizontal

W. H. Schneider IV, Department of Civil Engineering, ASEC 210, University of Akron, Akron, OH 44325-3905. P. T. Savolainen, Department of Civil and Environmental Engineering, Wayne State University, 5050 Anthony Wayne Drive, Detroit, MI 48202. K. Zimmerman, Civil Engineering Department, Valparaiso University, Gellersen Center, Room 138C, Valparaiso, IN 46383. Corresponding author: W. H. Schneider IV, whs4@uakron.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2102, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 85–92.
DOI: 10.3141/2102-11

curvature variables, including the type of curve (point, spiral, or normal), degree of curvature, and length of curve. The final roadway criteria for this study were rural two-lane highways with normal curves, which resulted in a data set with approximately 18,000 horizontal curves located throughout the state.

The curve data were then divided on the basis of curve radius into three categories: small, medium, and large. The classification criteria for the small, medium, and large horizontal curve radii are developed through guidance from the AASHTO Green Book (*36*) and the Texas *Roadway Design Manual* (*37*). TxDOT has two "minimum" radii for curves: an "absolute minimum radius," corresponding to the Green Book's minimum radius, and a "usual minimum radius," which is larger and is generally preferred over the absolute minimum radius (*37*). Additional preferences include use of a 6% maximum superelevation. This preference tends to create a larger proportion of horizontal curves with radii greater than the minimums shown in the Green Book, and these values are larger than curve radii used in other states (*38–40*).

The "small" radius curves, with a radius of less than 500 ft, are typical of roadways with low design speeds, generally under 45 mph (*36*). On higher-speed rural highways, such tight curves would be unusual and would require warning signs, advisory speed limits, or other warnings to drivers. The "medium" radius curves correspond to typical curve radii that are present on rural two-lane highways. The minimum radius curves for all design speeds between 45 and 75 mph are included in this range, which is the typical range of design speeds for high-speed two-lane highways and for superelevation rates of 6% and 8%. Since design speed is absent from the RI database for each roadway section, the range of medium radii is large to accommodate the appropriate range of typical curve radii. The large radius curves, with radii greater than 2,800 ft, correspond to curve radii that are substantially larger than the minimum for each design speed. At 80 mph, the choice of maximum superelevation rate determines whether 2,800 ft is greater than or less than the minimum curve radius—at 6% superelevation, 2,800 ft is less than the minimum curve radius, but at 8% superelevation, 2,800 ft is slightly more than the minimum curve radius.

The crash records are made up of the Texas Roadway Inventory Accident and Driver Vehicle Files for 1997 through 2001, which are maintained and provided by the Texas Department of Public Safety. The accident file includes the accident number, location of the crash, the most severe injury, and the description of the intersection- and nonintersection-related crashes. Other variables provided in the accident file include the date, the time of day, weather, lighting, and surface condition. The driver vehicle file provides more detailed information about the drivers and the vehicles involved in the crash. The driver vehicle file includes the age and sex of the driver, driver fatigue, procurement of a valid driver's license, safety equipment including seat belt use, air bag deployment and helmet use, presence of drugs or alcohol, number of passengers in the vehicle, and driver injury severity.

The crash data used in association with the roadside geometry include all single-vehicle, non-intersection-related crashes on rural two-lane highways. Crashes with missing information with regard to the accident and driver vehicle files were removed before the statistical analysis, which resulted in a final data set of 10,029 crashes. Among the crashes, 5.6% occurred on curves of small radius, 52.1% on curves of medium radius, and 42.3% on curves of large radius. The crash data for all 5 years were subsequently merged with the horizontal curve data from the RI geometry files. Over the 5-year study period, the crashes increased each year, from 1,811 in 1997 to 2,200 in 2001. Table 1 presents summary statistics for the variables included in the final analysis data set.

STATISTICAL METHODOLOGY

The analysis of crash injury severity data is well suited for discrete outcome models, since the injury level sustained is classified as one of five distinct injury severity categories: property damage only, possible injury, nonincapacitating injury, incapacitating injury, and fatal injury. This research utilizes the MNL model to examine driver injury severity conditioned on the fact that a crash has occurred. One common problem associated with crash data is the underreporting of crashes, particularly rural, single-vehicle crashes with minor or no injuries (*41*). Such underreporting may lead to biased or inconsistent model coefficient estimates, though in the context of the MNL modeling framework, this problem is limited to the category-specific constant terms as shown by McFadden (*42*). Consequently, this research utilizes an MNL model to assess driver injury severity, as has been done in the past by various researchers (*43–48*).

To assess driver injury severity, a linear function is first defined that determines driver n's injury severity outcome i as

$$S_{in} = \beta_I X_n + \epsilon_{in} \qquad (1)$$

where

X_n = vector of measurable characteristics (driver, vehicle, and roadway characteristics) that determine the injury severity for driver n,
β_I = vector of estimable coefficients, and
ϵ_{in} = error term accounting for unobserved effects influencing the injury severity of crash n.

McFadden (*42*) has shown that if the ϵ_{in} are assumed to be generalized extreme value distributed, the standard MNL model is estimable by standard maximum likelihood techniques, resulting in Equation 2:

$$P_n(i) = \frac{\exp[\beta_I X_{in}]}{\sum_{\forall I} \exp(\beta_I X_{In})} \qquad (2)$$

where $P_n(i)$ is the probability that crash n will result in driver injury severity outcome i. Such models quantify the association between various factors and the probability of a particular injury-severity category resulting given that a crash has occurred, and therefore there is no interpretation of crash risk in terms of exposure.

It is anticipated that the radius of horizontal curvature may influence the impact of factors contributing to driver injury severity. For example, factors contributing to injuries and fatalities on sharper curves of small radius may be substantially different from those contributing to various injury levels on broader curves of large radius. Furthermore, even if these factors are the same, their impacts may be substantially different, depending on the degree of curvature. If this is true, biased parameter estimates could result through the estimation of a single model that constrains each variable to have an equal impact on each of the three classes of curves. For example, Islam and Mannering developed separate injury models for three age groups of crash-involved drivers, based on the hypothesis that different injury causation mechanisms may be at work for crashes involving each particular group (*33*). In such instances, a likelihood ratio (LR) test is conducted to determine whether a single joint model is appropriate

TABLE 1 Summary Statistics: Number of Crashes by Radius Category and Other Variables

Variable Name	Description	Small	Medium	Large
Radius Category				
Small radius	Radius less than 500 feet	632	0	0
Medium radius	Radius between 500 and 2,800 feet	0	6,010	0
Large radius	Radius greater than 2,800 feet	0	0	3,387
Roadway Geometry and Environmental Factors				
Vertical curvature	Crash occurred on a vertical curve	4	36	25
Ditch	Vehicle struck a ditch	38	230	120
Embankment	Vehicle struck an embankment	26	193	111
Run off the road	Vehicle ran off the road	592	5,308	2,674
Tree	Vehicle struck a tree	95	932	471
Light	Crash occurred during daylight	328	3,050	1,635
Clear	Crash occurred during clear weather	521	5,019	2,786
Driver Factors				
Female	Driver was female	157	2,035	1,128
Passenger	Passengers present within the vehicle	115	941	583
Younger driver	Driver age is under 25 years	267	2,365	1,318
Intermediate driver	Driver age is between 25 years and 50 years	290	2,899	1,573
Older driver	Driver age is over 50 years	75	746	496
Driver fatigue	Driver was fatigued	22	464	418
Alcohol	Alcohol use suspected by investigating officer	111	1,182	517
Drugs	Drug use suspected by investigating officer	2	51	27
Speeding	Suspicion of driver speeding	452	3,506	1,384
Uninsured	Driver was uninsured	84	907	420
Vehicle Type				
Motorcycle	Crash-involved vehicle was a motorcycle	62	241	51
Car	Crash-involved vehicle was a passenger car	253	2,681	1,511
Pickup truck	Crash-involved vehicle was a pickup truck	282	2,804	1,611
Semi-truck	Crash-involved vehicle was a semi-truck	26	186	110
Safety Device Use				
Not wearing seat belt	Driver was not wearing a seat belt	91	870	419
Air bag deployed	Air bag was deployed	78	768	487

for modeling driver injury severity or separate submodels should be developed.

On the basis of the curve classification scheme (i.e., small, medium, and large radius) discussed previously, LR tests are conducted to determine whether it is appropriate to split the data set into three groups or combine the crash data into a single sample. To test whether the three separate radius-specific models are appropriate in comparison with a single model that includes all locations, an LR test is conducted. The LR test statistic is

$$\mathrm{LR} = -2\left(L_R - \sum_{\forall U} L_U\right) \tag{3}$$

where L_R is the log likelihood at convergence for the joint "restricted" model and L_U is the log likelihood at convergence for each of the separate "unrestricted" models. "Restricted" refers to the fact that in the single model, each parameter coefficient is constrained to have the same effect regardless of curve radius. In the unrestricted models, these coefficients are free to vary among the three groups. The LR statistic is χ^2-distributed with J degrees of freedom, where J is equal to the difference in the total number of parameters estimated for the unrestricted models and the number of parameters estimated for the restricted model. The null hypothesis for the likelihood ratio test is that the restricted model does not have a significantly lower log likelihood than the unrestricted models, which indicates a significant difference between the classification-specific models and the joint model. An LR test statistic larger than the χ^2-value with J degrees of freedom at a 95% confidence level will allow rejection of the null hypothesis. Further information on the LR test is given by Washington et al. (*49*).

MODELING RESULTS

The analysis data set contains 5 years of crash data, 1997 through 2001, for rural two-lane normal curves in the state of Texas. Of the 10,029 crashes within this data set, 44.8% resulted in property damage only, 18.9% in possible injuries to the driver, 23.0% in nonincapacitating injuries, 10.6% in incapacitating injuries, and 2.6% in fatalities. On the basis of these five discrete driver injury severity outcomes, MNL models were developed to identify factors affecting the propensity of a crash to result in each severity level for a particular crash-involved driver.

An initial MNL model that included all crashes within the data set was developed. For this restricted model, the log likelihood at convergence was equal to −12,048.8. Then three separate MNL models were developed on the basis of the range of horizontal curvature present among rural two-lane highways in Texas as explained previously: small (radius less than 500 ft), medium (radius from 500 to 2,800 ft), and large (radius greater than 2,800 ft). The sum of the log likelihood values for the three submodels is equal to −11,994.5. The LR statistic comparing these three submodels to the joint model is equal to 108.6 with 74 degrees of freedom, which is statistically significant at a 99 percent level of confidence and warrants the development of three separate models. Tables 2 through 4 present the results of the MNL models for the small, medium, and large radius data sets, respectively.

IMPACT OF MODEL PARAMETERS

As discussed by Washington et al. (*49*), the parameter coefficient estimates for MNL models may be misinterpreted, since a positive coefficient does not necessarily indicate an increase in the likelihood of that particular injury severity level. To assess the vector of the estimated parameter coefficients (β_i) properly, parameter-specific elas-

TABLE 2 Small Radius Model Estimation Results

Variable Name	Coeff.	Standard Error	*t*-Ratio	*P*-Value
Alternative Specific Constant				
Property damage only	6.016	0.597	10.074	<0.001
Possible injury	4.832	0.599	8.061	<0.001
Nonincapacitating injury	4.838	0.600	8.063	<0.001
Incapacitating injury	1.748	0.458	3.819	<0.001
Roadway Geometry and Environmental Characteristics				
Ditch (PDO)	1.170	0.403	2.901	0.004
Embankment (I)	1.377	0.536	2.570	0.010
Driver Factors				
Female (P, N, I, F)	0.496	0.200	2.481	0.013
Passenger (P, N)	0.953	0.245	3.882	<0.001
Passenger (I, F)	1.245	0.350	3.552	<0.001
Alcohol (F)	1.680	0.667	2.519	0.012
Uninsured (I)	1.032	0.342	3.016	0.003
Driver age (I, F)	0.034	0.009	3.651	<0.001
Vehicle Type				
Motorcycle (P)	1.079	0.551	1.96	0.050
Motorcycle (N)	2.263	0.453	4.994	<0.001
Motorcycle (I, F)	3.664	0.503	7.283	<0.001
Safety Device Use				
Not wearing a seatbelt (N)	0.807	0.279	2.892	0.004
Not wearing a seatbelt (I)	2.227	0.390	5.716	<0.001
Not wearing a seatbelt (F)	1.566	0.764	2.050	0.040
Airbag deployed (I)	1.639	0.397	4.132	<0.001

NOTE: PDO = property damage only; P = possible injury; N = nonincapacitating injury; I = incapacitating injury; F = fatal. Number of observations = 632; log likelihood at zero = −983.4; log likelihood at convergence = −730.1; ρ^2 = 0.258.

TABLE 3 Medium Radius Model Estimation Results

Variable Name	Coeff.	Standard Error	*t*-Ratio	*P*-Value
Alternative Specific Constant				
Property damage only	7.744	0.355	21.813	<0.001
Possible injury	4.876	0.285	17.079	<0.001
Nonincapacitating injury	4.261	0.265	16.094	<0.001
Incapacitating injury	2.383	0.243	9.823	<0.001
Roadway Geometry and Environmental Characteristics				
Run off the road (P)	0.451	0.115	3.907	<0.001
Run off the road (N, I, F)	0.546	0.105	5.223	<0.001
Tree (N, I)	0.216	0.082	2.625	0.009
Tree (F)	0.669	0.200	3.353	0.001
Light (N)	0.167	0.064	2.588	0.010
Clear (P)	0.211	0.094	2.235	0.025
Clear (N, I, F)	0.645	0.090	7.133	<0.001
Vertical curvature (F)	2.067	0.562	3.677	<0.001
Embankment (I)	0.590	0.215	2.745	0.006
Driver Factors				
Female (P, N, I, F)	0.611	0.064	9.517	<0.001
Passenger (P, N)	1.005	0.091	10.991	<0.001
Passenger (I, F)	1.228	0.122	10.095	<0.001
Driver age (I, F)	0.014	0.003	4.913	<0.001
Driver fatigue (P, N)	0.280	0.113	2.481	0.013
Driver fatigue (I)	0.693	0.166	4.177	<0.001
Driver fatigue (F)	1.235	0.280	4.417	<0.001
Alcohol (N, I)	0.660	0.078	8.487	<0.001
Alcohol (F)	1.558	0.180	8.661	<0.001
Drugs (F)	2.049	0.439	4.670	<0.001
Uninsured (N)	0.191	0.090	2.115	0.034
Uninsured (I)	0.358	0.119	3.016	0.003
Speeding (F)	0.567	0.183	3.108	0.002
Vehicle Type				
Motorcycle (P)	3.782	0.547	6.919	<0.001
Motorcycle (N)	5.034	0.519	9.700	<0.001
Motorcycle (I, F)	6.472	0.521	12.426	<0.001
Passenger car (P, N, I, F)	0.836	0.244	3.432	0.001
Pickup truck (P, N, I, F)	1.187	0.242	4.895	<0.001
Semi-truck (P, N, I, F)	1.496	0.286	5.231	<0.001
Safety Device Use				
Not wearing a seat belt (P)	0.578	0.123	4.679	<0.001
Not wearing a seat belt (N)	0.948	0.110	8.626	<0.001
Not wearing a seat belt (I)	2.130	0.127	16.766	<0.001
Not wearing a seat belt (F)	3.266	0.217	15.051	<0.001
Air bag deployed (P)	0.704	0.113	6.229	<0.001
Air bag deployed (N)	0.886	0.107	8.277	<0.001
Air bag deployed (I)	1.486	0.140	10.591	<0.001
Air bag deployed (F)	2.319	0.258	8.993	<0.001

NOTE: Number of observations = 6,010; log likelihood at zero = −9,416.8; log likelihood at convergence = −7,254.9; ρ^2 = 0.230.

TABLE 4 Large Radius Model Estimation Results

Variable Name	Coeff.	Standard Error	*t*-Ratio	*P*-Value
Alternative Specific Constant				
Property damage only	6.504	0.382	17.04	<0.001
Possible injury	4.137	0.319	12.982	<0.001
Nonincapacitating injury	3.143	0.305	10.298	<0.001
Incapacitating injury	1.697	0.285	5.951	<0.001
Roadway Geometry and Environmental Characteristics				
Run off the road (P)	0.388	0.117	3.308	0.001
Run off the road (N, I, F)	0.833	0.122	6.822	<0.001
Tree (N, I)	0.305	0.114	2.681	0.007
Tree (F)	0.730	0.301	2.422	0.016
Light (N)	0.274	0.095	2.889	0.004
Light (I)	0.412	0.129	3.200	0.001
Clear (N, I, F)	0.356	0.110	3.236	0.001
Driver Factors				
Female (P, N, I, F)	0.582	0.083	6.994	<0.001
Passenger (P, N)	0.871	0.108	8.042	<0.001
Passenger (I, F)	0.919	0.153	6.002	<0.001
Driver age (I, F)	0.01	0.004	2.686	0.007
Driver fatigue (P, N)	0.243	0.112	2.168	0.030
Driver fatigue (F)	1.105	0.286	3.861	<0.001
Alcohol (N, I)	0.354	0.118	2.994	0.003
Alcohol (F)	1.448	0.260	5.576	<0.001
Drugs (F)	1.940	0.612	3.169	0.002
Uninsured (I)	0.335	0.164	2.042	0.041
Vehicle Type				
Motorcycle (P)	3.197	0.852	3.754	<0.001
Motorcycle (N)	4.447	0.789	5.633	<0.001
Motorcycle (I, F)	5.664	0.779	7.271	<0.001
Passenger car (P, N, I, F)	0.636	0.241	2.64	0.008
Pickup truck (P, N, I, F)	0.675	0.238	2.834	0.005
Semi-truck (P, N, I, F)	0.608	0.310	1.958	0.050
Safety Device Use				
Not wearing a seat belt (P)	0.822	0.177	4.652	<0.001
Not wearing a seat belt (N)	1.498	0.158	9.488	<0.001
Not wearing a seat belt (I)	2.149	0.181	11.846	<0.001
Not wearing a seat belt (F)	3.448	0.296	11.628	<0.001
Air bag deployed (P)	0.609	0.138	4.413	<0.001
Air bag deployed (N)	0.924	0.135	6.854	<0.001
Air bag deployed (I)	1.246	0.174	7.168	<0.001
Air bag deployed (F)	1.094	0.429	2.551	0.011

NOTE: Number of observations = 3,387; log likelihood at zero = –5,369.1; log likelihood at convergence = 4,008.5; $\rho^2 = 0.253$.

ticities are used to measure the magnitude of the impact of individual parameters on the likelihood of the five injury severity outcomes. For continuous variables, such as driver age, the elasticity corresponding to each variable is computed by using the following formula:

$$E_{x_n}^{P_n(i)} = \left[1 - \sum_{I=I_n} P(i)\right]\beta_i x_n \tag{4}$$

where I_n is the subset of injury severity levels that include variable x_n in the severity function and β_i is the estimated coefficient that is associated with x_n. As described by Equation 4, an elastic change of 1% will correspond to an approximate 1% change in the injury severity outcome probability.

The calculation of elasticities for indicator variables using Equation 4 is inappropriate, since such variables take values of only 0 or 1, rendering a 1% change in a particular variable meaningless. To quantify the effects of such binary indicator variables appropriately, pseudoelasticities are calculated as shown in Equation 5, where all variables are as previously defined (*43*).

$$E_{x_n}^{P_n(i)} = \frac{\exp\left[\Delta\left(\beta_i X_n\right)\right]\sum_{\forall I}\exp\left(\beta_i x_n\right)}{\exp\left[\Delta\left(\beta_i X_n\right)\right]\sum_{I=I_n}\exp\left(\beta_i X_n\right)+\sum_{I\neq I_n}\exp\left(\beta_i X_n\right)} - 1 \tag{5}$$

These pseudoelasticity values are effectively equal to the average change in the likelihood of a particular severity level if the conditions corresponding to the variable of interest are met. For example, the results from this study show that when the driver of the crash-involved vehicle is female (i.e., the female variable is changed from 0 to 1), the likelihood of injury increases by 23.9%, 27.9%, and 30.7% on curves of small, medium, and large radius, respectively.

The calculated elasticity and pseudoelasticity values for all parameters from the three radius-specific submodels are shown in Table 5. The following section discusses the effects of these parameters in detail.

Roadway Geometry and Environmental Characteristics

Among the three curve radius groups, driver injury is more likely among the medium radius group (57.3%) than either the small (53.3%) or large (51.9%) radius groups. The degree of injury sustained is not significantly different among the three groups, although the percentage of crashes resulting in fatalities is slightly less among the small radius group (1.7%) than in the large (2.5%) and medium (2.8%) radius groups. The remaining discussion focuses on the factors affecting crash severity and highlights the differential impacts of these factors as they relate to horizontal curvature.

Driver injuries tend to be the most severe in crashes where the crash-involved vehicles run off the road, which occurred in approximately 85% of all crashes in the data set. Running off the road is found to increase possible injuries by 7.7% on curves of large radius and 18.9% on curves of medium radius. Evident injuries are 68.0% and 30.8% more likely under the same conditions. By running off the road, drivers are more likely to strike roadside objects and to lose control of their vehicles. In addition, run-off-the-road crashes may be a proxy for poor driving behaviors, since these types of crashes have been shown to be highly correlated with various high-risk driver groups (*46*). Running off the road presents drivers with the greatest risk for serious or fatal injury when they strike a tree. When crash-involved vehicles struck a tree, the probability of fatality increased by 74.9% to 82.2% for medium and large radii. Conversely, when drivers strike a ditch or embankment, injuries generally tend to be less severe.

The combination of horizontal and vertical curvature increased the likelihood of fatal crashes by 560% on curves of medium radius. Reduced sight distances and loss of control are likely to contribute to this finding.

TABLE 5 Model Elasticities

Variable (Severity Levels Affected)	Model Elasticities (%) Small Radii	Medium Radii	Large Radii
Roadway Geometry and Environmental Characteristics			
Run off the road (P)		18.9	7.7
Run off the road (N, I, F)		30.8	68.0
Vertical curvature (F)		560.2	
Ditch (PDO)	71.2		
Embankment (P)	214.9		
Embankment (I)		67.0	
Daylight (N)		13.4	19.8
Daylight (I)			37.5
Clear (N, I, F)		46.0	27.6
Tree (N, I)		11.2	19.1
Tree (F)		74.9	82.2
Driver Factors			
Female (P, N, I, F)	23.9	27.9	30.7
Passenger (P, N)	39.5	36.9	42.9
Passenger (I, F)	86.8	71.1	50.0
Alcohol (N, I)		39.8	18.7
Alcohol (F)	412.5	243.3	254.4
Drugs (F)		549.1	494.7
Uninsured (N)		10.7	
Uninsured (I)	142.3	30.8	35
Driver age (I, F)[a]	0.9	0.4	0.3
Driver fatigue (P, N)		0.8	8.9
Driver fatigue (I)		52.4	
Driver fatigue (F)		162.0	158.2
Driver speeding (F)		72.3	
Vehicle Type			
Pickup truck (P, N, I, F)		67.5	38.3
Passenger car (P, N, I, F)		42.6	35.3
Semi-truck (P, N, I, F)		56.7	29.1
Motorcycle (P)	–46.9	–50.6	–43.4
Motorcycle (N)	73.5	72.8	97.7
Motorcycle (I, F)	604.1	628	567.6
Safety Device Use			
No seat belt (P)		–24.6	–19.5
No seat belt (N)	24.5	9.1	58.2
No seat belt (I)	415	255.8	203.3
No seat belt (F)	165.9	1,008	1,012
Air bag deployed (P)		2.0	9.7
Air bag deployed (N)		22.4	50.3
Air bag deployed (I)	295.9	122.9	107.3
Air bag deployed (F)		412.8	78.1

[a]Age is a continuous variable, and its elasticity is computed per Equation 4. All other variables are binary indicators, and their pseudoelasticities are computed per Equation 5. Empty fields indicate that variable effects were not statistically significant for those severity categories.

Somewhat surprisingly, crashes tend to be more severe under daylight conditions and clear weather conditions. Sight distance is limited and reaction times are reduced during nighttime conditions and under adverse weather, the latter of which may also make it more difficult to maintain control of the vehicle. However, this finding is consistent with past research, which may be indicative of drivers reducing their speeds and driving with greater caution under such situations (*12*).

Driver Factors

Driver injuries are significantly affected by physiological factors, as well as risk-related factors. The probability of incapacitating or fatal injury is found to increase with driver age, and this effect becomes more pronounced as curve radius decreases. The elasticities for curves of large, medium, and small radius are 0.3%, 0.4%, and 0.9%, respectively. This finding may be an indication of decreased reaction times or driving abilities associated with older drivers navigating such curves.

Female drivers were 23% to 31% more likely to be injured than male drivers. This result is consistent with previous findings (*32–35*) and may be related to physiological or behavioral differences between males and females. The differences may include the relationship between driver body type and vehicle characteristics, such as differences in how air bags and seat belts affect drivers, and driving characteristics, such as aggression and risk perception.

Drivers who engaged in high-risk driving were found to be at a substantially higher risk for injury, as well. In crashes where speeding was cited as a contributory factor, the likelihood of fatal injuries increased by 72% on curves of medium radius. Speeding creates several problems by reducing the available reaction time and increasing the forces of impact with roadside objects.

The use of drugs or alcohol led to increases of 18% to 40% in the likelihood of evident injuries and increases of 243% to 549% in the likelihood of fatalities. These increases may be a result of aggressive driving, impaired judgment by the driver, or the negative impact of added stress on the body from processing the drugs or alcohol.

Driver fatigue affects hazard perception abilities and decreases reaction time, similar to the effects of alcohol and drug use. For the crash-involved driver who was under fatigue, the likelihood of minor injuries increased marginally, while substantial increases occurred in the probability of incapacitating and fatal injuries.

Uninsured drivers were more likely to be seriously injured in a crash, which may reflect poor driving abilities or increased risk-taking on the part of such motorists. These effects were particularly pronounced on curves of small radius, where the likelihood of incapacitating injuries increased by 142.3%.

When passengers were present in the vehicle, the probability of minor injuries increased by 36% to 43%. Passengers had a more pronounced effect on serious injuries, increasing the likelihood of incapacitating or fatal injuries by 50% on curves of large radius and 87% on sharp curves. The movement of the passenger within the vehicle may produce injury contact with the driver of the vehicle, and this contact suggests an increase in injuries. In addition, distraction may play a role on tighter curves, which require greater focus.

Increases in driver age are associated with an increase in the likelihood of incapacitating and fatal injuries. The results suggest that for a 1% increase in driver age, the probability of incapacitating and fatal injuries increases by 0.3% on curves of large radius and 0.9% on curves of small radius. One explanation for this finding may be that as age increases the reaction time decreases, which may result in a higher probability for under- or overcorrection of the vehicle and in more run-off-the-road crashes (*50*).

Vehicle Type

Motorcyclists are the group of drivers most likely to be seriously injured or killed in a crash because of their increased vulnerability compared with drivers of other vehicle types. Past research has shown motorcycles to be particularly prone to crash involvement and severe injury on horizontal curves (*48*). In the analysis data set, nonincapacitating injuries were 73% to 98% more likely than for other vehicle types, while the probability of fatal injuries increased by more than 560% regardless of curve radius.

Pickup truck drivers are also more likely to be injured, followed by drivers of passenger cars and semitrailer trucks, while sport utility vehicle and van drivers are the least likely to suffer injuries. The relationship between vehicle type and severity was not substantially affected by curve radius.

Safety Device Use

Seat belt use increased the likelihood that no evident driver injury would occur as a result of a crash, which confirmed the results of numerous past traffic safety studies (*51*). Nonuse was associated with up to a 58% increase in nonincapacitating injuries, a 415% increase in incapacitating injuries, and a 1,012% increase in fatalities. For the small radius group, the greatest impact was on incapacitating injuries, while fatalities were most affected for the medium and large radius groups. This may be an effect of the higher speeds associated with the curves of larger radius or an indication of increased driver caution on sharper curves.

Crashes that cause air bag deployment increased the likelihood of injury for each range of curve radii. For the medium radius group, air bags increased the likelihood of fatality by more than 400%. The effect on fatalities for the small and large radii groups was not as pronounced, possibly due to lower travel speeds associated with the small radius group and higher design standards associated with the large radius group, which generally have a higher design speed. However, in all cases, severe injuries were more likely when air bags were deployed because of the forces exerted by the crash. In addition, past research has shown drivers to be more aggressive when their vehicles are equipped with air bags, which may lead to more severe injuries (*51*).

CONCLUSION

Horizontal curvature was found to affect driver injury severity sustained in crashes on rural two-lane roads in Texas. Injuries were more likely on curves with a moderate radius of between 500 and 2,800 ft than on sharp, lower-speed curves and on more gradual, higher-speed curves. Run-off-the-road crashes were particularly hazardous for the driver, most notably on high-speed roads. Because of the high frequency of such crashes, collisions with roadside objects were common, and trees were found to create the greatest increase in incapacitating and fatal injuries.

Female drivers were more likely to be injured as a result of a crash, a finding that is consistent across the three curve radius groups. Older drivers were more likely to be seriously or fatally injured in a crash, and this trend was more pronounced on curves of smaller radius, a possible indication of degradation in driving abilities or reaction time.

Driver actions and behavior were significant determinants of injury severity. Seat belt usage is the most critical component in minimizing the likelihood of injuries and fatalities; unbelted drivers are up to 10 times more likely to suffer fatal injuries. Other high-risk behaviors also contributed to more severe injuries. Uninsured and fatigued drivers were more likely to be seriously injured, as were those who were under the influence of drugs or alcohol at the time of the crash. The presence of passengers in the vehicle also contributed to more severe driver injuries. Several of the driver-related factors were compounded on sharper curves, which generally require greater concentration and handling on the part of drivers.

The combination of geometric and behavioral factors that affect driver injury severity may be best addressed through a two-part approach. First, introducing geometric design improvements on curves along rural two-lane highways can help to mitigate the effects of curvature and collisions with roadside objects. Some of these improvements are being instituted in Texas (*6*). Second, in conjunction with geometric improvements, targeted enforcement activities may be used to address problematic driver behaviors, such as drug and alcohol use, driver fatigue, and driving without insurance.

ACKNOWLEDGMENT

The authors thank the Texas Department of Transportation for the research data provided for this study.

REFERENCES

1. Fitzpatrick, K., and M. A. Brewer. *Summary of Treatments for Crashes on Rural Two-Lane Highways in Texas.* Report FHWA/TX-05/4048-S. Texas Transportation Institute, Texas A&M University System, College Station, 2004.
2. Fitzpatrick, K., A. H. Parham, M. A. Brewer, and S. P. Miaou. *Characteristics of and Potential Treatments for Crashes on Low-Volume, Rural Two-Lane Highways in Texas.* Report FHWA/TX-02/4048-1. Texas Transportation Institute, Texas A&M University System, College Station, 2001.
3. Fitzpatrick, K., A. H. Parham, and M. A. Brewer. *Treatments for Crashes on Rural Two-Lane Highways in Texas.* Report FHWA/TX-02/4048-2. Texas Transportation Institute, Texas A&M University System, College Station, 2002.
4. Fitzpatrick, K., and M. A. Brewer. *Additional Characteristics of Crashes on Rural Two-Lane Highways.* Report FHWA/TX-03/4048-3. Texas Transportation Institute, Texas A&M University System, College Station, 2002.
5. Fitzpatrick, K., A. H. Parham, and M. A. Brewer. *Handbook Details Crash Treatments for Rural Highways.* Draft Report FHWA/TX-03/4048-4. Texas Transportation Institute, Texas A&M University System, College Station, 2004.
6. Brewer, M. A., and K. Fitzpatrick. *Preliminary Evaluation of Safety Treatments on Rural Highways in Texas.* Report FHWA/TX-05/4048-5. Texas Transportation Institute, Texas A&M University System, College Station, 2004.
7. *AASHTO Strategic Highway Safety Plan: A Comprehensive Plan to Substantially Reduce Vehicle-Related Fatalities and Injuries on the Nation's Highways.* AASHTO, Washington, D.C., 2005.
8. Zegeer, C. V., R. J. Stewart, F. M. Council, and D. W. Reinfurt. *Cost Effective Geometric Improvements for Safety Upgrading of Horizontal Curves.* Report FHWA-RD-90-021. FHWA, U.S. Department of Transportation, 1991.
9. Zegeer, C. V., D. W. Reinfurt, T. Neuman, J. R. Stewart, and F. M. Council. *Safety Improvements on Horizontal Curves for Two-Lane*

Rural Roads. Report FHWA-RD-90-074. FHWA, U.S. Department of Transportation, 1990.
10. Harwood, D. W., F. M. Council, E. Hauer, W. E. Hughes, and A. Vogt. *Prediction of the Expected Safety Performance of Rural Two-Lane Highways.* Report FHWA-RD-99-207. FHWA, U.S. Department of Transportation, 2000.
11. Farmer, C. M., and A. K. Lund. Rollover Risk of Cars and Light Trucks After Accounting for Driver and Environmental Factors. *Accident Analysis and Prevention,* Vol. 34, 2002, pp. 163–173.
12. Savolainen, P. T., and A. P. Tarko. Safety Impacts at Intersections on Curved Segments. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1908,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 130–140.
13. Pratt, M. P., and J. A. Bonneson. Assessing Curve Severity and Design Consistency Using Energy- and Friction-Based Measures. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2075,* Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 8–15.
14. Medina, A., and A. P. Tarko. Speed Changes in the Vicinity of Horizontal Curves on Two-Lane Rural Roads. *Journal of Transportation Engineering,* Vol. 133, No. 4, 2007, pp. 215–222.
15. Pratt, M. P., J. A. Bonneson, J. D. Miles, and P. J. Carlson. Curve Speeds and Advisory Speed-Setting Criteria. Presented at 86th Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.
16. Fitzpatrick, K., L. Elefteriadou, D. W. Harwood, J. M. Collins, J. McFadden, I. B. Anderson, R. A. Krammes, N. Rizzary, K. D. Parma, K. M. Bauer, and K. Passetti. *Speed Prediction for Two-Lane Rural Highways.* Report FHWA-RD-99-171. FHWA, U.S. Department of Transportation, 2000.
17. Koorey, G. Driver Comfort on Horizontal Curves. Presented at 86th Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.
18. Lord, D. Methodology for Estimating the Variance and Confidence Intervals for the Estimate of the Product of Baseline Models and AMFs. *Accident Analysis and Prevention,* Vol. 40, 2007, pp. 1013–1017.
19. Lord, D. Modeling Motor Vehicle Crashes Using Poisson-Gamma Models: Examining the Effects of Low Sample Mean Values and Small Sample Size on the Estimation of the Fixed Dispersion Parameter. *Accident Analysis and Prevention,* Vol. 38, 2006, pp. 751–766.
20. Mitra, S., and S. Washington. On the Nature of Over-Dispersion in Motor Vehicle Crash Prediction. *Accident Analysis and Prevention,* Vol. 39, 2007, pp. 459–468.
21. Caliendo, C., G. Maurizio, and A. Parisi. A Crash-Prediction Model for Multi Roads. *Accident Analysis and Prevention,* Vol. 39, 2007, pp. 657–670.
22. Hauer, E. Safety of Horizontal Curves. www.roadsafetyresearch.com. Accessed June 2008.
23. Kweon, Y.-J., and K. Kockelman. Spatially Disaggregate Panel Models of Crash and Injury Counts: Effect of Speed Limits and Design. Presented at 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2004.
24. Washington, S., K. Dixon, D. White, and C. Wu. *Investigation of Fatal Motor Vehicle Crashes on Two-Lane Rural Highways in Georgia.* Georgia Institute of Technology and Georgia Department of Transportation, Atlanta, 2002.
25. Dissanayake, S., and J. J. Lu. Factors Influential in Making an Injury Severity Difference to Older Drivers Involved in Fixed Object–Passenger Car Crashes. *Accident Analysis and Prevention,* Vol. 34, 2002, pp. 609–618.
26. Shankar, V., F. Mannering, and W. Barfield. Statistical Analysis of Accident Severity on Rural Freeways. *Accident Analysis and Prevention,* Vol. 28, 1996, pp. 391–401.
27. Garber, N. J., and R. E. Abel. Evaluation of Crash Rates and Causal Factors for High-Risk Locations on Rural and Urban Two-Lane Highways in Virginia. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.
28. Aarts, L., and I. van Schagen. Driving Speed and the Risk of Road Crashes: A Review. *Accident Analysis and Prevention,* Vol. 38, 2006, pp. 215–224.
29. Lam, L. Factors Associated with Young Drivers' Car Crash Injury: Comparisons Among Learner, Provisional, and Full Licensees. *Accident Analysis and Prevention,* Vol. 35, 2003, pp. 913–920.
30. Lenguerrand, E., J. Martin, A. Moskal, B. Gadegbeku, and B. Laumon. Limits of the Quasi-Induced Exposure Method When Compared with the Standard Case-Control Design Application to the Estimation of Risks Associated with Driving Under the Influence of Cannabis or Alcohol. *Accident Analysis and Prevention,* Vol. 40, 2008, pp. 861–868.
31. McMillan, G., T. Hanson, and S. Lapham. Geographic Variability in Alcohol-Related Crashes in Response to Legalized Sunday Packaged Alcohol Sales in New Mexico. *Accident Analysis and Prevention,* Vol. 39, 2007, pp. 252–257.
32. Kockelman, K., and Y. Kweon. Driver Injury Severity: An Application of Ordered Probit Models. *Accident Analysis and Prevention,* Vol. 35, 2002, pp. 313–321.
33. Islam, S., and F. Mannering. Driver Aging and Its Effect on Male and Female Single-Vehicle Accident Injuries: Some Additional Evidence. *Journal of Safety Research,* Vol. 37, 2006, pp. 267–276.
34. Ulfarsson, G., and F. Mannering. Differences in Male and Female Injury Severities in Sport-Utility Vehicle, Minivan, Pickup and Passenger Car Accidents. *Accident Analysis and Prevention,* Vol. 36, 2004, pp. 135–147.
35. Evans, L. Female Compared with Male Fatality Risk from Similar Physical Impacts. *Journal of Trauma,* Vol. 50, 2001, pp. 281–288.
36. *A Policy on Geometric Design of Highways and Streets,* 5th ed. AASHTO, Washington, D.C., 2004.
37. *Roadway Design Manual.* Texas Department of Transportation, Austin, Oct. 2006.
38. *Bureau of Environment and Design Manual.* Illinois Department of Transportation, Springfield, Dec. 2002.
39. *Indiana Design Manual,* English ed. Indiana Department of Transportation, 2003.
40. *Design and Location Manual, Volume 1—Roadway Design.* Ohio Department of Transportation, Columbus, Jan. 2007.
41. Hauer, E. The Frequency–Severity Indeterminacy. *Accident Analysis and Prevention,* Vol. 38, 2006, pp. 78–83.
42. McFadden, D. Econometric Models of Probabilistic Choice. In *Structure Analysis of Discrete Data with Econometric Applications* (C. F. Manski and D. McFadden, eds.), Massachusetts Institute of Technology Press, Cambridge, 1981.
43. Shankar, V., and F. Mannering. An Exploratory Multinomial Logit Analysis of Single-Vehicle Motorcycle Accident Severity. *Journal of Safety Research,* Vol. 21, 1996, pp. 183–194.
44. Chang, L., and F. Mannering. Analysis of Injury Severity and Vehicle Occupancy in Truck- and Non-Truck-Involved Accidents. *Accident Analysis and Prevention,* Vol. 31, 1999, pp. 579–592.
45. Carson, J., and F. Mannering. The Effect of Ice Warning Signs on Accident Frequencies and Severities. *Accident Analysis and Prevention,* Vol. 33, 2001, pp. 99–109.
46. Lee, J., and F. Mannering. Impact of Roadside Features on the Frequency and Severity of Run-off-Roadway Accidents: An Empirical Analysis. *Accident Analysis and Prevention,* Vol. 34, 2002, pp. 149–161.
47. Khorashadi, A., D. Niemeier, V. Shankar, and F. Mannering. Differences in Rural and Urban Driver-Injury Severities in Accidents Involving Large Trucks: An Exploratory Analysis. *Accident Analysis and Prevention,* Vol. 37, 2005, pp. 910–921.
48. Savolainen, P., and F. Mannering. Probabilistic Models of Motorcyclists' Injury Severities in Single- and Multi-Vehicle Crashes. *Accident Analysis and Prevention,* Vol. 39, 2007, pp. 955–963.
49. Washington, S. P., M. G. Karlaftis, and F. L. Mannering. *Statistical and Econometric Methods for Transportation Data Analysis.* Chapman and Hall/CRC Press, New York, 2003.
50. Reimer, B., L. D'Ambrosio, and J. Coughlin. Secondary Analysis of Time of Day on Simulated Driving Performance. *Journal of Safety Research,* Vol. 38, pp. 563–570.
51. Winston, C., V. Maheshri, and F. Mannering. An Exploration of the Offset Hypothesis Using Disaggregate Data: The Case of Airbags and Antilock Brakes. *Journal of Risk and Uncertainty,* Vol. 32, 2006, pp. 83–99.

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or polices of the Texas Department of Transportation or FHWA.

The Safety Data, Analysis, and Evaluation Committee sponsored publication of this paper.