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Safety sensitivity to roadway characteristics: A comparison across highway classes

Sikai Chen[a], Tariq Usman Saeed[a], Majed Alinizzi[b], Steven Lavrenz[c], Samuel Labi[d,*]

[a] Lyles School of Civil Engineering, Purdue University, Hampton Hall, 550 Stadium Mall Dr., W. Lafayette, IN, 47907, United States
[b] Civil Engineering Department, College of Engineering, Qassim University, Al-Mulida, Qassim, Saudi Arabia
[c] Wayne State University, 2100 Engineering Building, Detroit, MI, 48202, United States
[d] Lyles School of Civil Engineering, Purdue University, Hampton Hall, 550 Stadium Mall Dr., W. Lafayette, IN, 47907, United States

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ABSTRACT

This paper examined the accident risk factors associated with highway traffic and roadway design, for each of three highway classes in the United States using a bivariate modeling framework involving two levels of accident severity. With regard to the highest class (Interstates), the results suggest that, compared to no-casualty accidents, casualty accidents are more sensitive to traffic volume and average vertical grade, but less sensitive to the inside shoulder width and the median width. For US Roads, it was determined that, compared to no-casualty accidents, casualty accidents are more sensitive to traffic volume, outside shoulder width, pavement condition, and median width but less sensitive to the average vertical grade. For the relatively lowest-class roads (State Roads), it was determined that, compared to no-casualty accidents, casualty accidents are more sensitive to the traffic volume, lane width, outside shoulder width, and pavement condition. Compared to the relatively lower-class highways, accidents at higher-class highways are more sensitive to: changes in traffic volume, average vertical grade, median width, inside shoulder width, and the pavement condition (no-casualty accidents only); but less sensitive to changes in lane width, pavement condition (casualty accidents only), and the outside shoulder width. This variation in sensitivity across the different road classes could be attributed to the differences in road geometry standards across the road classes, as the results seem to support the hypothesis that these standards strongly influence accident occurrence. It is hoped that the developed bivariate negative binomial models can help highway engineers to evaluate their current design standards and policy, and to assess the safety consequences of changes in these standards in each road class.

1. Introduction

In 2014, the U.S. Center for Disease Control ranked highway accidents as the fourth leading cause of death in the United States. Also, highway accidents were ranked as the leading cause of death for people 1–44 years of age (U.S. Department of Health, Human Services, 2016). On a global scale, highway accidents are the ninth major cause of death, accounting for over 1.4 million deaths (World Health Organization, 2015). The cost of highway accidents is monumental – in the United States, the total economic and societal costs amounted to $836 billion in 2015; of this, the $242 billion in economic costs translates to $800 for each person or 1.6% of the Gross Domestic Product (Blincoe et al., 2015). Given the significant economic and social costs of highway accidents and the potential for their avoidance using cost-effective safety countermeasures, highway agencies continue to seek further knowledge on the relationships between highway accidents, and road geometry and traffic. It is expected that such knowledge will facilitate effective identification of hazardous areas and overall, will enhance decision-making based on strategic safety-related performance indicators aligned with a clear vision of the societal benefits of safety improvements (Qin et al., 2010; Dolan et al., 2016; Aguero-Valverde et al., 2016; Carhart et al., 2016).

There is a wide range of factor categories that affect highway accidents – attributes of the driver, vehicle, enforcement levels, natural environment, and road engineering features (Radwan and Sinha, 1978; Sinha et al., 1981; Sinha and Labi, 2007) as well as the complex interactions among them (Most et al., 2014; Park et al., 2016; Mannering et al., 2016; Tang et al., 2018). Unfortunately, the information contained in accident databases do not span this entire spectrum of accident factors. As such, efforts to model accident frequency and severity

* Corresponding author.
E-mail addresses: chen1670@purdue.edu (S. Chen), tusaeed@purdue.edu (T.U. Saeed), alinizzi@qec.edu.sa (M. Alinizzi), slavrenz@wayne.edu (S. Lavrenz), labi@purdue.edu (S. Labi).

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have often proceeded with tacit or explicit admission that the data is missing some accident factor information, thus often precluding a more revealing narrative and explanation of the accident experience. This problem of unobserved heterogeneity is further exacerbated by the spatial and temporal correlation of accident data and the correlation across the different levels of accident severity. Failure to account for these correlations may lead to invalid inferential statistics and unreliable parameter estimation (Guo et al., 2010; Huang and Abdel-Aty, 2010).

In this paper, the fatal and injury are combined as one level: "casualty," and property-damage-only accidents are termed "no-casualty". This is consistent with the views of past researchers who recommended combining fatal and injury crashes for modeling purposes (Bedard et al., 2002; Braver and Trempel, 2004 Ouimet et al., 2010; Deublein et al., 2015 Hall, 2017; Labi et al., 2017). Bivariate represents a special case of multivariate where the number of levels is 2; in the context of this paper, casualty (injury + fatal) and no-casualty (property damage only). Cross-severity correlation emerges from a variety of sources. For example, in an accident that was recorded as "multiple occupant injuries" accident, it may be the case that the different occupants actually experienced different levels of injury severity; there are often no data on the factors that capture these differences in injury. Secondly, there exists some correlation across these injury severity levels (Abay et al., 2013; Eluru et al., 2010; Yasmin et al., 2014). Efforts to estimate separate univariate models using the data can be expected to cause statistical problems because for a given roadway, the unobserved factors may possibly be impacting multiple accident counts (of different severity levels) simultaneously (Mannering et al., 2016). For such data, the use of a traditional fixed-parameter model or a univariate modeling approach (that is, modeling each severity level separately not accounting for any correlation between the accident counts across the accident severity levels) often leads to incorrect inferences and biased parameter estimates (Washington et al., 2011).

Safety researchers have risen to this challenge, as highway safety research has continued to advance the state of the art regarding analytical methods that characterize and address the effect of such unobserved factors. For example, over the past few decades, there has been a gradual upsurge in the development and application of the statistical multivariate techniques and approaches for joint modeling of accident frequencies (Hauer, 1980, 1992, Hauer and Persaud, 2001 El-Basyouny and Sayed, 2009; Sayed and Abdelwahab, 1998; Bijleveld, 2005; Ma and Kockelman, 2006; Ma et al., 2008; Song et al., 2006; Wang et al., 2011; Nashad et al., 2016; Chen et al., 2017a, b). Also, a number of research studies have used a variety of statistical tools to address other sources of possible error in modeling accident data (Qin and Reyes, 2011; El-Basyouny and Sayed, 2011; Abdel-Aty et al., 2013; Barua et al., 2016; Chen and Tarko, 2014; Park et al., 2015; Dinu and Veeraragavan, 2011; El-Basyouny et al., 2014a; Garnowski and Manner, 2011; Dong et al., 2014; El-Basyouny et al., 2014b; Lee et al., 2015a; Wang and Qin, 2014; Barua et al., 2016).These efforts have gradually led to substantial improvements in model predictive capability and reliability.

This paper examines the sensitivity of accident frequency and severity to different levels of the accident factors and assesses the variation in the sensitivities of the factors across the different highway classes and across the accident severities. In attempting to contribute to existing knowledge in this domain and to throw more light on this issue, the paper uses a bivariate modeling framework. The framework is intended to account for possible error correlation across the different levels of accident severity thus reducing the estimation error and enhancing the precision of estimates. It is hoped that addressing the issue will help highway engineers in evaluating their current design standards and policies with respect to the various design features (including those related to the highway cross section), and in assessing the safety consequences of changing (or not changing) these standards.

2. Methodology

The study methodology used a bivariate negative binomial framework that was implemented to investigate the impact of roadway geometric features on highway safety while accounting for the correlations across the two accident types (casualty accidents and no-casualty accidents). In contrast with the more common single-equation negative binomial framework (which estimates the models separately), the bivariate framework estimates the models for the different accident severity levels simultaneously. This is accomplished by introducing a shared error term matrix to account for the correlation between accident severity levels. The bivariate negative binomial (BNB) framework is a generalization of the multivariate framework that was described by Winkelmann (2000,2008). The paragraph below presents the Winkleman framework, modified to address the BNB problem in this paper.

Let z_i represent a J-dimensional vector, each element of which is Poisson-distributed with parameter λ_{ij},

Where: z_i is a vector of counts for the number of accidents in the i^{th} level of accident severity, on

$$z_i = (z_{i1}, z_{i2} ... z_{iJ})' \tag{1}$$

$i = 1, 2, ..., I$, and $j = 1, 2, ..., J$

In this paper, there are two levels of accident severity: casualty and no-casualty; therefore, $I = 2$. In addition, the number of observations, J, is different for each category of models (that is, each level of accident severity, and for each road class).

The expected number of accidents of the i^{th} severity level in j^{th} road segment is given by:

$$\lambda_{ij} = e^{x_{ij}' \beta_j} \tag{2}$$

x_{ij} = vector of independent variables associated with the geometric design, traffic volume, and pavement condition; β_j is a vector of coefficients for the corresponding independent variables.

To account for the presence of error term in the model, let $z_{ij}|\upsilon_{ij}$ a be Poisson distributed random variable with parameter $\lambda_{ij}\upsilon_{ij}$. Then Eq. (2) becomes:

$$\lambda_{ij}\upsilon_{ij} = e^{x_{ij}' \beta_j + \varepsilon_{ij}} \tag{3}$$

υ_{ij} is gamma distributed with mean 1 and variance α^{-1}.

The marginal distribution of z_{ij} after integration over υ_{ij} is negative binomial with mean $E(z_{ij}) = \lambda_{ij}$ and variance $Var(z_{ij}) = \lambda_{ij} + \alpha^{-1}\lambda_{ij}^2$.

In order to develop the probability generating function for the negative binomial distribution, the parameter α is parameterized as follows:

$$\alpha = \frac{\lambda_{ij}}{\sigma}$$

Where symbols have meanings as explained above.

The parameterization will not affect the mean; however, the variance $Var(z_{ij}) = \lambda_{ij}(1 + \sigma)$ becomes a linear function of the mean. After the parameterization, the negative binomial distribution has the following probability generating function:

$$P_z(s) = [1 + \sigma(1 - s)]^{-\lambda_{ij}/\sigma}$$

$$P_u(s) = [1 + \sigma(1 - s)]^{-\gamma/\sigma} \tag{4}$$

$$P_y(s) = [1 + \sigma(1 - s)]^{-(\lambda_{ij}+\gamma)/\sigma}$$

Where: u_i represents a scalar random variable with negative binomial distribution and mean γ. $y_{ij} = z_{ij} + u_i$, $s_i = min(y_{i1}, y_{i2} ... y_{iJ})$

The covariances between y_{ij} and y_{ik} are given by $Cov(y_{ij}, y_{ik}) = \gamma(1 + \sigma)$

The framework allows for overdispersion on the condition that $\sigma > 0$. The joint probability function of the multivariate negative binomial framework is expressed as:

$$f_{NB}(z_{ij}) = \frac{\Gamma(\lambda_{ij}/\sigma + z_{ij})}{\Gamma(\lambda_{ij}/\sigma)\Gamma(z_{ij}+1)}\left(\frac{1}{1+\sigma}\right)^{\lambda_{ij}/\sigma}\left(\frac{\sigma}{1+\sigma}\right)^{Z_{ij}}$$

Where: f_{NB} is the negative binomial probability function. Winkelmann (2000,2008) provided further details on the framework. If α is significantly different from 0, then the negative binomial framework is preferred. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) (Friedman et al., 2001) were used for select the final set of variables. These concepts help choose the best set of variables that provide the best fit to the data while penalizing model overfitting that is often associated with the use of a large number of variables. A large number of sets of potential variables (each set representing a given combination of these variables) was investigated. The AIC and BIC were calculated for the model corresponding to each set of potential variables, and the model which yielded the smallest AIC and BIC was selected as the final model.

In addition, the proposed framework was applied separately for each of the three road classes (i.e., Interstates, US roads and State roads). Due to the similarity of State Roads and US Roads (as will be observed subsequently in the data description section of this paper), a likelihood ratio test for parameter transferability was carried out in order to test if a single model or two separate models should be used to describe these two road classes. The likelihood ratio test for parameter transferability is given as (Washington et al., 2011):

$$\chi^2 = -2[LL(\beta_{ij}) - LL(\beta_i) - LL(\beta_j)]$$

where, $LL(\beta_{ij})$ is the log-likelihood at convergence of the model estimated with the data from both of the road classes i and j; $LL(\beta_i)$ is the log-likelihood at convergence of the model estimated with data from road class i; and $LL(\beta_j)$ is the log-likelihood at convergence of the model estimated with data from road class j.

The paper's methodology also includes an analysis of the elasticity of the crash frequency to the key explanatory factors. As defined in the literature, the elasticity of an accident outcome to an explanatory factor is the percentage change in the accident outcome in response to a 1% change in that factor. For continuous variables such as the shoulder width and average vertical grade, the elasticity, E, is given by:

$$E_{x_{ik}}^{\lambda_i} = \frac{\partial\lambda_i}{\lambda_i} \times \frac{x_{ik}}{\partial x_{ik}}$$

Where: E = Elasticity of accident frequency with respect to the factor X, x_{ik} is the value of the kth explanatory factor. λ_i is the expected count (frequency) for observation i. Elasticities are computed for each observation, and a single, average elasticity is typically reported across all i.

In the literature, a variety of functional forms have been used for the accident prediction equation: linear, product, and exponential (Forkenbrock and Foster (1997). These have been used in the context of negative binomial or Poisson regression. For non-continuous variables such as indicator variables that take on values of one or zero, a pseudo-elasticity is used (Washington, et al., 2011). From the elasticity equation given above, it is clear that the elasticity of safety outcome with respect to a given factor is a dimensionless value but depends on the existing value of the factor as well as the functional form used to model the accident frequency. The concept of elasticities help to acquire insight into the implications of parameter estimation results, particularly, to measure the effects of the explanatory factors. Elasticities provide an estimate of the impact of a variable on the expected frequency and are interpreted as the effect of a 1% change in the variable on the expected frequency λi. For example, an elasticity of −3.4 is interpreted as follows: a 1% increase in the variable reduces the expected frequency by 3.4%.

In the literature, the efficacy of highway safety countermeasures has been measured in terms of their accident reduction or accident modification factors, and in certain studies, elasticities. A crash reduction factor (CRF) is the percentage crash reduction that might be expected after implementing a given countermeasure at a specific site (Davis, 2000; Shen and Gan, 2003; Kim et al., 2012; Oh and Park, 2014). Elasticities are generally applicable if the change of the road factor (due to the countermeasure implementation) is small (Washington et al., 2011).

Table 1
Summary statistics for the key variables.

	Mean	Std Dev	Minimum	Maximum
Interstates				
Total number of casualty accidents per year	4.506	3.959	0	19
Total number of no-casualty accidents per year	18.030	15.206	0	79
Segment length in miles	5.130	2.241	0.560	11.310
Average annual daily traffic (in 10,000 s)	3.271	1.600	1.181	12.865
Lane width in ft.	12.030	0.784	8.750	14.46
Outside shoulder width in ft.	10.335	0.981	2.800	12
Pavement condition (PSI units)	3.618	0.401	2.031	4.864
Average vertical curve grade (%)	1.639	1.950	0	6.179
Road segments with inside shoulder or median	100%		0	1
Road segments with inside shoulder	100%		0	1
Inside shoulder width in ft.	4.562	1.765	3	8
Median width in ft.	61.236	14.308	2	99
Number of lanes on road segment	5.037	0.269	5	7
Road segment with more than 2 lanes	100%		0	1
US Roads				
Total number of casualty accidents	3.913	3.966	0	41
Total number of no-casualty accidents	12.644	11.129	0	110
Segment length in miles	5.852	2.495	0.620	16.610
Average annual daily traffic (in 10,000 s)	0.883	0.629	0.116	3.829
Lane width in ft.	12.755	2.175	9.060	16.21
Outside shoulder width in ft.	6.330	3.052	0.600	14
Pavement condition (PSI units)	3.326	0.573	1.119	4.788
Average vertical curve grade (%)	1.160	1.708	0	7.421
Road segments with inside shoulder or median	44.23%		0	1
Road segments with inside shoulder	32.37%		0	1
Inside shoulder width in ft.	1.337	2.061	0	6.85
Median width in ft.	16.345	23.067	0	75.870
Number of lanes on road segment	3.006	1.414	2	5
Road segment with more than 2 lanes	33.65%		0	1
State Roads				
Total number of casualty accidents	3.177	3.575	0	21
Total number of no-casualty accidents	10.587	11.052	0	94
Segment length in miles	5.947	2.620	1	15.140
Average annual daily traffic (in 10,000 s)	0.646	0.649	0.027	3.737
Lane width in ft.	12.202	2.179	8.290	16.36
Outside shoulder width in ft.	4.678	3.319	0	13
Pavement condition (PSI units)	3.341	0.574	1.438	4.790
Average vertical curve grade (%)	1.112	1.605	0	5.948
Road segments with inside shoulder or median	23.79%		0	1
Road segments with inside shoulder	15.86%		0	1
Inside shoulder width in ft.	0.647	1.614	0	6.21
Median width in ft.	8.834	19.643	0	81.560
Number of lanes on road segment	2.503	1.115	2	5
Road segment with more than 2 lanes	17.24%		0	1

3. Data description

Table 1 presents the summary statistics of the model's key variables for all the segments investigated in this paper. The table does this separately for three highway classes (also referred to as route types): Interstates, US Roads, and State Roads. Interstates generally have the highest levels of design standards regarding pavement quality and road geometrics; on the other hand, state roads generally have the lowest levels. For example, Interstates tend to have thicker pavements, fewer surface defects such as potholes, multiple lanes, wider lanes and shoulders, paved shoulders, gentle horizontal and vertical curves, and access control. On the other extreme, state roads tend to have relatively thinner pavements, more frequent or severe surface defects, single lanes, shoulders that are narrow, unpaved, or non-existent, less-gentle horizontal and vertical curves, and poor access control due to intersections and driveways.

As the table indicates, 100% Interstates have multiple lanes (no two-lane road section) while 66% and 82% of US Roads and State Roads, respectively, have two-lane sections. Multiple lanes generally provide the motorist with greater passing opportunities thus generally provide a safer environment in that regard. In addition, 100% of Interstates have an inside shoulder and a median; for US Roads, 44% and 32%, and for State Roads, 24% and 16% have an inside shoulder and a median, respectively. The pavement condition is expressed in terms of the present serviceability index which ranges from 0 (failed) to 5 (condition). The table shows that the Interstates generally have superior pavement condition (2.03–4.86 PSI), compared to US Roads (1.12–4.79 PSI) and State Roads (1.44–4.79 PSI).

Fig. 1 presents, for the three road classes, the overall safety performance (accident experience) and the key factors that generally influence the safety performance (geometrics and traffic volume). The mean values for each road class is shown. Also, for all segments in the state (all road classes), the mean and a fraction of standard deviation (band) are shown for each design factor or operational attribute. The figure confirms the marked differences in the geometric characteristics and accident experience across the road classes and provides some indication of their relative overall safety performance and design performance compared to each other. With regard to accident experience, state roads and US roads were similar but very distinct from Interstates. With regard to lane width and shoulder (inside and outside), the traffic volume, and the number of lanes, these two non-Interstate road classes seem to be somewhat similar but again much distinct from Interstates. With regard to the vertical alignment and the fraction of multiple-lane roads, all three road classes seem to be rather distinct from each other. Due to the relative closeness of the locations of State Roads and US Roads on the quadrant charts in Fig. 1, it may be hypothesized that the state of safety at these two classes are not significantly different from each other and that this could be described using a single rather than separate models. In order to test this hypothesis of similar state of safety at the US and the State roads, this article also carried out a likelihood ratio test for road class transferability. This test was performed to ascertain whether the hypothesis should be rejected.

Fig. 2 presents the accident frequency distributions by severity level, for each road class. As expected, the frequency of no-casualty accidents exceeds that of casual accidents for all road classes. In addition, the distributions of the frequency charts seemed to be generally similar across the road classes: a preponderance of zero-accident segments, then a sharp drop in frequency for low accident counts, followed by an increasing function to some maximum point after which the frequency decreases gradually, yielding an approximately right-skewed shape. The exact location of the inflexion points and the distribution curve slopes differ across the road classes and accident severity levels: relatively gentle for Interstates and relatively less gentle for the two non-Interstate classes.

4. Results and discussion

First, the hypothesis that the parameters for the US roads and State roads are significantly similar was postulated and tested.

$$\chi^2 = -2[LL(\beta_{US+State}) - LL(\beta_{US}) - LL(\beta_{State})] = 262.58$$

$$\chi^2_{c,0.01,14} = 29.14123774 \text{ (DOF = 14)}$$

$$\chi^2 > \chi^2_{c,0.01,DOF}$$

Hence, the null hypothesis is rejected at 99% confidence level. Therefore, the results of the likelihood ratio test for parameter transferability indicated that two separate models should be estimated to describe accident occurrence at US roads and State roads.

Next, the bivariate negative binomial models developed separately for Interstate, State roads and US roads, and the results are presented in Table 2. The table presents only the variables that were found to be statistically significant at the given level of significance. It is important to state that in some of the models, certain variables were not found statistically significant not necessarily because they play no role in accident occurrence but because they exhibited little or no variation in the dataset. As such, it should not be interpreted broadly that for these variables, changes in their values do not influence accident frequency. Rather, the results discussed herein are applicable only for the range of each variable in the data (see Table 1). Table 3 presents the goodness-of-fit values of the models.

4.1. Traffic volume

Researchers have often cautioned that traffic volume must be included in accident models only with a great deal of circumspection due to possible correlation with other explanatory variables such as the shoulder, number of lanes, and lane width. Some of the earliest studies on this topic were by Lundy (1965); Gwynn (1967); Kihlberg and Sharp (1968), and Satterly and Cleveland (1969) who developed relationships between accident rates on one hand, and traffic volume or volume-capacity ratios on the other hand. Subsequent studies by Cedar and Livneh, (1982),; TRB (1985), and Frantzeskakis and Iordanis (1987), threw more light on the issue using data spanning wider range of traffic conditions. More recently, Hall and Pendleton, (1990) analyzed traffic count and accident data and determined that when the hourly traffic volumes are far lower than capacity, the accident rates decreased with increasing traffic volumes and with increasing volume/capacity ratios. Duivenvoorden (2010) suggested that as traffic volumes increase, the number of accidents seems to increase but the accident rate seems to decrease.

In both casualty and no-casualty models developed in this paper, the variable representing traffic volume consistently had positive (albeit, non-identical) coefficients in the models for all three separate road classes. In other words, the relationship observed between traffic volume and accident frequency has the same direction but different magnitudes, across the road classes. This is consistent with findings of past research as discussed above. With regard to casualty accidents, the model indicated that a 1% increase in natural logarithm of traffic volume is associated with 8.0982% increase for Interstate roads, 5.6315% for US Roads, and 6.8664% for State Roads. With regard to no-casualty accidents, the model indicated that a 1% increase in natural logarithm of traffic volume is associated with 7.8605% increase for Interstate roads, 4.4678% for US Roads, and 5.7549% for State Roads. This suggests that (a) casualty accidents are generally more sensitive to changes in traffic volume compared to no-casualty accidents, for each road class, (b) for a given accident severity level, there is an ambiguous trend of the magnitude of the relationship from higher class to the lower class roads: the highest class of highways are most sensitive to changes in traffic volume, and the middle class of highways are least sensitive.

4.2. Vertical alignment

It is intuitive that steeper grades are generally more hazardous from a safety perspective. Therefore, gentle slopes are generally preferable in highway design. However, this is costly due to the amount of earthwork involved in designs that yield gentle slopes, particular on rolling terrain. Researchers including Miaou et al. (1993) and Harwood et al. (1998) have investigated the effect of vertical grade on accidents.

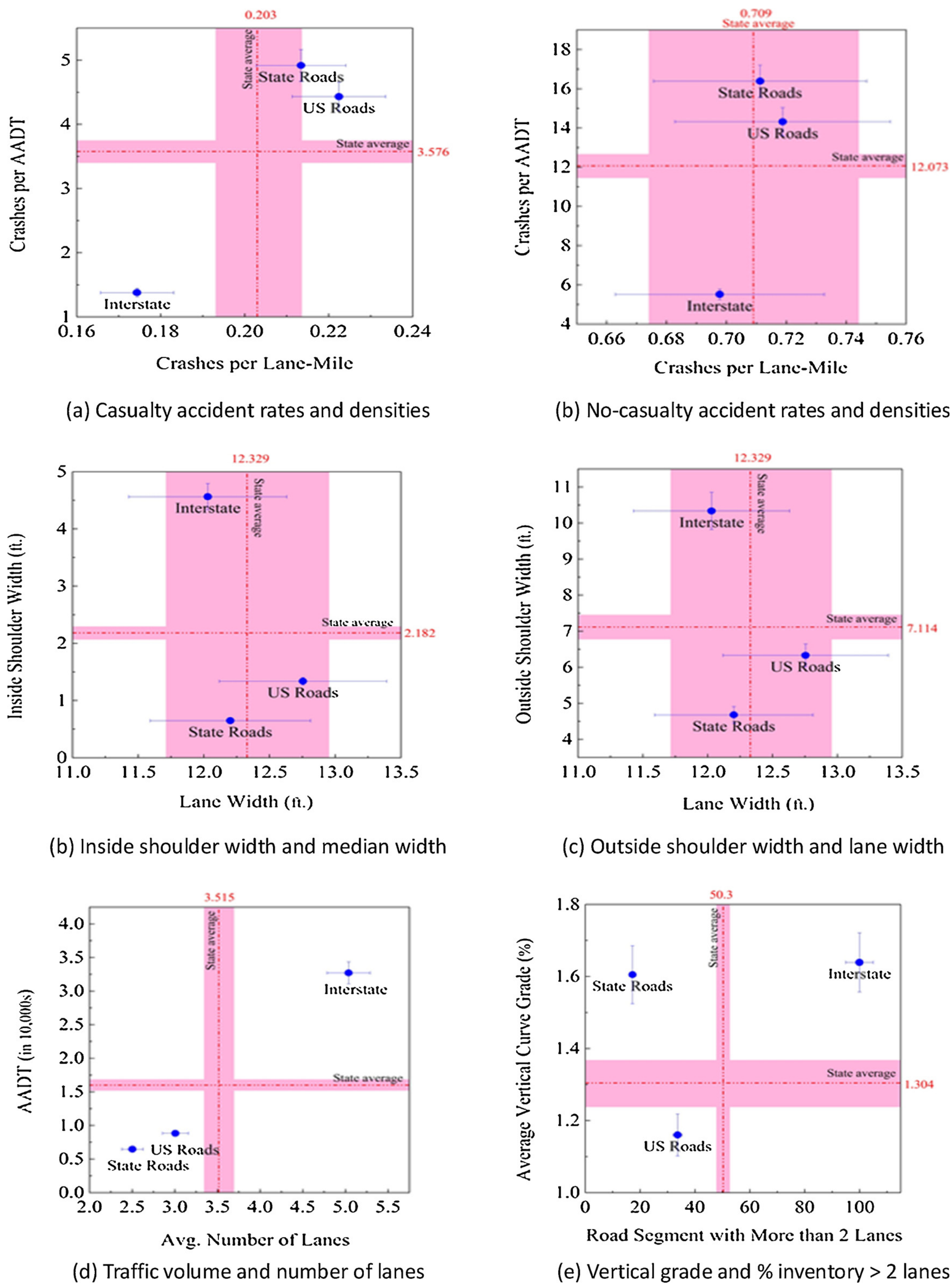

Fig. 1. Design and operational characteristics across the road classes (a) Interstate Roads, (b) US Roads, (c) State Roads.

In this paper, the average vertical curve grade was determined to have positive coefficients in the models for Interstate and US Roads. For each of these road classes, the effect of vertical grade on safety was different for each accident severity level. With regard to casualty accidents, a 1% increase in vertical grade is associated with 0.1019% increase for Interstate roads and 0.0432% for US Roads. With regard to no-casualty accidents, the model indicated that a 1% increase in vertical grade is associated with 0.0771% increase for Interstate roads and 0.0568% for US Roads. These results lead to a number of inferences. First, for a given road class, casualty accidents are more sensitive to changes in the vertical grade compared to no-casualty accidents. Second, for both levels of accident severity, higher-class highways are more sensitive to changes in vertical grade, compared to lower-class highways.

4.3. Shoulder width

The road shoulder can influence safety directly (by serving as a

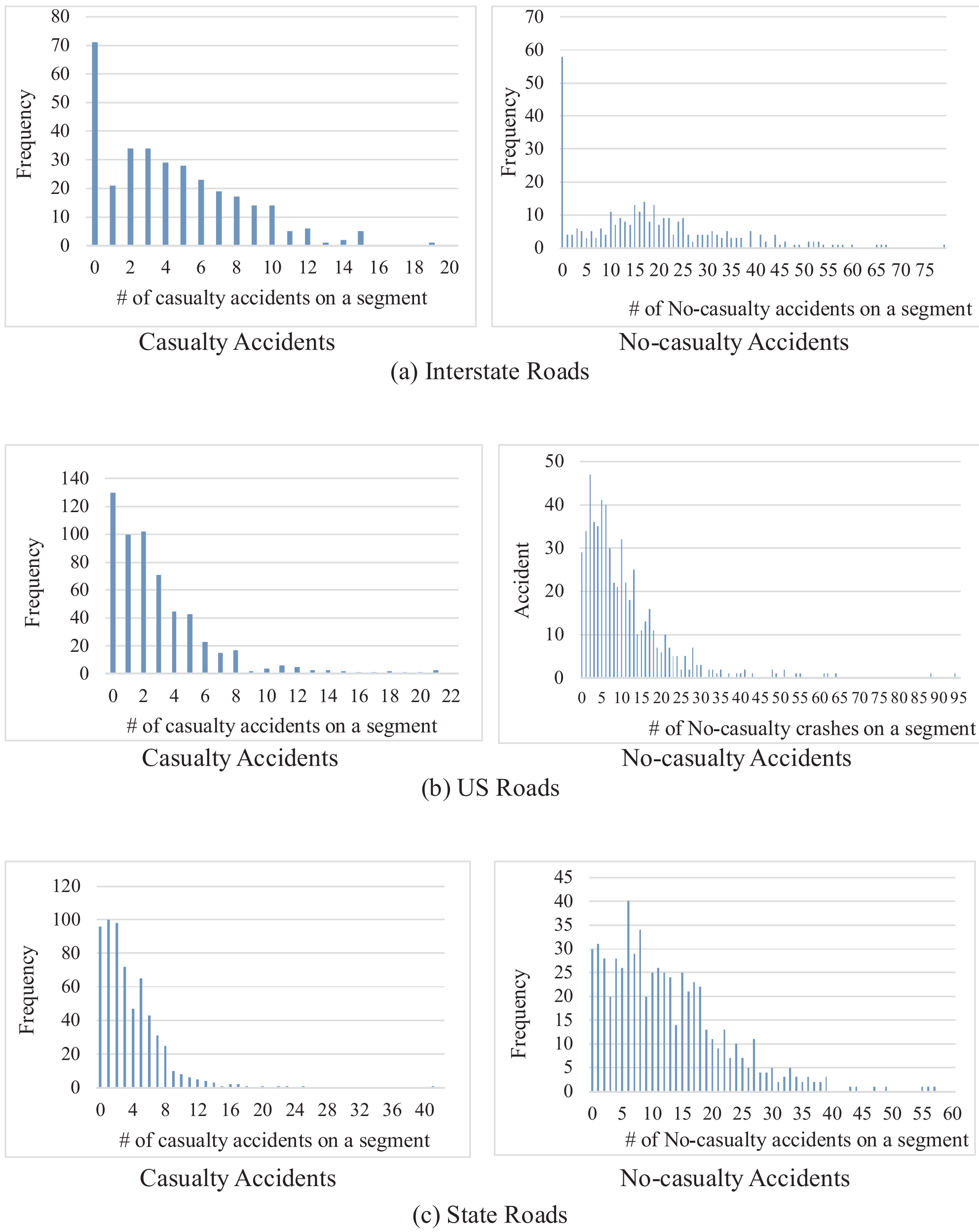

Fig. 2. Accident Frequency Distributions by Road Class and Accident Severity.

refuge area to avoid an accident) or indirectly (by increasing capacity thus reducing the v/c ratio which has been shown to affect accident occurrence). The shoulder, whose width is measured as the distance between the pavement edge to the start of the side-slope, and may be paved fully or partially, or unpaved. Empirical studies on the relationship between shoulder width and safety include those by Zegeer and Deacon, 1987; Vogt and Bared, 1998; Harwood et al., 1998; Fitzpatrick et al., 2000; Hauer, 2000). We provide below, separate discussion for the inside and outside shoulder widths.

4.4. Inside shoulder width

The impact of inside shoulder width on accident frequency, exhibits a clear curve form (Fig. 3). The figure suggests that this design feature is the most sensitive compared to all other design features. The plot is developed for Interstates only because the results showed that the presence or width of the inside shoulder has a significant impact on the number of casualty and no-casualty accidents for this road class only. As Table 4 indicates, for Interstate roads, a 1% increase in the inside shoulder width is associated with 1.7248% decrease in casualty accidents and a 2.9666% decrease in no-casualty accidents. This seems to suggest that for that class of highways, no-casualty accidents are more sensitive to changes in the inside shoulder width, compared to casualty accidents.

4.5. Outside shoulder width

The curves in Fig. 4 suggest that no-casualty accidents, compared are casualty accidents, are generally less sensitive to outside shoulder width. This figure is for the US roads but the general trend was found to be similar for State Roads. For US Roads, a 1% increase in the outside shoulder width is associated with a 0.2975% decrease in casualty accidents and a 0.0550% decrease in no-casualty accidents. For State Roads, a 1% increase in outside shoulder width is associated with a 0.3896% decrease in casualty accidents and a 0.2343% decrease in no-casualty accidents. These trends also suggest that for a given accident

Table 2
The Estimated Bivariate Negative Binomial Models.

Road class	Variables	coefficient estimates	standard error	p-value
Interstates	**Casualty Accidents**			
	β_0	−12.8332	2.2625	< 0.0001
	Segment length in miles	0.1582	0.0250	< 0.0001
	LN(average annual daily traffic)	0.7870	0.1432	< 0.0001
	Average vertical curve grade	0.0622	0.0289	0.0316
	Inside shoulder width in ft.	−0.3781	0.0571	< 0.0001
	Median width in ft.	−0.0082	0.0050	0.0979
	Number of lanes on the road segment	1.4570	0.4227	0.0006
	No-casualty Accidents			
	β_0	−18.9604	2.4805	< 0.0001
	LN(average annual daily traffic)	0.7639	0.1273	< 0.0001
	Pavement condition (PSI units)	−0.0738	0.0317	0.0198
	Average vertical curve grade	0.0471	0.0266	0.0777
	Inside shoulder width in ft.	−0.6503	0.0646	< 0.0001
	Median width in ft.	−0.0106	0.0044	0.0158
	Number of lanes on the road segment	3.2660	0.4923	< 0.0001
US Roads	**Casualty Accidents**			
	β_0	−4.5535	0.5534	< 0.0001
	Segment length in miles	0.1255	0.0129	< 0.0001
	LN(average annual daily traffic)	0.6349	0.0635	< 0.0001
	Outside shoulder width in ft.	−0.0470	0.0170	0.0059
	Pavement condition (PSI units)	−0.0916	0.0447	0.0406
	Average vertical curve grade	0.0373	0.0191	0.0511
	Inside shoulder (1 if exist, 0 otherwise)	−0.3066	0.1289	0.0174
	Median width in ft.	−0.0069	0.0023	0.0029
	No-casualty Accidents			
	β_0	−2.7617	0.4469	< 0.0001
	Segment length in miles	0.1238	0.0115	< 0.0001
	LN(average annual daily traffic)	0.5037	0.0533	< 0.0001
	Outside shoulder width in ft.	−0.0087	0.0049	0.0751
	Average vertical curve grade	0.0490	0.0167	0.0035
State Roads	**Casualty Accidents**			
	β_0	−6.3659	0.4980	< 0.0001
	Segment length in miles	0.1249	0.0136	< 0.0001
	LN(average annual daily traffic)	0.8253	0.0582	< 0.0001
	Lane width in ft.	−0.0381	0.0179	0.0338
	Outside shoulder width in ft.	−0.0833	0.0194	< 0.0001
	Pavement condition (PSI units)	−0.0894	0.0539	0.0989
	Inside shoulder (1 if exist, 0 otherwise)	−0.5604	0.3166	0.0767
	Number of lanes on the road segment	0.2128	0.1247	0.0879
	No-casualty Accidents			
	β_0	−3.9423	0.3833	< 0.0001
	Segment length in miles	0.1285	0.0116	< 0.0001
	LN(average annual daily traffic)	0.6917	0.0458	< 0.0001
	Lane width in ft.	−0.0365	0.0157	0.0206
	Outside shoulder width in ft.	−0.0501	0.0154	0.0011
	Inside shoulder (1 if exist, 0 otherwise)	−0.2264	0.0841	0.0072
	Number of lanes on the road segment	0.1134	0.0569	0.0465

Table displays model with only those variable that are statistically significant at 90% degree of confidence.

Table 3
AIC and BIC for developed bivariate negative binomial models.

	Interstates	US Roads	State Roads
Akaike information criterion (AIC)	3929.32	7127.97	5950.96
Bayesian information criterion (BIC)	3996.43	7199.78	6031.86
Number of observations	311	624	576

severity level, US Roads are less sensitive to changes in the outside shoulder width compared to their relatively lower-class counterparts (State Roads).

4.6. Lane width

The lane width of a two-lane road is the distance between the centerline of the roadway to the pavement edge. Lanes of adequate width increase the opportunity for recovery of errant vehicles and also provide increased lateral separation between passing and opposing vehicles. Several studies have been carried out to relate lane width to accident experience (Zegeer and Deacon, 1987; Tarko and Sinha, 1997 Harwood et al., 1998; Stamatiadis et al., 2009). Zegeer and Deacon, 1987 determined that widening a lane by 4 ft., for example, could yield as much as 40% reduction in accidents.

In this paper, the segments with wider lanes were generally found to have fewer accidents compared to those with narrower lanes: within the range of lane widths studied, the number of accidents on state roads reduces with increase in lane width (Fig. 5). The figure suggests that the sensitivity of accident reduction to lane width is generally higher for high volume segments compared to low volume counterparts. This observation is similar across the two severity levels (casualty vs. no-casualty), except that the accident frequency for the latter exceeds that for the former by a factor of approximately four, all other factors remaining the same.

For state roads, the lane width was found to be strongly associated with the accident experience: a 1% of increase in lane width will reduce the expected accident frequency by 0.4649% and 0.4453% for casualty and no-casualty accidents on state roads, respectively. For Interstate and US highways, no strong association was found between lane width

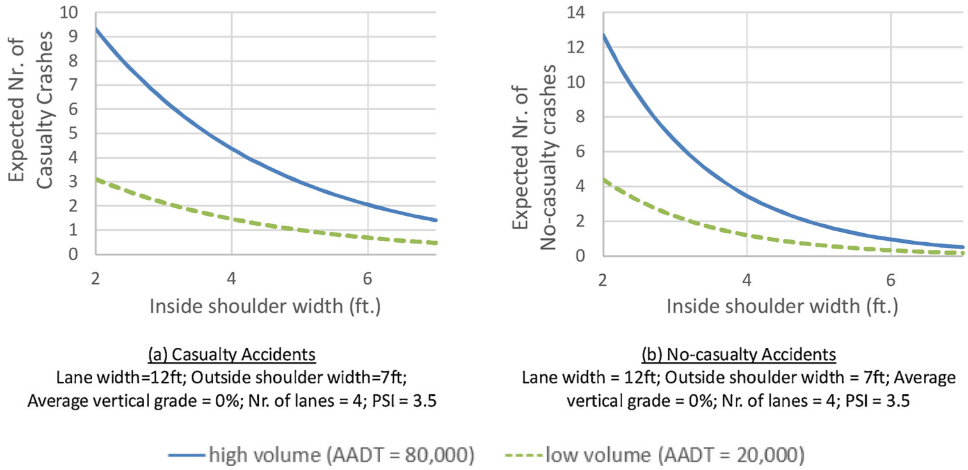

Fig. 3. Safety Impact of Inside Shoulder Width, Typical Interstate Segment.

Table 4
Sensitivity of the estimated bivariate negative binomial model parameters.

Variables	Interstates	US Roads	State Roads
Casualty Accidents			
Segment length in miles	0.8115	0.7344	0.7427
Natural logarithm of average annual daily traffic	8.0982	5.6315	6.8664
Lane width in ft.			−0.4649
Outside shoulder width in ft.		−0.2975	−0.3896
Pavement condition (PSI units)		−0.3046	−0.2986
Average vertical curve grade	0.1019	0.0432	
Inside shoulder width in ft.	−1.7248		
Median width in ft.	−0.5021	−0.1127	
No-casualty Accidents			
Segment length in miles	0.7936	0.7244	0.7641
Natural logarithm of average annual daily traffic	7.8605	4.4678	5.7549
Lane width in ft.			−0.4453
Outside shoulder width in ft.		−0.0550	−0.2343
Pavement condition (PSI units)	−0.2670		
Average vertical curve grade	0.0771	0.0568	
Inside shoulder width in ft.	−2.9666		
Median width in ft.	−0.6491		

[1]ft = 0.3048 m.

and accident experience. This does not necessarily mean that for the higher road classes, lane width is inconsequential to safety; rather, this result could be explained by the lack of variability in lane widths across Interstate segments and across US Road segments. In other words, for higher classes of highways, the lane width appears to be uniform compared to the lowest class (State Roads).

As we discuss in the future work section of this paper, a gamut of opportunities exists for further research inquiry regarding the impacts of lane width on highway safety. For example, it is intuitive that lane width affects certain accident patterns (such as run-off-road, head-on, and sideswipes) but not necessarily other accident patterns (such as angle and rear end accidents).

4.7. Median width

The primary role of a median is to provide traffic separation. A median is also useful in serving as a recovery area for errant drivers (Stamatiadis et al., 2009) or a refuge area for drivers seeking to avoid insipient danger. Other uses include accommodation of left-turn movements and the provision of an area of emergency stops. The median width variable is valid for divided highways only. 100% of Interstates are divided highways while less than 50% of US Roads and State Roads are divided. Hadi et al. (1995) showed that the median width of multi-lane roadways has a significant effect on safety. Hauer (2000) observed that wider medians reduced cross-median accidents involving opposing vehicles, median-related accidents increase as the median width increases, peaking at approximately 30 ft and decrease with widths beyond this point; the researcher also stated that the effect of median width on total accidents is questionable. Stamatiadis et al., 2009 developed accident modification factors for median width on 4-lane divided roads, and determined that every added ft. of median width yields a 0.9% reduction in injury accident frequency.

Figs. 6 and 7 present the impact of median width on accidents.

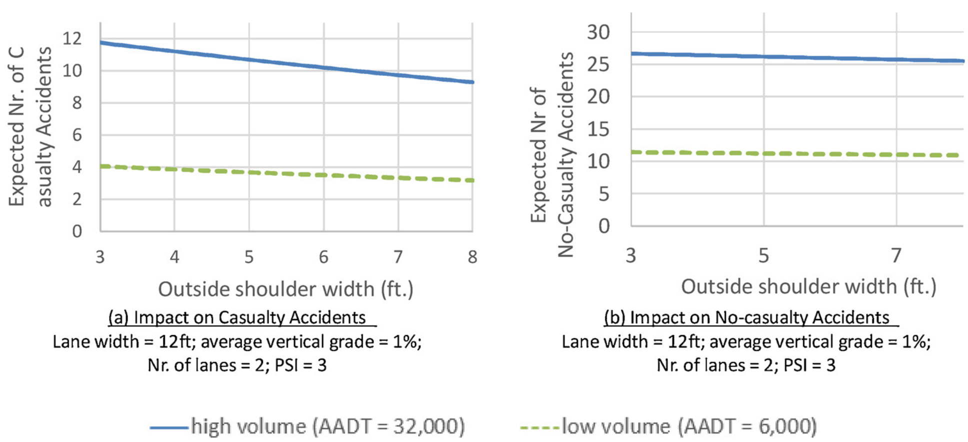

Fig. 4. Safety Impact of Outside Shoulder Width, Typical US Road Segment.

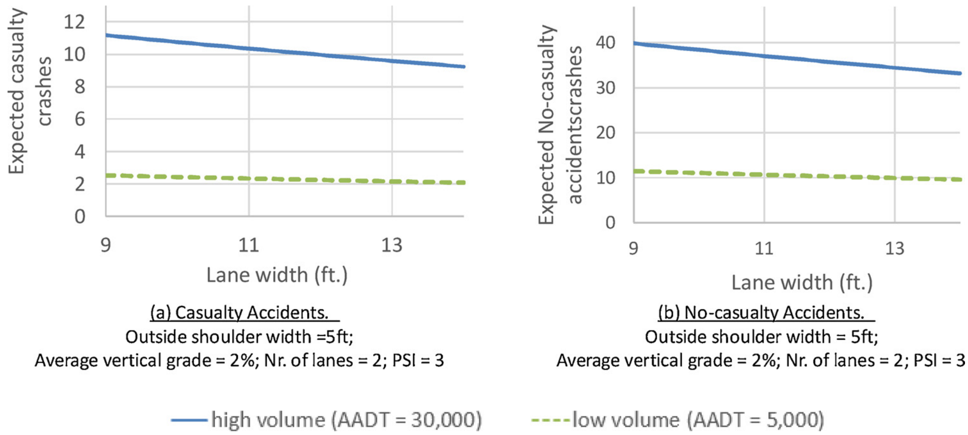

Fig. 5. Safety Impact of Lane Width, Typical State Road Segment.

Similar to the case of the other design features, the figure suggests that the sensitivity of accident reduction to median width is generally higher for high-volume segments compared to low-volume counterparts, for a given road class. This observation is similar across the two categories of accidents (casualty vs. no-casualty). Unlike the other design features, the accident sensitivity to median width is higher for no-casualty accidents compared to casualty accidents. The model found that for Interstates, a 1% increase in the median width is associated with a 0.5021% decrease in casualty accidents and a 0.6491% decrease in no-casualty accidents. For US Roads, a 1% increase in the median width is associated with a 0.1127% decrease in casualty accidents, but no significant correlation between no-casualty accidents and median width was found. For state roads, no significant correlation was found between accidents and median width. These trends suggest that (a) no-casualty accidents are more sensitive to changes in the median width compared to casualty accidents (for Interstates), (b) for a given accident severity level, higher-class highways are more sensitive to changes in the median width compared to their lower-class counterparts.

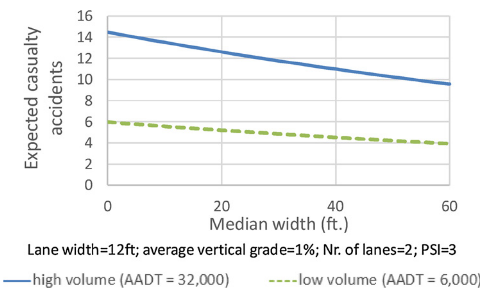

Fig. 7. Safety Impact of Median Width on Casualty Accidents, Typical US Road Segment.

4.8. Pavement condition

In general, a poor pavement condition is likely to cause drivers lose control of their vehicles and may lead to a crash, and such hazard is exacerbated if the driving situation has adversities associated with the operator (e.g., inebriation), vehicle (e.g., brake problems), environment (e.g., fog), and so on. A number of studies have investigated the influence of pavement condition on accidents using mechanistic or empirical models. Studies that used the former type of models include that by Velinsky and White, (1980) which measured the dissipation of vehicle energy due to a rough pavement, Wambold, (1985) who evaluated the effects of a rough pavement on vehicle dynamics, and McLean and Foley, (1998) who assessed the effect of rough pavements on highway operations. Other mechanistic studies were by Miege and Popov, (2005) and Jackson et al. (2011) who addressed the effects of rough pavement surfaces on the rolling resistance of tires under dynamic vertical loads, and Gagnon et al. (2014) who simulated energy dissipation due to rough pavements. Researchers who have analyzed the effect of pavement condition using empirical models include Sattaripour, (1977), Harwood et al. (2003) and Lamptey, (2004), and Labi (2006). Other researchers that have made significant contributions to this area include Chan et al. (2008), Labi (2011), Dong and Huang, (2012), and Lee et al., 2015b; Sarwar and Anastasopoulos, 2017). The safety risks of

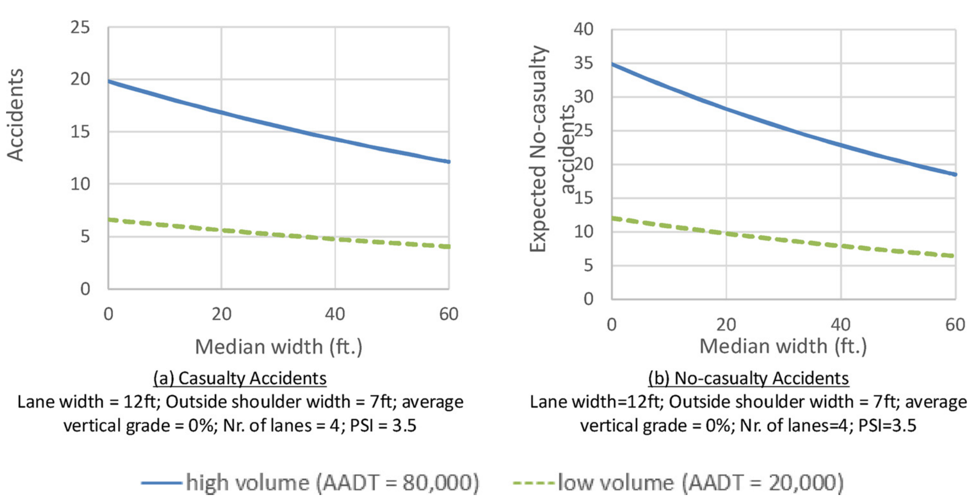

Fig. 6. Safety Impact of Median Width, Typical Interstate Segment.

pavement surface friction, in particular, has been studied by Wallman and Aström (2001) and Colonna et al. (2016).

The pavement condition is generally expressed in terms of present serviceability index (PSI), international roughness index (IRI) or road friction. In this paper, we use PSI. The results suggest that for both accident severity levels, the impact of pavement condition on roadway safety is the same in direction but not in magnitude, across various road classes. Specifically, the results indicate that pavement condition has a significant impact on the frequency of casualty accidents on the non-Interstates and on the frequency of no-casualty accidents on Interstates only. For each road class, the effect of pavement condition on safety was different for each accident severity level: For Interstates, a 1% increase in PSI is associated with a 0.2670% decrease in no-casualty accidents and no significant impact on casualty accidents. This suggests that for Interstates, the higher the level of accident severity (from no-casualty to casualty), the lower the sensitivity to changes in pavement condition. On the other hand, a 1% increase in PSI is associated with a 0.2986% and a 0.3046% decrease in casualty accidents at State Roads and US Roads, respectively but no significant impact on no-casualty accidents. This suggests that for non-Interstates, the higher the level of accident severity, the higher the sensitivity to the pavement condition.

5. Computation of elasticities

Table 4 presents the elasticity of accident frequency to the geometric factors that were found significant in this paper. It is important to point out that these elasticities may be somewhat different compared to those in the literature, due (probably) to differences in road class, topography, driving culture, and other attributes unique to the locations for which the crash data were collected.

The results suggest that for state roads, the accident propensity is generally less sensitive to outside shoulder width than it is to the lane width. This suggests that faced with a road with narrow lanes and narrow shoulders, it may be more effective, from a safety standpoint, to widen the lane than the shoulder. Also, the current paper presents probably the largest elasticity values for the inside shoulder compared to other studies.

6. Conclusions and future research

Highway geometric factors are found to have variable impacts on highway safety (across accident severity level and road class). For example, it is found that widening outside shoulder by 1% will have no impact on Interstate highways, but will lower 0.3896% casualty accidents and 0.2343% no-casualty accidents on State roads; will lower 0.2975% casualty accidents and 0.055% no-casualty accidents on US highways. Reducing the average vertical curve grade on a road segment will lower the expected accident frequency for Interstate and US highways, but not for state roads; increasing inside shoulder width has little impact on State roads and US highways. However, this feature has significant impacts at Interstate: it is found that a 1% increase of inside shoulder width will result in 1.7248% and 2.9666% reduction of expected accident frequency for casualty and No-casualty accidents, respectively. Widening the highway median is found to have no impact on state roads. However, a 1% increase in median width will expect to reduce 0.5021% casualty accidents and 0.6491% no-casualty accidents on Interstate highways; and 0.1127% casualty accidents on US roads. These results are consistent with past research that shows that lane and shoulder width have variable impacts on vehicle accidents by severity. For Interstates, the pavement condition was found to be statically significant for no-casualty accidents with an estimated mean value of –0.0738; while for state roads and US highways, the pavement condition was found to have significant impacts on more severe accident such as casualty accidents, the estimated mean values are –0.0894 and –0.0916 for state roads and US highways, respectively.

Elasticity analysis was carried out to ascertain the percent change in the expected values of casualty and no-casualty accidents resulting from 1% change of each variable. For each road class, such crash sensitivities to the design factors differed across the two levels of crash severity. For the highest class (Interstates), casualty accidents, compared to no-casualty accidents, were determined to be more sensitive to traffic volume and average vertical grade, but less sensitive to the inside shoulder width and the median width. For the US Roads, it was determined that, compared to no-casualty accidents, casualty accidents were more sensitive to traffic volume, outside shoulder width, pavement condition, and median width but less sensitive to the average vertical grade. For the relatively lower-class roads (State Roads), it was determined that, compared to no-casualty accidents, casualty accidents were more sensitive to the traffic volume, lane width, outside shoulder width, and pavement condition, but less sensitive for any design or operational attribute. Overall, compared to the relatively lower-class highways, accidents at higher-class highways seemed to be more sensitive to: changes in traffic volume, average vertical grade, median width, inside shoulder width, and the pavement condition (no-casualty accidents only) but less sensitive to changes in lane width, pavement condition (casualty accidents only), and the outside shoulder width.

The study results shed some light on the safety performance across the different highway classes, and seems to affirm the efficacy of the design features that exist at the higher-class highways, such as wider cross-sectional features (lane, shoulder, and median), superior pavement material and thicknesses (that translate into higher pavement quality and condition), higher levels of access control, superior vertical and horizontal alignment, wider and higher bridge clearances, superelevation, and other features that “forgive” errant drivers or faulty vehicles, or alleviates the safety hazards posed by inauspicious weather.

The models developed herein, hopefully, can help highway engineers to assess the safety effects of current geometric design policy or changes thereto, quantify the safety benefits of prospective road projects that are intended to improve road geometrics, and to assess the safety consequences of inaction at geometry-deficient road sections. Secondly, as more highway agencies embrace the principles of infrastructure asset management, the development of data-driven decision support tools supported by information technology systems are becoming indispensable. The models developed in this paper help provide some of the inputs needed for such decision support systems.

There are two issues in this paper that are worthy of discussion. First, the paper uses three road classes: Interstates, US Roads and State Roads. As we demonstrate earlier in this paper, with regard to the number of lanes, there is significant variation across these road classes to merit their consideration as distinct groups. Within each road class, there is relatively smaller variation compared to across-class variation: Interstates have 5 to 7 lanes mostly; 34% and 17% of US Roads and State Roads, respectively, have multiple lanes. Furthermore, the number of lanes is not the sole safety-related attribute that differs across the three road classes. There are other attributes that are not captured by the set of variables in our dataset, and our paper’s road class-based grouping may have helped uncover the effects of such heterogeneity. As such, it can be considered worthwhile to use these classes as a basis for the analysis as done in this paper. On the other hand, if it is assumed that the best way to classify road segments, for safety analysis purposes, is by the number of lanes, then it will be worthwhile, in future research, to carry out the analysis separately for multi-lane segments (all interstates, most US roads and a few State roads) and two-lane segments (no interstate, some US roads and most State roads). In the course of the research for this paper, this possibility was considered and the dataset was prepared in this manner. We found that there were too few observations in some of the categories and therefore were inadequate for model estimation (the data for this paper is from Indiana only). Future research could replicate this study using national-level data that are more plentiful. Secondly, the finding with regard to horizontal curves, is worth discussing. It is expected that the (average) horizontal radius of curvature will have significant safety impact particularly at the lower-class highways. However, this variable was not found to be significant (at the 90% confidence level) in the estimated model. This result is suggestive of lack of variability in horizontal curve attributes in our data and does not suggest that the effect of horizontal curve attributes to safety are insignificant.

In addition, future work in this domain could address the development of separate models for vertical downgrades and upgrades, examine accidents by accident pattern (for example, the effect of lane width may be applicable only specific patterns of accidents such as single-vehicle run-off-the-road accidents), and consider the median type (for example, grass only, grass with cable, grass with barrier, concrete, and so on). In addition, the work in this paper could be extended to account for spatial and temporal heterogeneity in a multivariate random parameters framework that accommodates additional levels of accident severity.

References

Abay, K.A., Paleti, R., Bhat, C.R., 2013. The joint analysis of injury severity of drivers in two-vehicle crashes accommodating seat belt use endogeneity. Transp. Res. Part B Methodol. 50, 74–89.

Abdel-Aty, M., Lee, J., Siddiqui, C., Choi, K., 2013. Geographical unit based analysis in the context of transportation safety planning. Transp. Res. Part A Policy Pract. 49, 62–75.

Aguero-Valverde, J., Kun-Feng, W., Donnell, E.T., 2016. A multivariate spatial crash frequency model for identifying sites with promise based on crash types. Accid. Anal. Prev. 87, 8–16.

Barua, S., El-Basyouny, K., Islam, M., 2016. Multivariate random parameters collision count data models with spatial heterogeneity. Anal. Methods Accid. Res. 9, 1–15.

Bedard, M., Guyatt, G.H., Stones, M.J., Hirdes, J.P., 2002. The independent contribution of driver, crash, and vehicle characteristics to driver fatalities. Accid. Anal. Prev. 34 (6), 717–727.

Bijleveld, F.D., 2005. The covariance between the number of accidents and the number of victims in multivariate analysis of accident related outcomes. Accid. Anal. Prev. 37 (4), 591–600.

Blincoe, L.J., Miller, T.R., Zaloshnja, E., Lawrence, B.A., 2015. The Economic and Societal Impact of Motor Vehicle Crashes, Rep. No. DOT HS 812 013. National Highway Traffic Safety Administration, Washington, DC.

Braver, E.R., Trempel, R.E., 2004. Are older drivers actually at higher risk of involvement in collisions resulting in deaths or non-fatal injuries among their passengers and other road users? Inj. Prev. 10 (1), 27–32.

Carhart, N.J., Bouch, C., Walsh, C.L., Dolan, T., 2016. Applying a new concept for strategic performance indicators. Infrastruct. Asset Manag. 3 (4), 143–153.

Cedar and Livneh, 1982. Relationship between road accidents and hourly traffic Flow-I and II. Accid. Anal. Prev. 14 (1), 19–44.

Chan, A., Keoleian, G., Gabler, E., 2008. Evaluation of life-cycle cost analysis practices used by the Michigan department of transportation. J. Transp. Eng. 134 (6), 236–245.

Chen, E., Tarko, A.P., 2014. Modeling safety of highway work zones with random parameters and random effects models. Anal. Methods Accid. Res. 1, 86–95.

Chen, S., Saeed, T.U., Labi, S., 2017a. Impact of road-surface condition on rural highway safety: a multivariate random parameters negative binomial approach. Anal. Methods Accid. Res. 16, 75–89.

Chen, S., Saeed, T.U., Alqadhi, S.D., Labi, S., 2017b. Safety impacts of pavement surface roughness at two-lane and multi-lane highways: accounting for heterogeneity and seemingly unrelated correlation across crash severities. Transp. A Transp. Sci. 1–21.

Colonna, P., Berloco, N., Intini, P., Perruccio, A., Ranieri, V., 2016. Evaluating skidding risk of a road layout for all types of vehicles. Transp. Res. Rec. 2591, 94–102.

Davis, G.A., 2000. Crash reduction factors and causal inference in traffic safety studies: a review. Accid. Anal. Prev. 32 (1), 95–109.

Dinu, R., Veeraragavan, A., 2011. Random parameter models for accident prediction on two- lane undivided highways in India. J. Safety Res. 42 (1), 39–42.

Dolan, T., Walsh, C.L., Bouch, C., Carhart, N.J., 2016. A conceptual approach to strategic performance indicators. Infrastruct. Asset Manag. 3 (4), 132–142.

Dong, C., Clarke, D.B., Yan, X., Khattak, A., Huang, B., 2014. Multivariate random-parameters zero-inflated negative binomial regression model: an application to estimate crash frequencies at intersections. Accid. Anal. Prev. 70, 320–329.

Dong, Q., Huang, B., 2012. Evaluation of influence factors on crack initiation of LTPP resurfaced-asphalt pavements using parametric survival analysis. J. Perform. Constr. Facil. 28 (2), 412–421.

Deublein, M., Schubert, M., Adey, B.T., García de Soto, B., 2015. A Bayesian network model to predict accidents on Swiss highways. Infrastruct. Asset Manag. 2 (4), 145–158.

Duivenvoorden, K., 2010. The Relationship Between Traffic Volume and Road Safety on the Secondary Road Network. SWOV Institute for Road Safety Research, The Netherlands.

El-Basyouny, K., Sayed, T., 2009. Accident prediction models with random corridor parameters. Accid. Anal. Prev. 41 (5), 1118–1123.

El-Basyouny, K., Sayed, T., 2011. A full Bayes multivariate intervention model with random parameters among matched pairs for before–after safety evaluation. Accid. Anal. Prev. 43 (1), 87–94.

El-Basyouny, K., Barua, S., Islam, T., 2014a. Investigation of time and weather effects on crash types using Bayesian multivariate Poisson lognormal models. Accid. Anal. Prev. 73, 91–99.

El-Basyouny, K., Barua, S., Islam, M., Li, R., 2014b. Assessing the effect of weather states on crash severity and type by use of full bayesian multivariate safety models. Transp. Res. Rec. 2432, 65–73.

Eluru, N., Paleti, R., Pendyala, R., Bhat, C., 2010. Modeling injury severity of multiple occupants of vehicles: copula-based multivariate approach. Transp. Res. Rec. 2165, 1–11.

Fitzpatrick, K.L., Harwood, D.W., Anderson, I.B., Balke, K., 2000. Accident Mitigation Guide for Congested Rural Two-Lane Highways, NCHRP Report 440. Transp. Research Board.

Forkenbrock, D.J., Foster, N.S.J., 1997. Accident cost saving and highway attributes. Transportation 24 (1), 79–100.

Frantzeskakis, J.M., Iordanis, D.I., 1987. Volume-to-Capacity ratio and traffic accidents on interurban four-lane highways in Greece. Transp. Res. Rec. 1112, 29–38.

Friedman, J., Hastie, T., Tibshirani, R., 2001. The Elements of Statistical Learning (Vol. 1, No. 10). Springer series in statistics, New York, NY, USA.

Gagnon, L., Richard, M.J., Masarati, P., Morandini, M., Doré, G., 2014. An implicit ring tire model for multibody simulation with energy dissipation. Tire Sci. Technol. 42 (2), 62–84.

Garnowski, M., Manner, H., 2011. On factors related to car accidents on German Autobahn connectors. Accid. Anal. Prev. 43 (5), 1864–1871.

Guo, F., Wang, X., Abdel-Aty, M., 2010. Modeling signalized intersection safety with corridor-level spatial correlations. Accid. Anal. Prev. 42 (1), 84–92.

Gwynn, D.W., 1967. Relationship of accident rates and accident involvements with hourly volumes. Traffic Q. (July Issue), 407–418.

Hadi, M.A., Aruldhas, J., Chow, L., Wattleworth, J., 1995. Estimating safety effects of cross-section design for various highway types using negative binomial regression. Transp. Res. Rec. 1500, 169–177.

Hall, J.W., Pendleton, O.J., 1990. Rural accident rate variations with traffic volume. Transp. Res. Rec. 1281, 62–70.

Hall, T., 2017. Project-Oriented Safety Management of Rural Local Roads, Ph.D. Dissertation. Purdue University, W. Lafayette, IN.

Harwood, D.W., Council, F.M., Hauer, E., Hughes, W.E., Vogt, A., 1998. Prediction of the Expected Safety Performance of Rural Two-lane Highways. Report No. FHWA-RD-4584-09. Federal Highway Administration, McLean, VA.

Harwood, D.W., Kohlman Rabbani, E.R., Richard, K.R., McGee, H.W., Gittings, G.L., 2003. Systemwide Impact of Safety and Traffic Operations Design Decisions of Resurfacing, Restoration, or Rehabilitation Projects. NCHRP Report 486. Transportation Research Board, Washington, D.C.

Hauer, E., 1980. Bias-by-selection: overestimation of the effectiveness of safety countermeasures caused by the process of selection for treatment. Accid. Anal. Prev. 12, 113–117.

Hauer, E., 1992. Empirical Bayes approach to the estimation of "unsafety": the multivariate regression method. Accid. Anal. Prev. 24 (5), 457–477.

Hauer, E., 2000. The Median and Safety. www.trafficsafetyresearch.com.

Hauer, E., Persaud, B., 2001. A Common Bias in Before and After Comparison and Its Elimination.

Huang, H., Abdel-Aty, M., 2010. Multilevel data and Bayesian analysis in traffic safety. Accid. Anal. Prev. 42 (6), 1556–1565.

Jackson, R.L., Willis, J.R., Arnold, M., Palmer, C., 2011. Synthesis of the effects of pavement properties on tire rolling resistance. NCAT Rep. 05–11.

Kim, S., Choi, J., Kim, M., Kim, S., 2012. Determination of accident modification factors for the median bus lanes on urban arterials. Int. J. Urban Sci. 16 (1), 99–113.

Kihlberg, J.K., Sharp, K.J., 1968. NCHRP Report 47: Accident Rates As Related to Design Elements of Rural Highways. HRB, National Research Council, Washington, D.C.

Lee, J., Abdel-Aty, M., Jiang, X., 2015a. Multivariate crash modeling for motor vehicle and non-motorized modes at the macroscopic level. Accid. Anal. Prev. 78, 146–154.

Lee, J., Nam, B., Abdel-Aty, M., 2015b. Effects of pavement surface conditions on traffic crash severity. J. Transp. Eng. 2015 (10), 141 04015020.

Labi, S., 2006. Effects Of Geometric Characteristics of Rural Two-Lane Roads on Safety, Tech. Rep. FHWA/IN/JTRP-2005/2. West Lafayette, IN. .

Labi, S., 2011. Efficacies of roadway safety improvements across functional subclasses of rural two-lane highways. J. Safety Res. 42, 231–239.

Labi, S., Chen, S., Preckel, P.V., Qiao, Y., Woldemariam, W., 2017. Rural two-lane highway shoulder and lane width policy evaluation using multiobjective optimization. Transp. A Transp. Sci. 13 (7), 631–656.

Lamptey, G., 2004. Optimal scheduling of pavement preventive maintenance using life cycle cost analysis. MS thesis.

Lundy, R.A., 1965. Effect of traffic volumes and number of lanes on freeway accident rates. Highway Research Record 99, 138–147.

Ma, J., Kockelman, K., 2006. Bayesian multivariate Poisson regression for models of injury count, by severity. Transp. Res. Rec. 1950, 24–34.

Ma, J., Kockelman, K.M., Damien, P., 2008. A multivariate Poisson-lognormal regression model for prediction of crash counts by severity, using Bayesian methods. Accid. Anal. Prev. 40 (3), 964–975.

Mannering, F.L., Shankar, V., Bhat, C.R., 2016. Unobserved heterogeneity and the statistical analysis of highway accident data. Anal. Methods Accid. Res. 11, 1–16.

McLean, J., Foley, G., 1998. Road Surface Characteristics and Condition: Effects on Road Users. (No. ARR 314).

Miaou, S.P., Hu, P.S., Wright, T., Davis, S.C., Rathi, A.K., 1993. Development of Relationship Between Truck Accidents and Geometric Design: Phase I. Report No. FHWA-RD-91-124. Federal Highway Administration, Washington, D.C.

Miege, A.J., Popov, A.A., 2005. The rolling resistance of truck tyres under a dynamic vertical load. Veh. Syst. Dyn. 43 (sup1), 135–144.

Most, A.S., Qin, Xiao, Chitturi, M.V., Noyce, D.A., 2014. Analysis of the safety effects of traffic, geometric and access parameters on truck arterial corridors. Transp. Res. Rec. 2404, 68–76.
Nashad, T., Yasmin, S., Eluru, N., Lee, J., Abdel-Aty, M., 2016. Joint modeling of pedestrian and bicycle crashes: copula-based approach. Transp. Res. Rec. 2601, 119–127.
Oh, J., Park, D., 2014. Analysis on crash reduction factors for road segment safety. Int. J. Urban Sci. 18 (3), 396–403.
Ouimet, M.C., Simons-Morton, B.G., Zador, P.L., Lerner, N.D., Freedman, M., Duncan, G.D., Wang, J., 2010. Using the US National Household Travel Survey to estimate the impact of passenger characteristics on young drivers' relative risk of fatal crash involvement. Accid. Anal. Prev. 42 (2), 689–694.
Park, J., Abdel-Aty, M., Lee, C., 2016. Evaluation of the safety effectiveness of installing roadside barriers with different driver, vehicle, weather, and time of day conditions. Transportation Research Board 95th Annual Meeting of the Transportation Research Board.
Park, J., Abdel-Aty, M., Wang, J.H., Lee, C., 2015. Assessment of safety effects for widening urban roadways in developing crash modification functions using nonlinearizing link functions. Accid. Anal. Prev. 79, 80–87.
Qin, X., Reyes, R., 2011. A conditional quantile analysis for crash count data, ASCE. J. Transp. Eng. 137 (9), 601–607.
Qin, X., Ng, M., Reyes, P., 2010. Identifying crash-prone locations with quantile regression. Accid. Anal. Prev. 42 (6), 1531–1537.
Radwan, A.E., Sinha, K.C., 1978. Effect of 55-MPH speed limit on the severity and cost of heavy truck accidents. Traffic Quarterly 319–328.
Sarwar, M.T., Anastasopoulos, P.C., 2017. The effect of long term non-invasive pavement deterioration on accident injury-severity rates: a seemingly unrelated and multivariate equations approach. Analytical Methods in Accident Research 13, 1–15.
Sattaripour, A., 1977. The effect of road roughness on vehicle behavior. Veh. Syst. Dyn. 6 (2-3), 157–161.
Satterly, G.T., Cleveland, D.E., 1969. Traffic Volume, Traffic Control and Roadway Elements -Their Relationship to Highway Safety. Automotive Safety Foundation, Washington, D.C.
Sayed, T., Abdelwahab, W., 1998. A comparison of fuzzy and neural classifiers for road accidents analysis. J. Comput. Civ. Eng. 12 (1), 42–47.
Shen, J., Gan, A., 2003. Development of crash reduction factors: methods, problems, and research needs. Transp. Res. Rec. 1840, 50–56.
Sinha, K.C., Kaji, T., Liu, C.C., 1981. Optimal allocation of funds for highway safety improvement projects. Transp. Res. Rec. 808, 24–30.
Sinha, K.C., Labi, S., 2007. Transportation Decision-making. Wiley.
Song, J.J., Ghosh, M., Miaou, S., Mallick, B., 2006. Bayesian multivariate spatial models for roadway traffic crash mapping. J. Multivar. Anal. 97 (1), 246–273.
Stamatiadis, N., Pigman, J., Sacksteder, J., Ruff, W., Lord, D., 2009. Impact of Shoulder Width and Median Width on Safety, NCHRP Report 633. Transportation Research Board, National Research Council, Washington, D.C.
Tang, Z., Chen, S., Cheng, J., Ghahari, S.A., Labi, S., 2018. highway design and safety consequences: a case study of interstate highway vertical grades. J. Adv. Transp. https://doi.org/10.1155/2018/1492614. Article ID 1492614.
Tarko, A.P., Sinha, K.C., Farooq, O.A., 1997. Methodology for identifying highway safety problem areas. Procs., 76th Annual Meeting of the Transp. Research Board.
TRB, 1985. Special Report 209: Highway Capacity Manual. Transportation Research Board, National Research Council, Washington, D.C.
U.S. Department of Health and Human Services, 2016. Centers for Disease Control and Prevention. National Center for Health Statistics, 1600 Clifton Road Atlanta, GA Accessed July 2016. http://www.cdc.gov/nchs/fastats/leading-causes-of-death.htm.
Velinsky, S.A., White, R.A., 1980. Vehicle energy dissipation due to road roughness. Veh. Syst. Dyn. 9 (6), 359–384.
Vogt, A., Bared, G.J., 1998. Accident Models for Two-Lane Rural Roads: Segments and Intersections. FHWA-RD-98-133. Federal Highway Administration, Washington, D.C.
Wallman, C.G., Aström, H., 2001.). Friction Measurement Methods and the Correlation Between Road Friction and Traffic Safety: a Literature Review. Swedish National Road and Transport Research Institute, Linkoping, Sweden.
Wambold, J.C., 1985. Road roughness effects on vehicle dynamics. In measuring road roughness and its effects on user cost and comfort. ASTM Int.
Wang, C., Quddus, M.A., Ison, S.G., 2011. Predicting accident frequency at their severity levels and its application in site ranking using a two-stage mixed multivariate model. Accid. Anal. Prev. 43 (6), 1979–1990.
Wang, K., Qin, X., 2014. Measuring single-vehicle crash severity: structural equation modeling approach. Transp. Res. Rec. 2432, 17–25.
Washington, S., Karlaftis, M., Mannering, F.L., 2011. Statistical and Econometric Methods for Transportation Data Analysis. Chapman and Hall/CRC, Boca Raton, FL.
Winkelmann, R., 2000. Seemingly unrelated negative binomial regression. Oxf. Bull. Econ. Stat. 62 (4), 553–560.
Winkelmann, R., 2008. Econometric Analysis of Count Data, 5th ed. Springer, Germany.
World Health Organization, 2015. Global Health Estimates (GHE) 2013: Deaths by Age, Sex and Cause. Author at. Accessed July 2016. http://www.who.int/mediacentre/factsheets/fs310/en/.
Yasmin, S., Eluru, N., Pinjari, A.R., Tay, R., 2014. Examining driver injury severity in two vehicle crashes–A copula based approach. Accid. Anal. Prev. 66, 120–135.
Zegeer, C.V., Deacon, J.A., 1987. Effect of Lane Width, Shoulder Width and Shoulder Type on Highway Safety, in State of the Art Report Number 6: Relationship Between Safety and Key Highway Features, 1–21. Transportation Research Board, Washington, D.C.