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Safety impacts of pavement surface roughness at two-lane and multi-lane highways: accounting for heterogeneity and seemingly unrelated correlation across crash severities

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Abstract

For purposes of project evaluation, safety audits, and project appraisal, highway agencies seek to establish the relationship between road safety and road-related factors including pavement condition. In addition, agencies show interest in measuring and comparing the strength of the safety influence of pavement surface roughness across the different highway classes. To this end, this paper estimates random-parameters seemingly-unrelated negative binomial regression (RPSUNB) models to account for the unobserved heterogeneity and correlation in the crash frequency across three levels of crash severity. Also, univariate negative binomial models were estimated for both highway classes for the purposes of comparison with the RPSUNB models. It was found that at multi-lane highways, the pavement condition generally has a far more significant impact on the number of crashes compared to two-lane highways. This result could be due to the effect of risk compensation where drivers offset the safety hazard associated with inherently less safe situations by driving more carefully. For both highway classes, a number of traffic and road geometric covariates were found to significantly influence the number of crashes of various severities. In addition, the RPSUNB models outperform their univariate counterparts, thus confirming the efficacy of the former in addressing seemingly-unrelated correlation among

the three severity levels. In sum, the paper throws more light on the effects of pavement roughness on highway crashes and establishes that the influence of this crash factor differs significantly across two-lane and multi-lane roads. The results can be useful in road safety audits, evaluation of the safety impacts of past or anticipated projects that improve in pavement condition, and assessing the safety consequences of delayed pavement rehabilitation.

Keywords: Pavement condition, Two-lane highways, Multi-lane highways, Heterogeneity, Seemingly unrelated correlation, Risk compensation.

1. Introduction

In the United States, the National Highway Traffic Safety Administration (NHTSA) attributes 32,800 fatalities and 2.24 million injuries to road crashes (Pulugurtha, 2013). These crashes are caused by a number of factors related to the vehicle, the driver, the natural or built-up environment, the road pavement and geometrics, policy and legislation, or a combination of these factors (Sinha and Labi, 2007). Of these factors, those associated with road geometrics and condition are particularly of interest to highway asset managers as they fall within their direct control and can be addressed through highway projects. The American Society of Civil Engineers (ASCE, 2014) advocates a significant, sustained effort to reduce traffic crashes and related deaths and injuries through improvements in all aspects of highway system performance and advocates for the reduction of crashes by "auditing existing roadway systems to identify roadway hazards and safety improvement opportunities, and implementing highway and other engineering-related improvements proven effective in reducing the potential for, and severity of, traffic crashes."

With regard to the road engineering factors, the literature is replete with studies that have investigated the safety impacts of road geometrics such as lane width, shoulder width, vertical and horizontal alignment (Zegeer et al., 1988; Zegeer and Council, 1995; Mujalli and De ONa, 2011; Polus et al., 2005; Zhang and Ivan, 2005; Das et al., 2010; Jung et al., 2014; Gabauer and Li, 2015; Ma et al., 2015; Gabauer, 2016; Labi et al., 2017), traffic operating conditions such as traffic volume, traffic stream composition (The Scientex Corporation, 1994; Ayati and Abbasi, 2011; Konduri et al., 2003; Anastasopoulos, 2012a) and weather conditions (Huang et al., 2014). However, the safety impact of the pavement surface condition has seen relatively little research. A number of researchers determined that rougher pavements negatively impact driver and passenger wellness (Fichera et al., 2007) and safety (Sattaripour, 1977; Bester, 2003; Ihs, 2005). Early studies that found pavement condition to be an influential factor at specific highway classes such as rural highways include Lamptey (2004) and Labi (2006). Bella et al. (2012) determined that pavement condition is particularly influential in crashes that involve specific user classes such as motorcyclists. More direct impacts on safety have been established as researchers found pavement surface roughness to be an important predictor of riding comfort and safety (Pearson, 2012), truck crashes (Dong et al., 2012), and single- and multiple-vehicle crashes (Karan et al., 1976; Al-Masaeid, 1997; Tighe et al., 2000). Larson et al. (2010) went as far as to attribute 30% of annual highway fatalities to the poor condition of pavement.

Correlations between road crash severity and pavement condition were investigated by a number of past studies (Li et al., 2013; Jiang, 2012; Anastasopoulos et al., 2008; Anastasopoulos and Mannering, 2009, 2011; Anastasopoulos, 2012a, 2012b). With regard to specific distresses, Chan et al. (2008) established correlations between crash frequency and rut depth. Lindenmann (2006) found that inadequate pavement skid could increase crash frequency in certain cases.

From a wider perspective, the peculiar nature of rural two-lane roads has motivated significant research into their safety and mobility characteristics. For example, based on the premise that passing maneuvers on rural two-lane highways significantly impair highway safety and other performance attributes, Farah et al. (2009) analyzed the passing (overtaking) decisions of drivers at two-lane rural highways using data from an interactive driving simulator.

The focus of this paper is to throw more light on the impact of pavement condition on highway safety, and to discern whether there is any difference in the magnitude and direction of such impacts across multi-lane and two-lane highways. For purposes of this paper, a multi-lane highway is one that has at least two lanes in each direction but excludes freeways and expressways; a two-lane highway has only one lane in each direction. It can be reasonable to postulate that at a multi-lane highway, the crash experience arising from poor pavement condition can be influenced by availability of recovery space such as additional lanes in the same direction thus making driving behavior on such highways different from that at two-lane roadways. Furthermore, at two-lane highways, there is relatively limited space for vehicles that need to leave their traveling lane in emergency maneuvers, and therefore there is higher possibility of head-on crashes (Wang, 2008). As such, it can be hypothesized, *a priori*, that the safety impact of pavement condition will be different for two-lane compared to multi-lane roads. Published research articles on the relative safety performance between two-lane and multi-lane highways do not account for pavement condition impact differences across these two classes of highways or at best make recommendations for this to be addressed in future research (for example, Wang (2008) argued that crash analysis of highways, crash risk models should account for differences in physical features).

Another important consideration is the use of appropriate statistical methodology for modeling the crash counts that involve different levels of crash severity. The model specifications traditionally used in modeling empirical crash data, such as univariate Poisson, negative binomial, and ordered probit, is widespread in the literature and seems appropriate; however, without accounting for correlation between the different levels of crash severity, these specifications may yield outcomes that are counterintuitive. If the crash frequency models are developed separately for each level of crash severity, significant estimation error could result because such separation of the models will miss any unobserved effects at the observations (road segments) that are shared across the different levels of crash severity (Anastasopoulos et al., 2012a). For this reason, the seemingly unrelated regression model is considered preferable for modeling crash data compared to its univariate counterpart. Furthermore, many previous studies of crash count model assumed that parameters are fixed, thus failing to account for any existing heterogeneity across road segments. Such approach could result in estimation bias (Washington et al., 2010). In the recent past, there has been an increasing effort to use a variety of advanced statistical tools to account for the unobserved heterogeneity across crash observations (through the use of random parameters) and also the correlation between the crash counts across the crash severity levels (Anastasopoulos and Mannering, 2009; 2011; Anastasopoulos et al., 2012b; Barua et al., 2016; Chen and Tarko, 2014; Dinu and Veeraragavan, 2011; Garnowski and Manner, 2011; Milton et al., 2008; Russo et al., 2014; Venkataraman et al., 2011; 2013; Xiong and Mannering, 2013; Aguero-Valverde and Jovanis, 2009; Anastasopoulos et al., 2012; Barua et al., 2016; Bijleveld, 2005; Dong et al., 2014; Lee et al., 2015; Ma and Kockelman, 2006; Ma et al., 2008; Park and Lord, 2007, Song et al., 2006; Wang et al., 2011).

To address the objectives of this study, this paper presents a random-parameters seemingly-unrelated negative binomial (RPSUNB) regression model to evaluate the safety impact of pavement condition across multilane and two-lane highways. To do this, the paper models the empirical crash count data jointly across the three levels of crash severity, thus duly accounting for seemingly-unrelated correlation.

2. Methodology

In recognition of the count nature of the crash frequency data, the unobserved effects across different crash severity levels, and the existing heterogeneity across road segments, this paper investigates the use of a random-parameters seemingly unrelated negative binomial (RPSUNB) model specification to analyze the impact of pavement condition on multi-lane and two-lane highway safety. In both cases, the overdispersion parameters were found statistically significant showing an evidence that negative binomial models are preferable over Poisson models in this case. The general framework of this model specification for modeling the expected number of crashes in i^{th} road segment and k^{th} crash severity level is as follows:

$$\lambda_{ik} = \text{EXP}(\boldsymbol{\beta}_k \boldsymbol{X}'_{ik} + \varepsilon_{ik}) \qquad k = 1,2,3$$

where,

$\boldsymbol{X}_{ik}= (1,\ X_{1k},\ X_{2k}, \ldots ,\ X_{Nk})$, is the vector of independent variables

$\boldsymbol{\beta}_k= (\beta_{0k}, \beta_{1k}, \ldots, \beta_{Nk})$, is the vector of coefficients

$\text{EXP}(\varepsilon_{ik})$ is a multivariate gamma-distributed error term with mean 1 and variance α^{-1}

The k crash severity levels are fatal, injury and no-injury.

The seemingly unrelated negative binomial model has a joint probability function:

$$\text{f}(Y_{1k}, \ldots, Y_{ik}) = \sum_{m=0}^{S_k} f_{NB}(m) \prod_{i=1}^{N} f_{NB}(Y_{ik} - m)$$

where $S_k = \min(Y_{1k}, \ldots, Y_{ik})$ and for $Z_{ik} = Y_{ik} - m$

$$f_{NB}(Z_{ik}) = \frac{\Gamma(\lambda_{ik}/\alpha + Z_{ik})}{\Gamma(\lambda_{ik}/\alpha)\Gamma(Z_{ik}+1)} \left(\frac{1}{1+\alpha}\right)^{\lambda_{ik}/\alpha} \left(\frac{\alpha}{1+\alpha}\right)^{Z_{ik}}$$

where $\Gamma(.)$ is the gamma function. (please see Anastasopoulos et al., 2012; Shi et al., 2014 for details on the framework).

The Poisson regression is a limiting model of the negative binomial regression as α approaches 0. If α is significantly different from 0, the negative binomial is appropriate and if it is not, the Poisson model is appropriate (Winkelmann, 2008; Washington et al., 2010). Also, the error term ε_{ik} follows multivariate normally and independently distribution with zero mean, variance σ^2 and correlation ρ based on the unstructured correlation covariance matrix:

$$\Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho_{21} & \sigma_1\sigma_3\rho_{31} \\ \sigma_2\sigma_1\rho_{21} & \sigma_2^2 & \sigma_2\sigma_3\rho_{32} \\ \sigma_3\sigma_1\rho_{31} & \sigma_3\sigma_2\rho_{32} & \sigma_3^2 \end{bmatrix}$$

Unobserved heterogeneity arises from differences in the effects of individual independent variables across the road segments. This motivated the introduction of random parameters into the model framework. In this case, the estimated parameter should not be a fixed value but follow a distribution such as the normal or the uniform distribution. Greene (2008) described estimation procedures for incorporating random parameters in Poisson and negative binomial count-data models. The estimable parameters are then written as:

$$\boldsymbol{\beta_k} = \boldsymbol{\beta} + \boldsymbol{\omega}_k$$

Where: the term $\boldsymbol{\omega_k}$ follows some probability distribution, for example, a normal distribution with mean 0 and variance σ^2). It may be noted that a random parameter should be used only if its estimated σ^2 is significantly greater than zero, otherwise, a fixed parameter is preferred (Anastasopoulos and Mannering, 2009).

3. Data description

The study database, consisting of 1,842 highway segments, was developed by merging two independent datasets: a road pavement condition dataset and a road safety dataset. The combined data contains the historical data on vehicle crashes at highways in Indiana over a three-year period. The database was further segregated into two subsets: multi-lane highway segments (832 observations) and two-lane highway segments (1,010 observations). Each of these subsets contains pavement surface performance (in terms of the International Roughness Index (IRI)), road geometric information including the lane width, inside and outside shoulder width, vertical alignment, and horizontal alignment. A high IRI implies a poor pavement performance and vice versa. In addition, the number of vehicle crashes at each segment was established for each level of crash severity (fatal, injury and no-injury). Table 1 presents the summary statistics of the key variables.

From the crash frequency distributions by crash severity level of multi-lane and two-lane highways, it was noted that in a few rare cases, some road segments have several hundreds of vehicle crashes. During the three-year period, of the 832 multi-lane highway segments, 169 (20%)

had at least one fatal crash; 697 (84%) segments had at least one injury crash; and 746 (90%) had at least one no-injury crash. Of the 1,010 two-lane highway segments, 142 (14%) had at least one fatal crash; 794 (79%) had at least one injury crash; and 935 (93%) had at least one no-injury crash.

4. Model estimation and interpretation of results

The developed model and elasticities

The estimation results (Table 2) are presented for two sets of models: multi-lane highways and two-lane highways. Each set contains one RPSUNB model and a separate univariate negative binomial model for each crash severity level: fatal, injury, and no-injury. A confidence level of 90% was used to identify the statistically significant variables. The estimated coefficients in the table are found intuitive from an engineering standpoint. The overdispersion parameters for univariate and multivariate were found to have estimated values of 0.9097 and 0.5362, with standard errors 0.03626 and 0.02375, respectively. This result suggests that the estimation of negative binomial models in this case, is more appropriate compared to Poisson models.

Table 3, which presents the goodness-of-fit values of the developed models, indicates that the RPSUNB models are statistically superior than their univariate counterparts in terms of model overall fit and prediction accuracy. As such, the model discussion below focuses on the former. For the multi-lane models, the RPSUNB has a McFadden pseudo value (ρ^2) of 0.289 compared with 0.114, 0.217 and 0.149 for fatal, injury and no-injury crashes, respectively. For the two-lane models, the RPSUNB has ρ^2 of 0.138 compared with 0.083, 0.098 and 0.135 for fatal, injury and no-injury crashes, respectively. Interestingly, the results indicated that the multi-lane models have much higher overall fit compared to the two-lane models. From a general viewpoint, this result suggests that the geometric design, pavement condition, and traffic data can be considered more adequate predicators of multi-lane highway safety but only to a lesser extent in the case of two-lane roads. In other words, for two-lane highways, other road-related factors (such as roadside safety hazards including fences and electric poles) makes these roads more vulnerable (compared to multi-lane roads) to the adverse safety effects of other non-road safety factors such as poor weather, and impaired driver characteristics and vehicles. Such data (incorporating more variables into the model), could help explain better the crash experience at two-lane roads and give a better fit model.

The pavement performance (in terms of IRI) was found to be statistically significant in the multi-lane highway only. With regard to the no-injury crashes, the random-parameter results for the IRI model are: the estimated coefficient has a mean value of 0.0014 and standard deviation of 0.0006, which indicates that poor pavement condition (that is, high IRI) nearly always increases the expected crash frequency (the cumulative probability that the coefficients are greater than or equal to zero is 0.99). In general, a high IRI is likely to cause drivers to lose control of their vehicles, which may lead to crashes. For injury crashes at multi-lane highways, IRI was found to have fixed impacts on the expected crash frequency. With regard to fatal crashes on multi-lane highways and all three crash severity levels at two-lane highways, however, IRI was found to be statistically insignificant at the given level of confidence.

By virtue of the mathematical form of the RPSUNB model, the coefficients of the developed model are interpreted as exponents. For example, for a multi-lane highway segment with length exceeding another by 1 mile, all other variables in the model remaining the same, the number of fatal crashes is expected to be 15% higher at the former segment compared to the latter ($e^{0.1396} - 1 = 0.1498$).

Table 4 shows the computed elasticity of each estimated parameter. Elasticity refers to the percent change in the dependent variable (the number of fatal, injury, and no-injury crashes) in response to a 1% change in an independent variable.

The Pavement Condition Factor

The elasticity analysis in Table 4 suggests that a 1% increase in the pavement condition can be expected to increase the injury and no-injury crash frequencies by 0.174% and 0.128%, respectively at multi-lane highways. This result can be used to assess the safety impacts of multi-lane highway investments that increase pavement condition. In order to demonstrate the application of the developed model, for instance, recent studies (Khurshid et al., 2008; Ahmed et al., 2010; Dong and Huang, 2011) that used data from a national pavement experiment can be used. These studies provided the extent of improvement in pavement condition (in other words, decrease in IRI) arising from various rehabilitation or maintenance treatments (Table 5). Using the results of these studies as well as this one, the resulting reduction in crash frequency is estimated and presented in the table. Also, the impacts of deferred rehabilitation or maintenance, can be estimated in terms of the increased crashes that arise due to a delay in reducing the IRI.

With regard to the pavement condition factor, the analysis yielded interesting results some of which, on the surface, may be deemed unexpected. The results indicate that the strength of influence of the pavement condition on highway safety differs across the two highway classes (multi-lane and two-lane). This was an expected result. What was unexpected is that poor pavement condition was found to increase crashes at multi-lane sections but has no significant effect at two-lane highways. This seemingly counter-intuitive result could be attributed to the phenomenon of risk compensation: drivers at two-lane highways are aware of the inherently less safe nature of that highway class and therefore drive more carefully at such highways. The unsafe nature of two-lane highways is evident in the features that often characterizes this class of highways: inadequacy of recovery space, limited opportunity for vehicles that need to leave their lane for emergency maneuvers, and the possibility of head-on crashes. Risk compensation, which is synonymous or closely related to the concepts of risk homeostasis (Wilde, 1998), offset hypothesis (Segen's Medical Dictionary, 2012; Mannering, 2009; Labi 2016), or the Peltzman Effect (Peltzman, 1975), is a theory which suggests that people adjust their behavior in response to the perceived level of risk; they are more careful where they sense greater danger and less careful if they perceive less risk. As such, safety records at obviously unsafe conditions or locations often indicate, paradoxically, fewer incidents compared to those at obviously safe conditions or locations. In other areas of highway transportation, this phenomenon has been observed by Traynor (1993), Smiley (2000), and Winston et al. (2006).

Other Crash Factors

With regard to the other crash factors, the results were generally consistent with the literature, as the geometric factors were found to have significant impacts on multi-lane and two-lane highway safety. For non-fatal crashes (injury and no-injury) at multi-lane highways, segments with wide lanes were determined to have lower number of crashes compared with those with narrow lanes. It was also determined that 1% of increase in lane width will reduce expected crash frequency by 0.958% and 0.889% for injury and no-injury crashes, respectively. However, for fatal crashes at multi-lane highways and for all three crash severity levels at two-lane highways, the lane width was not found to be a significant factor. The outside shoulder width has significant impact on non-fatal crashes: widening the outside shoulder by 1% will lower injury and no-injury crashes by 1.011% and 0.636% respectively, at multi-lane highways; and by 0.315% and 0.223% at two-lane highways. With regard to the inside shoulder, the results suggest that an increase in the dimension of that feature will cause no statistically significant increase in safety at two-lane highways but significant increase in fatal crashes at multi-lane highways: a 1% increase of the inside-shoulder width will result in 0.472% reduction of expected fatal crash frequency. These findings are consistent with past research results.

In general, the results of the elasticity analysis suggest that from a purely engineering standpoint, there are three potential and feasible options to reduce the frequencies of injury and no-injury crashes on multilane highways: widening the lane, widening the outside shoulder and improving the pavement condition (lowering the IRI). In addition, for further reducing fatal crash frequency at this class of highways, the model suggests that widening the inside shoulder can be a feasible countermeasure. For two-lane highways, the options seem to be relatively fewer, as the model suggests that widening outside shoulder could potentially reduce injury and no-injury frequencies. However, as discussed previously, it is found that other information is required to estimate more reliable models for two-lane roads. Figure 1 helps visualize the elasticities of crash frequency with respect to the crash factors for the different crash severity levels.

5. Summary and concluding remarks

Highway safety literature is replete with the use of model specifications that may not adequately account for unobserved heterogeneity and correlation between the crash counts across the three levels of crash severity. As such, many previous studies on crash count modeling assumed that the model parameters are fixed, an unduly restrictive assumption that fails to account for any existing heterogeneity across road segments and could result in estimation bias. In addition, most past research on crash modeling did not account for the different effects of pavement condition across multi-lane and two-lane highways. In order to address these issues, random-parameters seemingly unrelated negative binomial regression models (RPSUNB) were estimated in this paper. The information for the analysis included pavement surface roughness data in order to explore empirically the relationship between pavement condition and safety, and to compare the nature of this relationship across multi-lane and two-lane highways. In addition, univariate negative binomial models were also estimated for both highway classes.

The results suggest that the RPSUNB models perform better than the univariate models in predicting crash frequency at two-lane and multi-lane highways. This results seems to support Anastasopoulos et al (2012)'s findings which used multivariate tobit models. Secondly, the pavement condition was found to have significant impact on the number of injury and no-injury crashes at multi-lane highways but no statistically significant impact on two-lane highway crash frequency. The results can be used by an agency to estimate the safety impacts of projects that involve different work types (such as resurfacing, patching, and overlays) on flexible or concrete pavements, because such projects cause a reduction in the surface roughness. The results can also be useful when carrying out road safety audits, evaluating the safety impacts of past or anticipated projects that improve in pavement condition, and assessing the safety consequences of delayed improvements of the pavement surface condition (roughness).

Thirdly, the results indicate that the strength of influence of the pavement condition on highway safety differs across the two highway classes (multi-lane and two-lane): poor pavement condition was found to increase crashes at multi-lane sections but no significant effects at two-lane highways. This seemingly counter-intuitive result can be attributed to risk compensation: drivers at two-lane highways are aware of the inherently less safe nature of that highway class and therefore drive more carefully at such highways. The unsafe nature of two lane highways is evident in the obvious inadequacy of recovery space, the limited space for vehicles that need to leave the road for emergency maneuvers, and the possibility of head-on crashes.

Fourth, consistent with road safety literature, a number of traffic and road geometric covariates were found to significantly influence the number of crashes, the degree of impact depending on the covariate under consideration and the crash severity level in question. The results of the elasticity analysis suggest that from a purely engineering standpoint, there are three potential and feasible options to reduce the frequencies of injury and no-injury crashes on multilane highway: widening the lane, widening the outside shoulder and improving the pavement condition (lowering IRI). Also, reducing fatal crashes on multi-lane highway, the model suggests that widening the inside shoulder would be a potential by feasible treatment. For two-lane highways, the model suggests that widening outside shoulder could potentially reduce the frequencies of injury and no-injury crashes. Moreover, the estimated models indicate that as the annual average daily traffic (in the form of natural logarithm) increases by 1%, the expected crash frequency will increase by 5.914%, 6.924% and 6.537% for fatal, injury and no-injury crashes, respectively, on multi-lane highway; and will increase by 2.171%, 7.132% and 6.414% for fatal, injury and no-injury crashes, respectively, on two-lane highway.

Overall, the RPSUNB models were found to outperform their univariate counterparts, thus confirming the efficacy of the former in addressing the seemingly-unrelated correlations that exist among the three crash severity levels. The paper not only throws more light on the pavement condition effects on highway crashes but also establishes that the influence of this crash factor differs significantly across two-lane and multi-lane roads. The results of this paper can be useful in assessing maintenance policy, highway project appraisal from safety perspectives such as evaluating the safety impacts of improved pavement condition, and in quantifying the safety consequences of delayed pavement maintenance, rehabilitation or reconstruction. Future work could include the investigation of the safety impacts of pavement condition in terms of other indicators such as skid number, rutting, faulting, potholing, and other distresses.

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Table 1: Descriptive statistics of key variables

	Mean	Std Dev	Minimum	Maximum
Multi-lane highway				
Total number of fatal crashes	0.271	0.661	0	7
Total number of injury crashes	9.323	25.330	0	243
Total number of non-injury crashes	34.568	96.523	0	1272
Segment length in miles	5.819	3.548	0.400	26.550
Average annual daily traffic (in 10,000s)	2.614	1.934	0.254	12.865
Lane width in ft.	11.994	0.750	8.290	18
Outside shoulder width in ft.	9.750	1.969	0	14
Inside shoulder width in ft.	4.222	2.189	0	18
Median width in ft.	50.060	19.534	0	99
IRI (in/mile)	91.792	43.649	46	363
Two-lane highway				
Total number of fatal crashes	0.157	0.415	0	4
Total number of injury crashes	3.403	4.790	0	55
Total number of non-injury crashes	11.822	17.585	0	292
Segment length in miles	5.623	2.664	0.560	16.610
Average annual daily traffic (in 10,000s)	0.607	0.484	0.027	5.375
Lane width in ft.	12.935	2.594	9	26.520
Outside shoulder width in ft.	3.967	2.190	0	12
Median width in ft.	1.314	5.387	0	51.870
IRI (in/mile)	103.287	45.803	54	304

Table 2 (a): Univariate NB and RPSUNB models for multi-lane highway safety

Variables	Univariate models				RPSUNB models			
	Coefficient Estimates	**Standard error**	**90% credible interval**	**p-value**	**Coefficient Estimates**	**Standard error**	**90% credible interval**	**p-value**
Multi-lane highway								
Constant [FAT]	–8.0769	1.320	(-10.247, -5.9067)	<0.0001	–7.8661	1.099	(-9.7347, -5.9955)	<0.0001
Constant [INJ]	–4.2817	0.794	(-5.5967, -2.9529)	<0.0001	–4.3921	0.767	(-5.6649, -3.1391)	<0.0001
Constant [NINJ]	–2.8144	0.769	(-4.0537, -1.5826)	0.0002	–3.0183	0.697	(-4.1581, -1.8691)	<0.0001
Segment length in miles [FAT]	0.1517	0.018	(0.1223, 0.1811)	<0.0001	0.1396	0.012	(0.1186, 0.1581)	<0.0001
Segment length in miles [INJ]	0.1662	0.010	(0.1492, 0.1833)	<0.0001	0.1658	0.009	(0.1507, 0.1814)	<0.0001
Segment length in miles [NINJ]	0.1595	0.010	(0.1434, 0.1758)	<0.0001	0.1593	0.009	(0.1444, 0.1743)	<0.0001
Natural log. of AADT [FAT]	0.6130	0.137	(0.3882, 0.8377)	<0.0001	0.5947	0.115	(0.4000, 0.7910)	<0.0001
Natural log. of AADT [INJ]	0.7103	0.057	(0.6155, 0.8040)	<0.0001	0.6963	0.059	(0.5994, 0.7941)	<0.0001
Natural log. of AADT [NINJ]	0.6531	0.051	(0.5714, 0.7357)	<0.0001	0.6574	0.051	(0.5730, 0.7419)	<0.0001
Lane width in ft. [INJ]	–0.1045	0.051	(-0.1892, -0.0202)	0.0415	–0.0799	0.046	(-0.1557, -0.0037)	0.0845
Lane width in ft. [NINJ]	–0.0912	0.050	(-0.1708, -0.0117)		–0.0742	0.043	(-0.1462, -0.0036)	0.0839
Outside shoulder width, ft. [INJ]	–0.0973	0.019	(-0.1284, -0.0661)	<0.0001	–0.1037	0.018	(-0.1329, -0.0744)	<0.0001
Outside shoulder width, ft. [NINJ]	–0.0600	0.018	(-0.0885, -0.0316)	0.0005	–0.0653	0.017	(-0.0927, -0.0378)	<0.0001
IRI (in/mile) [INJ]	**0.0016**	<0.001	(0.0002, 0.0031)	0.0643	**0.0019**	<0.001	(0.0004, 0.0034)	0.0373
IRI (in/mile) [NINJ]	**0.0013**	<0.001	(0.0000, 0.0027)	0.0932	**0.0014**	<0.001	(0.0002, 0.0028)	0.0615
(*Standard dev. of parameter distribution*)					(*0.0006*)	(<0.001)		
Inside shoulder width in ft. [FAT]	-0.1274	0.045	(-0.2008, -0.0541)	0.0042	-0.1118	0.034	(-0.1696, -0.0545)	0.0014
Covariance matrix								
$\sigma^2[FAT]$					2.983			
$\sigma^2[INJ]$					2.583			
$\sigma^2[NINJ]$					0.884			
$\rho[FAT/INJ]$					0.849			
$\rho[FAT/NINJ]$					0.133			
$\rho[INJ/NINJ]$					0.126			

AADT – Annual average daily traffic
FAT, fatal crashes; INJ, injury crashes; NINJ, no-injury crashes.
Variables shown are statistically significant at 90% level of confidence.
1 ft. = 0.3048 meters. 1 mile = 1.609 km

Table 2 (b): Univariate NB and RPSUNB models for two-lane highway safety

Variables	Univariate models				RPSUNB models			
	Coefficient Estimates	Standard error	90% credible interval	p-value	Coefficient Estimates	Standard error	90% credible interval	p-value
Two-lane highway								
Constant [FAT]	–4.8826	0.961	(-6.5166, -3.2733)	<0.0001	–4.8693	0.976	(-6.4748, -3.2637)	<0.0001
Constant [INJ]	–6.6828	0.370	(-7.3104, -6.0589)	<0.0001	–6.6327	0.368	(-7.2382, -6.0272)	<0.0001
Constant [NINJ]	–4.7704	0.296	(-5.2484, -4.2943)	<0.0001	–4.7373	0.303	(-5.2358, -4.2387)	<0.0001
Segment length in miles [FAT]	0.1319	0.027	(0.0864, 0.1778)	<0.0001	0.1356	0.028	(0.0901, 0.1812)	<0.0001
Segment length in miles [INJ]	0.1382	0.012	(0.1190, 0.1584)	<0.0001	0.1400	0.011	(0.1224, 0.1576)	<0.0001
Segment length in miles [NINJ]	0.1411	0.010	(0.1240, 0.1577)	<0.0001	0.1399	0.010	(0.1241, 0.1558)	<0.0001
Natural log. of AADT [FAT]	0.2617	0.109	(0.0792, 0.4469)	0.0186	0.2575	0.111	(0.0759, 0.4390)	0.0197
Natural log. of AADT [INJ]	0.8529	0.043	(0.7808, 0.9250)	<0.0001	0.8459	0.042	(0.7765, 0.9153)	<0.0001
Natural log. of AADT [NINJ]	0.7645	0.035	(0.7089, 0.8203)	<0.0001	0.7608	0.035	(0.7027, 0.8189)	<0.0001
Outside shoulder width, ft. [INJ]	-0.0795	0.015	(-0.1052, -0.0544)	<0.0001	–0.0796	0.014	(-0.1035, -0.0559)	<0.0001
Outside shoulder width, ft. [NINJ]	–0.0574	0.013	(-0.0780, -0.0367)	<0.0001	–0.0562	0.012	(-0.0767, -0.0358)	<0.0001
Covariance matrix								
$\sigma^2[FAT]$					1.091			
$\sigma^2[INJ]$					0.978			
$\sigma^2[NINJ]$					1.018			
$\rho[FAT/INJ]$					0.607			
$\rho[FAT/NINJ]$					0.112			
$\rho[INJ/NINJ]$					0.161			

AADT – Annual average daily traffic

FAT, fatal crashes; INJ, injury crashes; NINJ, no-injury crashes.

Variables shown are statistically significant at 90% level of confidence.

1 ft. = 0.3048 meters. 1 mile = 1.609 km

Table 3: Goodness-of-fit of the univariate NB and RPSUNB models

Road Functional Class	Multi-lane Highways				Two-lane Highways			
Model Specification	Univariate NB			RPSUNB	Univariate NB			RPSUNB
Crash Severity Level	FAT	INJ	NINJ	ALL	FAT	INJ	NINJ	ALL
$McFadden\ pseudo\ \rho^2$	0.114	0.217	0.149	0.289	0.083	0.098	0.135	0.138
N	832	832	832	832	1010	1010	1010	1010

FAT, fatal crashes; INJ, injury crashes; NINJ, no-injury crashes. ALL: all crash severity levels estimated simultaneously.

Table 4: Elasticities of the estimated RPSUNB regression parameters

Variables	Elasticity (%) Multi-lane highway	Elasticity (%) Two-lane highway
Segment length in miles [FAT]	0.812	0.762
Segment length in miles [INJ]	0.964	0.787
Segment length in miles [NINJ]	0.927	0.786
Natural logarithm of AADT [FAT]	5.914	2.171
Natural logarithm of AADT [INJ]	6.924	7.132
Natural logarithm of AADT [NINJ]	6.537	6.414
Lane width in ft.[INJ]	–0.958	
Lane width in ft. [NINJ]	–0.889	
Outside shoulder width in ft. [INJ]	–1.011	–0.315
Outside shoulder width in ft. [NINJ]	–0.636	–0.223
IRI (in/mile) [INJ]	0.174	
IRI (in/mile) [NINJ]	0.128	
Inside shoulder width in ft. [FAT]	–0.472	

AADT – Annual average daily traffic

FAT, fatal crashes; INJ, injury crashes; NINJ, no-injury crashes. 1 ft. = 0.3048 meters.

Table 5: Improvements in pavement condition and safety due to rehabilitation/maintenance treatments

Pavement surface type	Rehabilitation type	Decrease in IRI (m/km)	Decrease in IRI (in/mile)	Expected reduction in crash frequency (%)	
				INJ	NINJ
Rigid	Surface repair and HMA Overlay	0.63	39.92	7.31	5.44
	Patching of rigid pavement	0.70	44.35	8.09	6.03
	Concrete overlay of rigid pavement	0.66	41.82	7.65	5.69
Flexible	Minimal surface preparation with 2-inch recycled AC overlay	1.03	65.26	11.68	8.74
	Intensive surface preparation with 5-inch virgin AC overlay	1.18	74.76	13.26	9.95

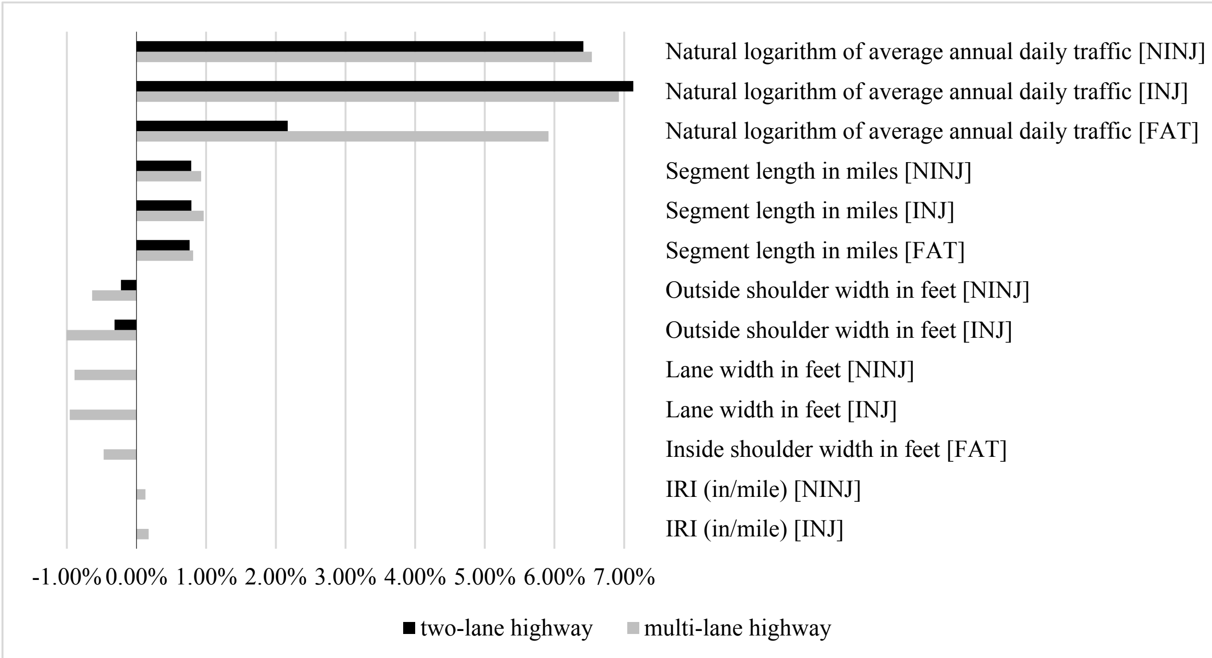

Figure 1: Tornado diagram comparing the elasticities of crash frequency with respect to significant variables across the two highway classes