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The crash severity impacts of fixed roadside objects

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Abstract

Introduction: This study analyzes the in-service performance of roadside hardware on the entire urban State Route system in Washington State by developing multivariate statistical models of injury severity in fixed-object crashes using discrete outcome theory. The objective is to provide deeper insight into significant factors that affect crash severities involving fixed roadside objects, through improved statistical efficiency along with disaggregate and multivariate analysis. *Method:* The developed models are multivariate nested logit models of injury severity and they are estimated with statistical efficiency using the method of full information maximum likelihood. *Results:* The results show that leading ends of guardrails and bridge rails, along with large wooden poles (e.g. trees and utility poles) increase the probability of fatal injury. The face of guardrails is associated with a reduction in the probability of evident injury, and concrete barriers are shown to be associated with a higher probability of lower severities. Other variables included driver characteristics, which showed expected results, validating the model. For example, driving over the speed limit and driving under the influence of alcohol increase the probability of fatal accidents. Drivers that do not use seatbelts are associated with an increase in the probability of more severe injuries, even when an airbag is activated. *Impact on industry:* The presented models show the contribution of guardrail leading ends toward fatal injuries. It is therefore important to use well-designed leading ends and to upgrade badly performing leading ends on guardrails and bridges. The models also indicate the importance of protecting vehicles from crashes with rigid poles and tree stumps, as these are linked with greater severities and fatalities.

Keywords: Injury severity; Injury prevention; Fixed-objects; Roadside hardware; Guardrails

1. Introduction

In the United States, collisions with fixed objects and non-collisions account for 19% of all reported crashes; yet they result in 44% of all fatal crashes (National Highway Traffic Safety Administration [NHTSA], 2003). Washington State follows the national average for fatalities in run-off-the-roadway single-vehicle crashes—with a great portion of run-off-the-road fatalities occurs in collisions with fixed objects at the roadside, including roadside hardware. Roadside hardware is meant to prevent fatal injuries caused by more dangerous collisions, for example collisions involving utility poles, trees, steep slopes, or cliffs. However, roadside hardware also contributes directly to fatal and disabling injury risks. Significant work has been done in the area of controlled crash-testing of roadside hardware to assess their effectiveness in run-off-the-road crashes but there remains a need for further research on the in-service performance of roadside hardware with respect to injury severities. It is still uncertain how the combination of factors often encountered in service affect injury severities (e.g., collision angles, roadway characteristics, variations in driver characteristics, environmental conditions at the time of the crash, as well as the condition of the roadside hardware and its interaction with different vehicle types; all these confounding factors may contribute to inferences not normally available from controlled crash testing).

1.1. Objectives

The objective of this paper is to perform a comprehensive analysis of the effects of various factors (e.g., driver,

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vehicle, environmental, and roadway characteristics) on injury severity in crashes with in-service roadside hardware and fixed-objects. This will show which factors are of statistically significant importance, which factors have the largest effect on severities, and whether they tend to prevent greater severities or contribute to them. The disaggregate multivariate modeling approach employed in this paper allows us to simultaneously account for the factors. This is important because simple categorization and count analysis of the number of crashes for a particular road condition versus another, can yield misleading results when other correlated covariates are not accounted for.

The results help roadway engineers identify gaps in roadside design, and improve public safety while minimizing hardware lifecycle costs. To this end, an urban, system-wide model of in-service performance of roadside hardware is developed, and the resulting relative impacts of roadside hardware on injury severity are reported. The remainder of this paper is organized as follows: previous research, methodology, empirical setting, model estimation, conclusions, and recommendations.

2. Previous research

A number of recent studies have addressed run-off-the-road crashes. General overviews of roadside safety have been introduced (Mak, 1995) and the possible adverse effects that could be caused by a policy goal of having zero fatalities have also been discussed (Elvik, 1999). In addition, numerous run-off-the-road crash studies have considered particular types of roadside hardware (e.g., bridge rails, guardrails, utility poles, sign supports, ditches and fences) and their effect on accident severity; (Good, Fox, & Joubert, 1987; Gattis, Varghese, & Toothaker, 1993; Viner, 1993; Michie & Bronstad, 1994; Viner, 1995; Kennedy, 1997; Mauer, Bullard, Alberson, & Menges, 1997; Reid, Sicking, Faller, & Pfeifer, 1997; Ray, 1999). Multivariate techniques that exploit information on in-service data on roadside hardware have emerged as useful tools (e.g., Shankar & Mannering, 1996; Shankar, Albin, Milton, & Nebergall, 2000; Lee & Mannering, 2002). These studies are focused efforts as well, with emphasis on specific corridors and interactions of vehicle type with the roadside or specific hardware (e.g., bridge rails). The Shankar et al. (2000) study illustrated the usefulness of statistically efficient techniques for severity modeling. Statistical and econometric techniques, such as the *full-information maximum likelihood nested logit* model (FIML-NL), are able to provide additional insights that are consistent with engineering knowledge drawn over several years of observation of roadside hardware performance.

However, due to the lack of usable system-wide data and the cost associated with collecting such data, little research material exists in the area of system-wide, in-service performance modeling of roadside hardware, especially in the crash severity context. This research takes a further look at injury severities in collisions with roadside hardware by examining system-wide data on in-service impacts of roadside hardware on crash severities. Statistical models are used to provide additional insight into the significance that roadside objects have on the severity of accidents. This is done by isolating fixed-object crashes and controlling for geometric features, environmental and temporal characteristics, specific state routes, vehicle characteristics, driver characteristics, and roadside hardware.

3. Methodology

The development of a severity model begins by *conditioning on the event*, to use a phrase from statistics. This means it is taken as given that an accident has occurred and the models do not predict the probability of a crash occurring. Rather, the models focus on the injury severity of observed crashes. Injury severity is separated into five categories consistent with the national Fatal Accident Reporting System (FARS) standards: *property damage only*, *possible injury*, *evident injury*, *disabling injury*, and *fatality*.

This study focuses on *driver injury severity*, as opposed to passenger injury. To study the effects of multiple factors on driver injury severity, a model is formed to predict the probability of each severity category as a function of the explanatory factors. Since the severity categories are discrete, the appropriate model structure is a discrete outcome probability model. The derivation of such models follows the derivation of discrete choice models from random utility theory (McFadden, 1974, 1981), but rather than form utility functions for choices, we form *severity propensity functions* for the severity categories. Depending on assumptions about the distribution of unobserved terms in the function, many different probability models can be derived. McFadden's (1981) generalized extreme value (GEV) model has as special cases the multinomial logit model and the nested logit model. The nested logit model is the form used in this research. Ulfarsson (2001) gives a detailed demonstration of the derivation of the multinomial logit model in the context of injury severity propensity. A discussion of injury severity propensity functions is also provided by Shankar, Mannering, and Barfield (1996), and Ulfarsson and Mannering (2004), to name two examples.

It could be questioned why this study uses models for unordered categorical variables rather than ordered categorical variables, since injury severity is clearly ordered from the least severe to the most severe. The reason is greater flexibility in specification. Ordered models place a restriction on the effects of the explanatory factors, causing those factors to either increase the probability of greater severity (implying a reduced probability of lesser severities) or to increase the probability of lesser severity (implying a reduced probability of greater severities). This restriction is avoided by the use of unordered models, which means that a single explanatory factor can increase (decrease) the probability of both the greatest and least severe categories, implying a reduced (increased) probability of middle severities. This phenomenon can occur in injury severity modeling. For example, in the case of inclement weather, the number of low severity injury crashes goes up but the number of serious crashes can also go up (i.e., there is less middle ground).

In constructing the propensity functions, it is useful to accommodate the possibility of what can be called shared unobservable terms, or more mathematically, correlations among two or more alternative outcomes (here injury severities). The multinomial logit model assumes that the alternatives are independent—the independence of irrelevant alternatives (IIA) property. Prior research (e.g., Shankar, Mannering, & Barfield, 1996; Lee & Mannering, 2002) has shown that lower severity crashes, such as property damage only and possible injury, may share immeasurable and therefore unobserved effects (i.e., the severity categories are correlated). For example, offset crash angles in property damage and possible injury crashes may exhibit similar patterns, whereas those for higher severity crashes may follow patterns unique to more serious crashes. Unobserved effects that are shared by all injury severity categories do not affect the model. This is because the logit model depends on the difference in propensities toward the categories and when the difference is taken, any joint effect cancels out. However, effects that cause a correlation among some, but not all alternative outcomes, must be accounted for, or the model results become biased. To account for this correlation, a nested logit model is used, where the lower severity categories, property damage only and possible injury, are grouped (i.e., nested together). Their shared effects therefore cancel out, and do not bias the model coefficients. A statistical test will show if this correlation is significant or not. Fig. 1 shows the model structure, along with the conditional framework of the model. Levels 2 and 3 in Fig. 1 represent the nested logit model that is estimated in this research. Level 1 indicates the unconditional probability of a fixed-object crash occurring; statistical estimation of this level is beyond the focus of this paper.

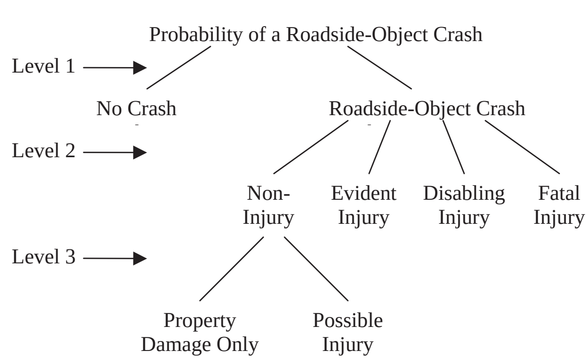

Fig. 1. A nested structure of roadside-object-involved crash severities.

Formally, the model is based on a propensity function:

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

where S_{ni} is the propensity of driver n toward injury severity category i; X_{ni} is a vector of explanatory variables (i.e. driver, vehicle, roadway, weather and temporal characteristics) along with variables indicating the type of roadside object; β_i is a vector of estimable coefficients on the explanatory variables, and ε_{ni} is a generalized extreme value distributed term of unobserved factors. Following McFadden (1981) the probability of a driver experiencing an injury severity category on the lowest level in the nest (level 3 in Fig. 1) is of the multinomial logit form:

$$P_{nj} = \frac{e^{s_{nj}}}{\sum\limits_{\forall j' \in J} e^{s_{nj'}}}, \tag{2}$$

where j is an outcome in the lower nest, J represents all outcomes on that level, and we have used $s_{nj}=X_{nj}\beta_j$. Let us now define the *inclusive value*, which represents the overall propensity of the lower nest under upper level outcome i (McFadden, 1981):

$$L_{ni} = \begin{cases} \ln\left[\sum\limits_{\forall j' \in J|i} e^{s_{nj'}}\right] & \text{if there is a nest under } i, \\ 0 & \text{if there is no nest at } i. \end{cases} \tag{3}$$

In our model (Fig. 1), we have only one lower injury severity nest (level 3), and its outcomes are represented with $J|i$. The probability of a driver being in an injury severity category in the upper nest (level 2 in Fig. 1) is then written:

$$P_{ni} = \frac{e^{s_{ni}+\theta_i L_{ni}}}{\sum\limits_{\forall i' \in I} e^{s_{ni'}+\theta_{i'} L_{ni'}}}, \tag{4}$$

Here we use i to range over I, the injury severity categories in the upper nest (level 2 in Fig. 1). Because there is only one lower level nest (level 3 in Fig. 1) in this study, there is only one inclusive value. The index i on the coefficient on the inclusive value, θ_i, is therefore not necessary and will be dropped in the following discussion. If we had nested the higher severities in a separate nest, we would require a second θ and need an index, however, our tests did not indicate the validity of such a nesting.

The coefficient θ on the inclusive value for the lower nest has to be in the interval [0,1] to ensure that (4) will be consistent with the assumptions of shared unobservable effects among property damage and possible injury (see McFadden, 1981, for a detailed mathematical proof on nest validation). This means the coefficient must be significantly larger than zero, and significantly less than one. If the coefficient is not significantly different from one the model is reduced to the multinomial logit model form and it indicates that the alternatives in the nest are not correlated.

The estimable parameters (i.e., the coefficient vector β_i and the inclusive value coefficient θ), are estimated simultaneously using maximum likelihood. This is an established method of estimating coefficients in closed-form, non-linear models such as the logit model (e.g., Greene, 2002). For non-closed-form models a Bayesian approach, such as Markov-Chain Monte Carlo, could be used.

In this research, the whole model (i.e., levels 2 and 3 in Fig. 1) is estimated simultaneously, rather than sequentially estimating the coefficients of each level. This is called *full information maximum likelihood* (FIML). The FIML estimator ensures consistent and statistically *efficient* parameter estimates (for details see Shankar et al., 1996), whereas the usual sequential estimation approach, *limited information maximum likelihood* (LIML), is statistically inefficient and results in biased estimates of standard errors. The FIML estimates of the top-level (level 2 in Fig. 1) variance-covariance matrix are unbiased, whereas LIML estimates are biased. This gives improved estimates of standard errors of the coefficients, compared to LIML, and thereby gives greater statistical confidence in significance tests of the coefficients.

4. Empirical setting

The Washington State Patrol records detailed crash information in a police report for every crash they respond to on the Washington State Highway system. The Washington State Department of Transportation accumulates and stores these police records in a database, the Washington State Master Accident Record System (MARS). Data on all single-vehicle crashes with a roadside object, occurring from January 1993 to July 1996, were read from the MARS database to form the database for this study. These crashes were then separated into urban and rural crashes because of the differences between urban and rural crashes. Information on vehicle types, contributing vehicle defects, roadway and environmental characteristics, driver contributions, and type of object struck, are included in the police records. Table 1 provides summary statistics in the urban setting for crashes with roadside objects and their severity distributions. The hardware types experiencing the greatest number of crashes were (a) concrete barrier face (32.0%), and (b) face of guardrail (16.0%). In addition, poles (including light poles, trees, utility, traffic, railway, and overhead sign poles) experienced a significant number of crashes (11.7%). The proportion of severe injury (including disabling and fatal injury) in pole crashes was approximately 6.3%, compared to 3.0% for the face of guardrail and 2.8% for crashes into the face of a concrete barrier. Overall, the proportion of severe injury in all fixed-object crashes was approximately 3.6%, while it is approximately 2.6% in all reported crashes on the state system.

It should be noted that with police data the likelihood of under-reporting exists, especially for property damage only crashes and lower severity crashes. It is expected that high severity crashes are all reported to the police. This under-reporting causes a stratification of the data, based on injury outcome, and as such will bias the alternative-specific constant for each outcome.

However, the underreporting is expected to be largely independent of the explanatory variables, which means the estimated coefficients on those variables will all remain unbiased and consistent.

5. Model estimation

A nested logit model of driver injury severity was estimated to analyze the effect of the observed driver, vehicle, roadway, and environmental factors on injury

Table 1
Summary of frequency of crashes into roadside objects on urban Washington State Department of Transportation highways between 1993 and 1996

Object Struck	Property Damage Only	Possible Injury	Evident Injury	Disabling Injury	Fatality
Retaining wall, bridge abutment, bridge column, pier or pillar	140	52	39	7	1
Wood and metal sign post, guide post	292	48	48	11	0
Pole - light, railway, utility, traffic, overhead pole, or sign box	514	114	170	44	6
Culvert end or other appurtenance in ditch, roadway ditch	287	84	52	8	0
Crash Cushion	120	29	39	8	1
Guardrail, leading end	54	24	33	4	3
Guardrail face	1,012	257	239	40	6
Concrete barrier, leading end	15	8	8	3	0
Concrete barrier face	1,981	597	452	70	16
Bridge rail, leading end	16	6	5	1	2
Bridge rail face	344	82	91	14	0
Road or construction machinery	67	12	7	3	1
Rock bank or ledge	12	2	9	0	0
Earth bank or ledge	282	105	111	24	3
Tree or stump (stationary)	144	55	66	13	9
Fence	163	28	41	7	0
Mail box	14	3	9	1	1
Other	668	140	183	39	4
Total	6,125	1,646	1,602	297	53

severity probabilities in single-vehicle crashes into fixed objects on the roadside. Likelihood ratio tests indicated that urban and rural crashes should be modeled separately, which is reasonable as most factors are significantly different between the two. In the discussion of findings, the urban model is presented. In addition, a summary is presented showing the predicted relative impacts of roadside hardware on severe injury proportions, when all other factors are controlled for. The data consisted of 9,723 observations in the urban setting, of which 6,125 (63.0%) resulted in property damage only, 1,646 (16.9%) involved possible injury, 1,602 (16.5%) involved evident injury, 297 (3.1%) involved disabling injury, and 53 (0.5%) resulted in fatalities. In comparison, the rural setting consisted of 10,640 observations, of which 6,514 (61.2%) resulted in property damage only, 1,357 (12.7%) involved possible injury, 2,191 (20.6%) involved evident injury, 474 (4.5%) involved disabling injury, and 104 (1.0%) resulted in fatalities (Holdridge, 2001).

Numerous nesting structures other than the one shown in Fig. 1 were considered and tested to find the statistically preferred structure, which has the correct specification with regards to unobserved correlation between the severity outcomes. The structure presented in this paper, and shown in Fig. 1, accounts for shared unobserved effects that cause a correlation between property damage only and possible injury. This nested structure was found to be appropriate for both urban and rural crash severities. The lower nest (property damage only and possible injury, level 3 in Fig. 1) estimation results for urban roadside crashes are presented in Table 2, and the upper nest (level 2 in Fig. 1), which includes the effect from the lower nest through the inclusive value, are presented in Table 3. These tables show that the signs of all coefficients are plausible and that the model has a good overall fit with a log-likelihood at convergence of −9,029.1, which yields a ρ^2 of 0.52. The ρ^2 is a measure of goodness-of-fit that ranges from 0 to 1, where 1 is a perfect fit. A value of 0.52 can be considered a good value, as too high values are likely to indicate that the data has too little variance to be interesting. In addition, the inclusive value coefficient is 0.477 with a standard error of 0.086. This gives a t-statistic >5 when measured against 0 and 1, showing that the inclusive value parameter is significantly different from both 0 and 1. This indicates the nesting structure cannot be statistically rejected at any reasonable level of significance. This also confirms the a priori expectation that a correlation exists between property damage only and possible injury severities. It should be noted here that a simpler non-nested model, a multinomial logit with all five severities on a single level, was also rejected by the Small and Hsiao (1985) test.

The coefficients of the nested logit model can be interpreted as differences in propensity relative to the selected base case. The lower nest (level 3 in Fig. 1) models property damage only and possible injury. Possible injury was selected as the base case. All coefficients in Table 2 are therefore viewed as in the propensity equation for property damage only; a positive (negative) value indicates an increased (decreased) propensity toward property damage only and simultaneously away from (toward) possible injury. The upper nest (level 2 in Fig. 1) is presented in Table 3 and models non-injury, evident injury, disabling injury, and fatal injury. Fatal injury was selected as the base case. The coefficients in Tables 2 and 3 are grouped in columns, one for each injury severity category. A blank value in a column indicates the coefficient on that variable in that injury severity category was not significantly different from the base case (i.e., odds-ratio = 1). A positive (negative) coefficient value in a category column indicates an increased (decreased) propensity toward that category and simultaneously away from (toward) fatal injury and all categories not affected significantly differently from fatal. The coefficients can be given odds-ratio interpretations quite easily within each

Table 2
Estimation results for the *non-injury* conditional model (lower nest)

Variable	Property Damage Only Coefficient	t-statistic
Constant	0.7387	11.51
Roadway characteristics		
Primary arterial highway, indicator	0.3359	5.02
Sag vertical curve, indicator	−0.4159	−2.04
State route 90, indicator	0.3207	2.94
State Route of crash occurrence (SR 7, 16, 500, 509 520, 522, or 167), indicator	−0.5203	−5.86
Temporal characteristics		
Crash occurred in 1993 indicator	−0.1665	−2.74
Vehicle characteristics		
Vehicle is a heavy truck, exceeding 4,536 kg in mass, indicator	0.6272	3.74
Vehicle age	0.0146	3.65
Driver characteristics		
Male driver, indicator	0.7258	12.68
No form of driver restraints used, indicator	−1.2182	−11.87
Air bag activated and seat belt used, indicator	−0.9849	−4.22
Driver inattention is primary contributing cause, indicator	0.2039	2.16
Number of passengers	0.1384	4.13
Roadside hardware characteristics		
Struck column/wall (object is a retaining wall, bridge abutment, column, pier, or pillar), indicator	−0.3279	−2.07
Struck sign post (object stuck was wood or metal sign post, or guide post), indicator	0.4888	3.04
Struck earth bank or ledge, indicator	−0.3179	−2.80
Struck a fence, indicator	0.5567	2.85

Note: The estimated coefficients are specific to the *property damage only* category and are relative to the *possible injury* category. A positive coefficient indicates an increased probability of *property damage only* and a decreased probability of *possible injury*; conversely a negative coefficient indicates a decreased probability of *property damage only* and an increased probability of *possible injury*. Indicator variables take the value 1 if the condition holds and are 0 otherwise.

Table 3
Estimation results for the *non-injury, evident injury, disabling injury, and fatal injury* (upper nest) model

Variable	Non-Injury		Evident Injury		Disabling Injury	
	Coefficient	t-statistic	Coefficient	t-statistic	Coefficient	t-statistic
Injury severity-specific constant	6.5979	11.90	4.8834	15.40	3.1848	9.16
Roadway characteristics						
Crash occurred in an underpass or tunnel, indicator	0.9382	2.40				
Crash occurred at an intersection, indicator					0.6325	2.60
Crash is intersection related, indicator					−0.7376	−2.33
Posted speed limit [mph]	*−0.0164*	*−1.95*				
Temporal/environmental characteristics						
Crash occurred in 1994, indicator	−0.1590	−2.44	−0.4730	−2.97		
Roadway icy or snowy, indicator	0.4984	4.70				
Roadway wet, indicator	0.2520	3.83				
Foggy weather, indicator	−0.4342	−2.48				
Dark but street lights on, indicator					−0.3217	−2.22
Vehicle characteristics						
Pickup truck or panel delivery truck under 4,536 kg, indicator	−0.1456	−2.29				
Defective brake were primary contributing cause, indicator			−0.6911	−2.00		
Driver characteristics						
No form of driver restraints used, indicator	−1.1839	−11.22			0.6244	4.49
Driver used only lap belt, indicator	−0.5378	−4.52				
Air bag activated but no belt used, indicator	−4.4989	−5.72	−2.3672	−3.15	−2.3672	−3.15
Air bag activated and seat belt used, indicator	−0.9852	−4.68				
Driver used only shoulder belt, indicator	−2.8923	−3.83	−2.1107	−2.71	−2.1107	−2.71
Driver is between 20 and 40 years old, indicator	0.6584	2.17	0.6584	2.17	0.6584	2.17
Driver had been drinking and ability impaired, indicator	−0.7024	−5.01			−0.6768	−3.72
Driver had not been drinking, indicator			−0.4176	−3.41		
Driver had been drinking but ability not impaired, indicator					−1.0372	−2.19
Driver under the influence of alcohol, indicator	−1.7644	−5.27	−1.7644	−5.27	−1.7644	−5.27
Over posted speed limit, indicator	−1.8426	−2.78	−1.2903	−1.96	−1.2903	−1.96
Exceeding reasonable safe speed, indicator	−0.2898	−3.45				
Driver apparently asleep, indicator	−0.8478	−6.84				
Driver inattention is primary contributing cause, indicator	−0.3791	−3.30				
Roadside hardware characteristics						
Struck sign post (object stuck was wood or metal signpost, or guidepost), indicator	0.5178	3.00				
Struck roadway ditch, culvert end or other appurtenance in ditch	0.6546	4.16				
Struck guardrail/bridge rail leading end, indicator	−2.0553	−3.89	−2.0553	−3.89	−2.0553	−3.89
Struck guardrail face, indicator			−0.2446	−2.84		
Struck face or leading end of concrete barrier, indicator			−0.2445	−2.40	−0.2445	−2.40
Struck rock bank or ledge, indicator			0.9888	2.06		
Struck roadway or construction machinery, indicator			−1.0448	−2.62		
Struck one of: tree or stump, pole (light, utility, railway, traffic, overhead), or sign box, indicator	−1.0152	−3.10	−1.0152	−3.10	−1.0152	−3.10
Inclusive value of non-injury (lower) nest	0.4773	5.56				

1. Number of observations is 9,723; Log-likelihood at zero is −18,865.39; Log-likelihood at convergence is −9,029.12; $\rho^2=0.52$.
2. *Italic*: The posted speed limit was instrumented because of possible endogeneity with injury severity.
3. All variables (except the posted speed limit which is in miles per hour) are indicators, which take the value 1 if the condition holds and are 0 otherwise.
4. Coefficients are specific to one or more of the categories: *non-injury*, *evident injury*, *disabling injury*, and are relative to the base case which is *fatal injury*.
5. A negative (positive) coefficient on a variable in an injury category indicates the relative propensity toward that category is reduced (increased).
6. A blank cell indicates the coefficient on that variable was not significantly different from the base case, *fatal injury*.
7. Coefficients that were not found significantly different across categories were restricted to be equal.

nest by taking $\exp(\beta)$, as the conditional probability within a nest is of the multinomial logit form. This odds-ratio represents the ratio between the probability of the category containing the coefficient and the probability of the base case.

The discussion is focused on findings from the in-service model on the performance of existing roadside hardware in urban contexts. This discussion will deal mainly with the impact of roadside objects on crash severity, along with a few insightful findings on roadway, vehicle, and driver characteristics.

5.1. Property damage only and possible injury

5.1.1. Roadside hardware factors

When controlling for roadway, vehicle, and driver characteristics the model shows that columns and walls (which include retaining walls, bridge abutments, bridge columns, piers and pillars) decrease the propensity toward a property damage only crash, relative to possible injury. Striking a sign post (which include wooden and metal sign posts and guide posts) or a fence increases the propensity toward a property damage only crash, while earth banks increase the propensity toward possible injury.

5.1.2. Other factors

When considering roadway characteristics, it can be seen that vertical alignment (such as if a crash occurred on a sag curve) increases the propensity toward possible injury, relative to property damage only. Injury severities in run-off-roadway crashes on Interstate 90, which has wide clear-zones, were associated with a higher propensity toward property damage only, compared with other state routes in Washington State. In terms of vehicle characteristics, heavy trucks are associated with an increase in the propensity toward property damage only, compared to lighter trucks or passenger cars. Lack of driver use of a restraint system increases the propensity toward possible injury. Air bag activation for drivers wearing seat belts is associated with a higher propensity toward possible injury. The air bags shouldn't generally inflate in minor crashes so this shows a correlation with a more significant crash. This does not indicate that air bags and seat belts cause higher injury. Male drivers experience a greater propensity toward property damage only in low severity crashes, and so do drivers with passengers. Inattention, as the primary contributing cause, was found associated with an increase in the propensity toward property damage only.

5.2. Non-injury, evident injury, disabling injury, and fatal injury

5.2.1. Roadside hardware factors

When controlling for roadway, vehicle, and driver characteristics, several roadside features were found to have significant impacts on crash severities. As stated previously, signposts (including wood or metal signposts and guide-posts) increase the propensity toward non-injury (i.e., the lower nest in the estimation). Crashing into ditches (includes ditches, culvert ends, and other appurtenances in ditches) increases the propensity toward non-injury. It is impossible to tell the difference between the numerous types of ditches and culverts. This result should therefore be viewed as an aggregate average result for this category. Striking the leading end of a guardrail or bridge rail increases the propensity toward fatal injury. Striking the face of a guardrail or bridge rail decreases the propensity toward evident injury. This variable cannot be determined for fatal and disabling injuries due to the lack of observations. The result is that striking the face of guardrails or bridge rails is associated with reduced propensities toward injuries, whereas striking a leading end is associated with an increase in the propensity toward fatal injury. Further, there is no distinction in the database between W-beam or thrie-beam guardrail types. A prior study has reported that thrie-beam hardware is associated with an increase in the probabilities of non-injury, in the context of bridge-railing crashes (Shankar et al., 2000). Crashing into a tree or a wooden pole (this category includes crashing into a tree or stump, light pole, utility pole, railway pole, traffic pole, overhead pole, or sign box) increases the propensity toward fatal injuries and indicates the significant injury prevention benefit of protecting traffic from crashes with such poles.

If the crash involved a collision with a concrete barrier, the propensities toward evident and disabling injuries are reduced. The few observations for fatal crashes are likely to cause the insignificance for that category, so the interpretation is that non-injury propensities are increased in concrete barrier collisions. Striking a rock bank (includes ledges) will increase the propensity toward evident injury, relative to the other severity types. Crashes with roadway or construction machinery are associated with a decrease in the propensity toward evident injury. This result cannot be taken to indicate the safe nature of heavy machinery. It is more likely to be the effect of lower speed since these crashes are more likely to happen in work-zones, which typically have lower speeds. Table 4 shows the relative impacts of roadside objects on severities.

5.2.2. Other factors

Turning to roadway characteristics, it is notable that crashes that occurred at intersections are associated with a higher propensity toward disabling injuries, whereas crashes that occurred away from the intersection, but are still considered intersection related, are associated with a lower propensity toward disabling injury. Accidents occurring in tunnels or underpasses are linked with a higher propensity toward non-injuries. As speed limits increase, the propensity toward non-injury decreases.

Environmental characteristics, such as slick roads (because of ice or snow), increase the propensity toward non-injury, which is likely due to increased caution exercised by drivers and generally lower vehicle speeds. Wet roadways are also associated with an increase in the propensity toward non-injury. Foggy weather tends to decrease the propensity toward non-injury (i.e., increase the propensities of injuries). Darkness with lit streetlights is associated with a decrease in the propensity toward disabling injury. Many state routes were proven significant in the model but are left out from the discussion since these variables control for the different physical characteristics specific to each roadway (i.e., these are fixed-effects that are capturing heterogeneity) and are difficult to interpret in a more general context. When considering vehicle types, pickup trucks and delivery trucks are shown to be associated with a decrease in the propensity toward non-injury. Defective brakes as the primary contributing cause is a factor associated with a decrease in the propensity toward evident injury.

Table 4
The effect of roadside objects on propensities toward injury severities

Object struck	Non-injury	Evident injury	Disabling injury	Fatality
Wood or metal sign post or guide post	↑	↓	↓	↓
Roadway ditch, culvert end, or other appurtenance in ditch	↑	↓	↓	↓
Guardrail or bridge rail Leading End	↓	↓	↓	↑
Guardrail face	↑	↓	↑	↑
Concrete barrier	↑	↓	↓	↑
Rock bank or ledge	↓	↑	↓	↓
Roadway or construction machinery struck	↑	↓	↑	↑
Tree or stump, pole (light, utility, railway, traffic, overhead), or sign box	↓	↓	↓	↑

Many driver restraint combinations were proven significant in the model. The results show that it is less effective to wear either shoulder belts or lap belts when compared to a shoulder and lap belt. In crashes where airbags activate, it is more effective to also wear seat belts. Using neither seat belts nor airbags is associated with higher injury severities.

Middle-aged drivers (between the ages of 20 and 40 years) are associated with a reduced propensity toward fatal injury. Driver violations, such as driving under the influence of alcohol, exceeding reasonable safe speed, apparently falling asleep, or inattention, are all associated with a decreased propensity toward non-injury (i.e., these drivers are more likely to suffer injuries). In particular, driving over the posted speed limit is associated with an increased propensity toward fatal injury (interpreted from a decreased propensity toward the other injury categories).

6. Conclusions

This study provides empirical analysis of injury severity in collisions with fixed roadside objects, while accounting for roadway, vehicle, environmental, temporal, and driver characteristics. The study includes collisions from the entire state route system in Washington State, but the presented results are from urban areas. This research sheds light on the importance of roadside design and provides insights into ways to decrease the severity of run-off-the-roadway crashes. Nested logit models were estimated with full information maximum likelihood to yield statistically efficient results.

Certain characteristics of roadside objects prove to be significant in high severity accidents. Beam-guardrail leading ends, bridge rail leading ends, as well as tree stumps, light poles, utility poles, railway poles, traffic poles, overhead poles, and sign boxes increase the propensity toward fatal injuries. The impacts of concrete barriers, beam-guardrail faces, and construction machinery on crashes, are to move propensities away from evident and disabling injuries (i.e., toward the non-injury category). The effect of these on fatal injuries is insignificant because of too few observations for that category. Roadside objects that are unambiguous in their effect to increase the probability of non-injury include wood and metal signposts, guideposts, and roadway ditches. The result regarding ditches is not transferable to all areas because ditches vary considerably. This result holds for the urban ditches in Washington State. Rock banks increase the propensity toward evident injury.

Though this study is insightful in terms of driver injury severity in fixed-object collisions, further research is needed to examine the injury severity of passengers involved in such crashes. Currently, this type of data is limited in content and quality, but as data becomes available this type of analysis will provide even greater understanding of fixed-object crashes. In spite of such limitations, this analysis provides a tool that can be used for design policy. In combination with national crash contexts, and other in-service analyses of roadside objects, the findings of this paper can be extended to provide an integrated assessment of roadside hardware.

7. Impact on industry

The presented models, analyzing the in-service performance of roadside hardware, show the importance of guardrail leading ends in contributing to fatal injuries. It is therefore important to use well-designed leading ends and upgrade badly performing leading ends on guardrails and bridges. The models also indicate the importance of protecting vehicles from crashes with rigid poles and tree stumps because such crashes are linked with higher severities and fatalities.

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