Analysis of Crash Severity Based on Vehicle Damage and Occupant Injuries

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In recent years, the reduction of injury crashes has been heralded as a great success. Improvements in federally mandated safety standards and advancements made by automotive industries to enhance vehicle safety can be partially credited with the decline. Now the national strategy on highway safety is to move toward zero deaths. From this vision zero perspective, one of the appropriate strategies is to manage kinetic energy in crashes and collisions—that is, to minimize the energy transferred to the human body—because the kinetic energy is responsible for occupant injuries and fatalities. Vehicle damage conditions are an unbiased indicator of kinetic energy in collisions, and injury severity is the ultimate measure of occupant risk. In this study, vehicle damage and occupant injury models were developed for single-vehicle and multiple-vehicle crashes. The results of these models provide a complete view of crash severity determinants and how they affect occupant injuries and vehicle damage. Some factors have a consistent impact across both injury severity and vehicle damage; others are contradictory. Combining information from both occupants and vehicles is valuable for an impartial evaluation of specific components in highway design; this combining also provides an accurate assessment of the impacts of occupant characteristics, driver behavior, and error on the resulting bodily injuries.

Improving traffic safety was, is, and will continue to be the first priority on the national transportation agenda. The goal has always been to reduce injuries, deaths, and economic losses from motor vehicle crashes. Some success has been achieved in recent years, thanks to significantly increased investment and collective efforts directed at transportation safety. According to NHTSA, the number of injury crashes dropped to 2.25 million in 2010 compared with 2.9 million in 2002 (*1, 2*). Because of this reduction, the safety focus has shifted from reducing the number of crashes to reducing the number of fatal and serious injury crashes; this shift led to the development of a new AASHTO National Strategic Highway Safety Plan entitled “Toward Zero Deaths” (TZD) (*3*). The appropriate strategy from a “vision zero” perspective, as Johansson suggested, is to manage kinetic energy in crashes and collisions, that is, to minimize the energy transferred to the human body (*4*). This design principle can be carried out through both highway design and innovations in automobile safety technology.

The crashworthiness of a vehicle provides the first and direct protection to occupants. A crash may reduce the vehicle to a twisted wreck, yet a good structural design can keep passenger space intrusion to a minimum. Nonetheless, damage to a vehicle may serve as an indication of the severity of passenger injury as a result of the collision. From the physical perspective, a collision is an event in which two or more (moving) objects exert forces on each other for a relatively short time, and when vehicles are involved in these collisions, the result is a measurable amount of vehicle damage and resulting bodily injuries. The extent of vehicle damage, usually coded as from very severe to none, captures the degree of external deformation caused by the impact magnitude (*5*). In crash data, the description of a vehicle’s damage severity is more objective because the damage is more visible and the notations are usually more descriptive.

However, injury severity information is usually classified on the basis of the *Model Minimum Uniform Crash Criteria* guidelines (*6*), in which crash severity attributes include fatal injury (K), suspected serious injury (A), suspected minor injury (B), possible injury (C), and property-damage-only (O) (*5*). The terms “suspected” and “possible” describe vague boundaries between injury types A, B, and C. Furthermore, the result can be heavily influenced by the accident victims’ descriptions, complaints, and reactions, which may be biased. Another issue that presents itself when injury severity is used as the dependent variable is that the injury severity model can be susceptible to complicated interrelations between human and nonhuman factors. With conventional models, each predictor is modeled independently; however, in real-life situations human factors may be confounded with highway, traffic, and environmental factors. The driver’s physical condition, experience, judgment, behavior, decisions, and acquaintance with the environment may be critical in abating one’s risk of being injured. In addition, highway and traffic engineers may be more interested in knowing the effects of highway and traffic design on injury severity without interference from human error.

Therefore, the injury severity model that uses injury severity as the dependent variable cannot reveal all the important aspects and relationships between crash severity and contributing factors. One could also conclude that the vehicle damage model that uses vehicle damage as the dependent variable cannot make a suitable substitute for the injury severity model either. By combining information provided through both of these methods it will be possible to accurately emphasize the impact of occupant characteristics, driver behavior, and human error on injury severity and objectively evaluate the physical collision force related to highway, traffic, and environmental factors. The objective of this study was to identify the association of crash injury severity and vehicle damage severity by identifying the factor or factors that are most likely to cause a specific type of vehicle damage or bodily injury and to compare the effects of a set of common factors (i.e., highway, traffic, and environmental factors) on the consequences for a vehicle or an occupant in the most harmful event.

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LITERATURE REVIEW

Crash severity models have been studied extensively in the past decades. In these models, vehicle type, a proxy variable of vehicle weight, size, speed, and crashworthiness, is often considered as a critical factor in affecting crash severity. Some studies explicitly estimated the injury severity for crashes involving sport utility vehicles (SUVs), vans, light trucks, or large trucks (*7–12*). Other studies were dedicated to investigating the consequences of collisions between different types of vehicles, such as between trucks and passenger cars, SUVs and passenger cars, and passenger cars and pickup trucks (*13–15*). The results of the studies can be complicated, depending on the type of crash and who was more vulnerable during a collision. For example, Khattak and Rocha found that SUVs have greater crashworthiness during a collision but are more likely to roll over and therefore cause more severe injuries to their occupants (*7*). Kockelman and Kweon concluded that light-duty trucks and heavy-duty trucks have greater crashworthiness. These results become more apparent in a two-vehicle crash where a heavy-duty truck's crashworthiness is more significant as the driver of the other vehicle withstands more severe injury (*11*). In a follow-up study, Wang and Kockelman used the National Automotive Sampling System's crashworthiness data system to thoroughly analyze the effects of vehicle weight and type and found that vehicle weight and type can simultaneously affect the injury outcome (*12*).

Vehicle damage is an important indicator of the magnitude of the collision energy. Compared with the abundance of information presented in the area of crash injury severity, the studies on vehicle damage are relatively sparse. For instance, Huang et al. created a binary response variable by combining both injury severity and vehicle damage indicators to identify the significant factors affecting crash severity with specific consideration of the correlations between driver and vehicle units (*16*). Conroy et al. studied whether exterior vehicle damage distribution across the front vehicle plane influenced injury severity in head-on crashes, and the results suggested significant differences in the type of object struck and the intrusion into the passenger compartment at the driver's seat location (*17*). Quddus et al. developed injury severity and vehicle damage models separately and found similar and different factors affecting the increased probability of severe injuries and motorcycle damage (*18*). The preceding research, although limited, offered valuable insight from the vehicle damage perspective.

In a different context, researchers and engineers working with automobile manufacturers constantly test their products to ensure that they meet Federal Motor Vehicle Safety Standards (FMVSS) outlined in FMVSS Title 49, Parts 571–572 (*19*). In addition, NHTSA and the Insurance Institute for Highway Safety conduct their own crash tests to ensure compliance (*20*). The popular metric of crash severity is a measure of *g*-force (acceleration) acting on the vehicle or a crash dummy, or some measure of change in vehicle velocity over the duration of the crash event (Δv) (*21*). The purpose of crash tests is to ensure that safety devices such as passenger restraints, front and side airbags, laminated windshields, crumple zones, and collapsible steering columns are performing as intended. These "destroyable" features serve to absorb or deflect the impact energy caused by collisions and minimize the forces transferred to occupants.

However, these test situations do not accurately simulate real-world scenarios because the crash dummies do not make cognitive decisions such as whether to wear safety restraints or drive under the influence of alcohol or drugs. Moreover, tests are usually conducted in a controlled laboratory environment that differs from the real-world situations in which crashes occur. Confirmed by Council and Stewart, who explored the relationship between occupant risk as measured in crash tests (50-ms longitudinal and lateral forces to the vehicle) and driver injury, it was found that a strong relationship between the two was absent (*21*). The actual crash data, both injuries and vehicle damage, will certainly disclose critical information that may not be available in laboratory testing conditions.

DATA COLLECTION AND PREPARATION

For the study, crash injury severity and vehicle damage information was collected from 3-year crash data between 2008 and 2010. According to the data set, a total of 14,095 crashes occurred in Madison, Wisconsin, during this period. With the *Model Minimum Uniform Crash Criteria* guidelines or KABCO scale, the injury severities of these incidents were categorized into five levels: O (no apparent injury), C (injury possible), B (suspected minor injury), A (suspected serious injury), and K (fatal injury). For vehicle damage, the incidents were categorized into six levels: NONE (no damage), V MNR (cosmetic damage or very minor damage), MNR (dents but no creased metal), MOD (broken or missing parts), SVR (not drivable, but salvageable), and V SVR (total loss). Table 1 shows the levels and frequency of injury severity and vehicle damage. In order to obtain sufficient observations in each category, crash injury severities were aggregated into three types: O, B, and C; K; and A. Likewise, vehicle damage was aggregated into three types: none or minor, which combines none, very minor, and minor; moderate; and severe, which combines severe and very severe.

The crash data were split into single-vehicle (SV) and multi-vehicle (MV) crashes. Of these, 2,286 (16.22%) accidents were SV crashes and 11,809 (83.78%) were MV crashes. The independent variables were divided into five categories—human factors, highway and traffic factors, accident characteristics, environmental factors, and vehicle factors—as shown in Table 2.

Human factors include occupant characteristics and driver behavior. Occupant characteristics such as gender and the use of safety constraints were applied to the occupants who sustained the most harmful injuries. Driver behavior represents any possible contributing circumstances to the accident that a driver may have had, as determined by

TABLE 1 Frequency of Injury Severity and Vehicle Damage

Severity or Damage Level	Description	Count	Percent
Injury Severity			
O	Property damage only	9,736	69.07
C	Possible injury	3,698	19.14
B	Nonincapacitating injury	1,383	9.80
A	Incapacitating injury	247	1.75
K	Fatal injury	31	0.24
Vehicle Damage			
NONE	No damage	302	2.14
V MNR	Very minor damage	810	5.75
MNR	Minor damage	2,422	17.18
MOD	Moderate damage	6,538	46.39
SVR	Severe damage	3,083	21.87
V SVR	Very severe damage	792	5.31
MISS	Missing value	148	1.36

TABLE 2 Variable Definitions and Frequency

			SV Crash		MV Crash	
Variable	Description	Variable Type	Count	Percent	Count	Percent
Injsvr	Injury severity of crash	Categorical				
	(O) Property damage only		1,216	53.19	8,520	72.15
	(B + C) Type B or C		919	40.20	3,162	26.78
	(A + K) Type A or killed		151	6.61	127	1.08
Vehdmg	Vehicle damage	Categorical				
	None, very minor, or minor		706	30.88	2,828	23.95
	Moderate		683	29.88	5,855	49.58
	Severe or very severe		755	33.03	3120	26.42
Human Factors						
Alcflag	Driver had been drinking	Indicator	342	14.96	437	3.70
Drugflag	Driver had been taking drugs	Indicator	36	1.57	52	0.44
Young	Driver age was under 25	Indicator	1,010	44.18	3,646	30.87
Old	Driver age was above 55	Indicator	239	10.45	1,860	15.75
Female	Driver was a female	Indicator	747	32.68	5,349	45.30
Safety constraints	Driver used safety constraints	Indicator	2,173	95.06	11,441	96.88
Speed	Speed relevant factors	Indicator	851	37.23	1,612	13.65
Rule violation	Violating the traffic rules	Indicator	434	18.99	4,135	35.06
Reckless driving	Reckless driving	Indicator	46	2.01	2,735	23.16
Highway and Traffic Factors						
Roadhor	Horizontal curve	Indicator	531	23.23	919	7.78
Roadvert	Vertical curve	Indicator	502	21.96	1,639	13.88
Debris	Debris prior to accident	Indicator	20	0.87	20	0.17
Visibility	Visibility obscured	Indicator	25	1.09	181	1.53
Trfcont	Type of traffic control	Categorical				
	Traffic signal		189	8.27	1,820	15.41
	Two-way traffic control		26	1.14	752	6.37
	Four-way traffic control		9	0.39	188	1.59
	Yield sign or no traffic control		792	34.65	4,481	37.95
	No traffic control		1,270	55.55	4,568	38.68
Hwyclass	Highway classification	Categorical				
	Urban city highway		1,564	68.39	8,214	69.56
	Urban state highway		573	25.05	3,413	28.90
	Urban Interstate highway		150	6.56	182	1.54
Accident Characteristics						
Guardrail	Struck guardrail	Indicator	102	4.46	na	na
Median barrier	Struck median barrier	Indicator	115	5.03	na	na
Bridge	Accident caused by circumstances of bridge (parapet, pier, rail)	Indicator	17	0.74	na	na
Ditch	Struck ditch	Indicator	37	1.62	na	na
Tree	Struck tree	Indicator	272	11.90	na	na
Pole	Struck pole (traffic sign or utility pole)	Indicator	122	5.34	na	na
Jackknife	Vehicle jackknifed	Indicator	3	0.13	na	na
Overturn	Vehicle overturned	Indicator	89	3.89	na	na
Mnrcoll	Manner of collision	Categorical				
	Angle		na	na	3,612	30.59
	Head-on		na	na	222	1.88
	Rear-end		na	na	5,017	42.48
	Sideswipe–same direction		na	na	2,117	17.93
	Sideswipe–opposite direction		na	na	354	3.00
	No collision		na	na	487	4.12

(continued on next page)

TABLE 2 *(continued)* **Variable Definitions and Frequency**

Variable	Description	Variable Type	SV Crash Count	SV Crash Percent	MV Crash Count	MV Crash Percent
Environmental Factors						
Lgtcond	Light condition	Indicator				
	Dark		317	13.87	795	6.73
	Light (street light)		825	36.09	2,398	20.31
Roadcond	Road condition	Indicator				
	Ice		148	6.47	596	5.05
	Snow		380	16.62	1,375	11.64
	Wet		344	15.05	1,948	16.50
Vehicle Factors						
Unitype	Vehicle types in crashes	Categorical				
	Light truck with PC		na	na	2,220	18.80
	Heavy truck with PC		na	na	401	4.40
	Light truck with light truck		na	na	141	1.19
	Light truck with heavy truck		na	na	56	0.47
	Heavy truck with heavy truck		na	na	15	0.13
	PC with PC		na	na	8,433	71.41
Vehtype	Vehicle types in SV crashes	Categorical				
	Light truck		1,320	57.74	na	na
	Heavy truck		183	8.01	na	na
	Passenger car		57	2.49	na	na

NOTE: PC = passenger car; na = not applicable.

the responding police officer. Of prime interest to engineers may be the highway and traffic factors, which include highway geometric characteristics and traffic control. In addition, some possible contributing circumstances of the roadway based on officers' opinions were included. The accident characteristics describe the vehicle hitting a fixed object, a not-fixed object, or no collision. Because of the extremely small number of pedestrian, bicyclist, and motorcyclist collisions, they were removed from the data set (0.8% of the total data). The manner of collision describes the orientation in which vehicles collided in the crash and the unit type indicates the vehicle classes that collided with each other. Environmental factors were investigated to determine the correlation between weather variables and road surface condition by using a Pearson correlation test. The weather condition factor was excluded in the final model because the correlation between these two factors is very strong ($\rho > 0.8$).

METHODOLOGY

Injury severity and vehicle damage were separately modeled to explore the factors affecting the overall crash severity measured by occupant and vehicle. Four sets of models are specified in this paper: SV injury severity model, MV injury severity model, SV vehicle damage model, and MV vehicle damage model. One of the major differences between the injury severity model and vehicle damage model is that the vehicle damage model did not contain any human factors; instead, vehicle damage is an explanatory variable in the injury severity model. The relationships between dependent variables and independent variables for the four models are as follows:

- SV crash injury severity = *f* [human factors, highway and traffic factors, environmental factors, accident characteristics (accdtype), vehicle factors (vehtype, vehdmg)],
- MV crash injury severity = *f* [human factors, highway and traffic factors, environmental factors, accident characteristics (mnrcoll, unitype), vehicle factors (vehdmg)],
- SV crash vehicle damage = *f* [highway and traffic factors, environmental factors, accident characteristics (accdtype), vehicle factors (vehtype)], and
- MV crash vehicle damage = *f* [highway and traffic factors, environmental factors, accident characteristics (mnrcoll, unitype)].

To account for the ordinal nature of the crash severity data, ordered probability models (both logistic and probit) are used. The ordered probability models are derived by defining an unobserved latent variable *U*, which is typically specified as a linear function for each observation:

$$U = \boldsymbol{\beta}'\mathbf{X} + \varepsilon \tag{1}$$

where

$\mathbf{X}$ = vector of independent variables determining discrete ordering for each observation,
$\boldsymbol{\beta}$ = vector of estimable parameters, and
ε = error term.

Observed ordinal injury severity data (y) for each observation are defined (*22*) as

$$\begin{aligned} y &= 1 \quad \text{if } U \le \mu_1 \\ y &= 2 \quad \text{if } \mu_1 \le U \le \mu_2 \\ y &= 3 \quad \text{if } \mu_2 \le U \le \mu_3 \\ &\dots \\ y &= I \quad \text{if } U \le \mu_{I-1} \end{aligned} \tag{2}$$

where the μ's are estimable thresholds that define y and I is the highest integer-ordered response. If the random error term ε is assumed to follow a standard normal distribution, the model is an ordered probit model. The probability of each category can be written as follows:

$$\text{prob}(y = i) = \Phi(\mu_i - \boldsymbol{\beta}'\mathbf{X}) - \Phi(\mu_{i-1} - \boldsymbol{\beta}'\mathbf{X}) \tag{3}$$

where Φ(•) is the cumulative standard normal distribution.

If the error term is instead assumed to be logistically distributed across observations, it is an ordered logit model. Because the default coefficient estimate of ordered logistic models is the log odds ratio and it is difficult to explain how changes in explanatory variables affect the outcome probabilities (*8*), the ordered probit model was used in this study.

The interpretation of parameters **β** is as follows: positive signs indicate higher injury severity or vehicle damage as the value of associated variables increases, negative signs suggest the converse. The relationship must be compared against the range between thresholds μ's in order to determine the most likely injury or vehicle damage classification for a particular crash (*11*).

A measure of the goodness of fit can be obtained by calculating (*22*)

$$R^2 = \frac{\text{SSR}}{\text{SST}} \tag{4}$$

where SSR represents the variation of the fitted regression line $\hat{y}_i$ around the mean $\bar{y}$:

$$\text{SSR} = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 \tag{5}$$

and SST represents the total variation, the variation of each observation around the mean $\bar{y}$:

$$\text{SST} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{6}$$

The R^2 can be interpreted as the proportion of the total variance explained by **X**.

MODEL RESULTS

In the SV crash results in Table 3, the coefficients lead the utility function to increase or decrease on the basis of the magnitude of the value. The positive values can lead to a possible increased injury severity or vehicle damage and negative values can lead to a possible reduced risk of injury severity or vehicle damage. Only variables that were considered significant to a level of 5% are included in the following tables. Some statistically insignificant variables may be included for comparison between injury severity and vehicle damage models.

In the SV crash results there are few findings that defy conventional wisdom or logical explanations. One exception is that dark conditions or dark-with-street-light conditions may decrease the possibility of a more severe injury but increase the possibility of vehicle

TABLE 3 Coefficient Estimates for SV Injury Severity and Vehicle Damage Models

Variable	Coeff.	SE	z	$P > \lvert z \rvert$	Variable	Coeff.	SE	z	$P > \lvert z \rvert$
Injury Severity					Vehicle Damage				
Human factors					Highway and traffic factors				
Alcflag	0.23	0.08	2.92	<0.01	Horizontal curve	0.14	0.07	2.03	0.04
Rule violation	0.74	0.07	10.60	<0.01	Environmental factors				
Safety constraints	–0.76	0.14	–5.91	<0.01	Dark	0.29	0.09	3.27	<0.01
Environmental factors					Light	0.20	0.07	3.02	<0.01
Dark	–0.19	0.08	–2.35	0.02	Ice road	–0.48	0.11	4.46	<0.01
Light	–0.33	0.06	–5.16	<0.01	Snow road	–0.42	0.07	5.59	<0.01
Ice road	–0.35	0.12	–2.99	<0.01	Accident characteristics				
Snow road	–0.37	0.08	–4.64	<0.01	Ditch	0.64	0.21	3.09	<0.01
Accident characteristics					Guardrail	0.45	0.13	3.38	<0.01
Ditch	0.47	0.20	2.33	0.02	Median barrier	0.59	0.12	4.88	<0.01
Guardrail	*–0.15*	*0.15*	*–1.01*	*0.31*	Overturn	0.89	0.16	5.56	<0.01
Median barrier	*0.13*	*0.13*	*0.98*	*0.33*	Pole	0.61	0.12	4.91	<0.01
Overturn	0.38	0.13	2.81	<0.01	Tree	0.78	0.09	8.64	<0.01
Pole	–0.31	0.13	–2.46	0.01	Bridge	0.83	0.29	2.86	<0.01
Highway class					Highway class				
Urban state highway	*0.05*	*0.07*	*0.70*	*0.49*	*Urban state highway*	*0.05*	*0.08*	*0.70*	*0.49*
Urban Interstate highway	–0.54	0.13	–4.20	<0.01	Urban Interstate highway	–0.25	0.12	–2.10	0.04
Urban city highway		Base level			Urban city highway		Base level		
Vehicle damage					Vehicle factors				
Moderate damage	–0.50	0.07	–7.10	<0.01	Vehicle type				
Severe damage	*–0.10*	*0.07*	*–1.52*	*0.13*	Light truck	–0.20	0.10	2.08	0.04
None–minor damage		Base level			Heavy truck	–1.76	0.20	8.78	<0.01
					Passenger car		Base level		

NOTE: Italics indicate that the variable is not statistically significant at 5% level; coeff. = coefficient; SE = standard error. Summary statistics for injury severity: log likelihood, −1,696.10; likelihood ratio chi-square (*16*), 417.00; probability > chi-square, < .01; R^2, .11. Thresholds: $\mu_1 = -0.94$; $\mu_2 = 0.70$. Summary statistics for vehicle damage: log likelihood, −1,384.23; likelihood ratio chi-square (*16*), 277.95; probability > chi-square, <.01; R^2, .09. Thresholds: $\mu_1 = -0.77$; $\mu_2 = 0.43$.

damage. From Table 3, it is found that human factors have a great influence on the injury severity outcome. Among all the human factors, using alcohol or violating traffic rules considerably increases the severity of injury, and using safety constraints (seat belts) substantially reduces the possibility of more severe injuries. Vehicle damage, as an explanatory variable in the injury model, is negatively correlated with injury severity. In other words, injury severities decrease when vehicle damage increases. Compared with the baseline of none or minor damage, moderate vehicle damage appears to be associated with the considerable decrease in injury severity, whereas the severe damage factor is not statistically significant. A plausible reason is that the structural design of the vehicle can protect occupants from sustaining injuries, but limitations exist and violent collisions may reduce the effectiveness of the structural design.

Compared with the reported injury severity, the after-crash vehicle conditions can be a more unbiased reflection of the violence of the collision. Focusing on highway design characteristics, the comparison between the results from the injury severity and vehicle damage models shows similarities and differences. In SV crashes, the comparison of urban city highways with urban state highways shows an increase in both injury severity and vehicle damage, but the result is not statistically significant. Despite the greater vehicular speed on Interstate highways, Interstate highways show a decrease of SV injury severity and vehicle damage. This finding may be attributed to the high design standards as well as low roadside hazards of Interstate highways compared with other highway classes.

In addition, one of the most interesting findings is that striking guardrails and poles may lead to more severe vehicle damage but less severe injuries. The explanation is found in the breakaway design of roadside objects such as poles and flexible protections such as guardrails. For more rigid fixed objects such as bridges or ditches, both vehicles and occupants sustain a more severe outcome. Trees and bridges increase the possibility of more severe vehicle damage, but their effects are not statistically significant for injury severity. Vehicles were found to withstand more severe damage in the presence of horizontal curves, though none of the highway and traffic factors were determined to be statistically significant in the SV injury severity models for comparisons. Therefore, performing respective analyses for injury severity and vehicle damage is valuable for an impartial evaluation of the design components of the highway (i.e., cross section, alignment, and roadside design standards). Moreover, nonhuman factors may become more statistically significant in the vehicle damage model than in the injury severity model because of the dominant effects of human factors.

Different perspectives of the injury severity and vehicle damage models imply that the management of kinetic energy in crashes requires following the design principle of integration and separation, that is, integrating compatible design elements and separating incompatible ones (*4*). For example, different design alternatives including the placement of crash barriers or relocation may be applied to protect occupants under the circumstances of bridges (parapet, pier, rail, etc.) or trees. In addition, special protective design needs should be considered in the proximity of horizontal curves.

In the MV injury severity results shown in Table 4, similar conclusions can be drawn about the effect of human factors on injury severity; however, vehicle damage was more strongly related to severe injuries than was found within the SV injury severity model. For the common set of variables between the injury severity and vehicle damage models, the vehicle damage model results seem to be consistent with the conventional wisdom for all the findings. In the manner of collision, the order of vehicle damage severity from high to low was head-on, angle, sideswipe (opposite direction), rear end, and sideswipe (same direction). At intersections with different traffic control strategies, the order of vehicle damage from high to low was traffic signal, two-way stop, four-way stop, and probably yield–no traffic control, which was not statistically significant. However, in the injury severity model the results are slightly reordered: the order of injury severity from high to low was traffic signal, yield–no traffic control, two-way stop, and four-way stop. In these intersections, the speed and speed differential between vehicles at the approach may account for the severity of injury crashes.

Signalized intersections represent relatively higher speed on all approaches; two-way stop-controlled intersections represent the largest speed differentials and four-way stop-controlled intersections represent the smallest speed differentials between intersecting roads or highways. Similarly, another variable related to speed is highway class. Compared against city highways, both state highways and Interstate highways will increase injury severity and vehicle damage significantly. This finding may be due to the fact that higher speeds increase the force of collision between vehicles. The results of each of these models hence provide a unique perspective of how the factors affect injury severity and vehicle damage. Some factors have a consistent impact across both vehicle damage and injury severity, and others are contradictory.

SUMMARY AND CONCLUSION

Traffic safety is an important issue affecting the nation's highways, and reducing the injuries and deaths due to traffic crashes is an undisputed priority. In recent years, the reduction of injury crashes has been heralded as a great success. Improvements in federally mandated safety standards and advancements made by automotive companies to enhance the safety of their products can be partially credited with the decline. However, the focus has now shifted toward the elimination of fatalities due to traffic crashes and a new National Strategic Highway Safety Plan, TZD, is under way. The successful strategies toward this vision should include the management of kinetic energy in crashes and collisions (*4*).

Managing kinetic energy requires an impartial evaluation of crash collision force or momentum change, which can be reflected through vehicle damage conditions. Driver injury severity, the ultimate measure of occupant risk, can be modeled through human factors, vehicle damage, and other variables. Developing respective models for injury severity and vehicle damage reveals a complete view of the crash severity.

The study shows that in both SV and MV injury severity models, there is an association between vehicle damage and injury severity; injury severities decrease when the vehicle damage increases. Furthermore, the MV crash results show that vehicle damage is more strongly related to severe injuries than was found within the SV crashes. This finding serves as a good representation of the innovative automotive safety features that reduce the likelihood of injuries by reducing or redirecting impact energies around occupants. Human factors are absolutely critical in affecting the injury outcomes, which probably explains why an early study failed to identify a strong relationship between forces to crash test vehicles and occupant injury (*21*). Among all the human factors, using alcohol or violating traffic rules considerably increases the severity of injury, and using safety constraints (seat belts) substantially reduces the possibility of more severe injuries.

TABLE 4 Coefficient Estimates for MV Injury Severity and Vehicle Damage Models

Variable	Coeff.	SE	z	$P > \lvert z \rvert$
Injury Severity				
Human factors				
Alcflag	0.21	0.07	3.11	<0.01
Drug	0.39	0.18	2.15	0.03
Young	–0.25	0.03	–8.78	<0.01
Female	0.24	0.03	9.19	<0.01
Speed	0.14	0.04	3.55	<0.01
Rule violation	0.15	0.04	3.91	<0.01
Environmental factors				
Ice road	–0.18	0.06	–2.85	<0.01
Snow road	–0.19	0.04	–4.43	<0.01
Highway and traffic factors				
Highway class				
Urban state highway	0.15	0.03	4.53	<0.01
Urban Interstate highway	0.31	0.11	2.80	<0.01
Urban city highway		Base level		
Traffic control				
Two way	0.35	0.12	2.87	<0.01
Signal	0.43	0.12	3.71	<0.01
Yield–none	0.32	0.11	2.83	<0.01
Four way		Base level		
Accident characteristics				
Manner of collision				
Angle	–0.14	0.04	–3.42	<0.01
Rear-end	*0.08*	*0.09*	*0.92*	*0.36*
Sideswipe (same direction)	–0.67	0.04	–15.37	<0.01
Sideswipe (opposite direction)	–0.50	0.08	–5.86	<0.01
Head-on		Base level		
Vehicle damage				
Moderate damage	–0.10	0.03	–3.08	<0.01
Severe damage	0.54	0.04	14.79	<0.01
None–minor damage		Base level		

Variable	Coeff.	SE	z	$P > \lvert z \rvert$
Vehicle Damage				
Environmental factors				
Dark	0.11	0.04	2.61	0.01
Light	0.09	0.03	3.33	<0.01
Snow road	–0.13	0.03	–3.78	<0.01
Highway and Traffic factors				
Highway class				
Urban state highway	0.12	0.03	4.25	<0.01
Urban Interstate highway	0.49	0.09	5.41	<0.01
Urban city highway		Base level		
Traffic control				
Two way	0.24	0.07	3.40	<0.01
Signal	0.25	0.06	3.95	<0.01
Yield–none	*0.11*	*0.13*	*0.80*	*0.42*
Four way		Base level		
Accident characteristics				
Manner of collision				
Angle	–0.29	0.08	–3.63	<0.01
Rear-end	–0.82	0.08	–10.25	<0.01
Sideswipe (same direction)	–0.99	0.09	–11.12	<0.01
Sideswipe (opposite direction)	–0.57		–5.70	<0.01
Head-on		Base level		

NOTE: Italics indicate that the variable is not statistically significant at 5% level. Summary statistics for injury severity: log likelihood, –6,648.99; likelihood ratio chi-square (*19*), 1,145.83; probability > chi-square, < .01; R^2, .08. Thresholds: $\mu_1 = 1.00$; $\mu_2 = 2.90$. Summary statistics for vehicle damage: log likelihood, –11,382.61; likelihood ratio chi-square (*12*), 776.33; probability > chi-square, <.01; R^2, .03. Thresholds: $\mu_1 = -0.36$; $\mu_2 = 1.05$.

Vehicle damage models provide a unique depiction of the factors associated with crash severity. In the SV crash results, one noteworthy finding is that striking guardrails and poles may lead to more severe vehicle damage but less severe injuries. For more rigid fixed objects such as bridges or ditches, both vehicles and occupants will sustain a more severe outcome. Moreover, horizontal curves, although not statistically significant in the injury severity model, may increase the likelihood of vehicle damage affecting injury severity.

In the MV crash results, the magnitude of impacts for vehicle damage and injury severity in the order of highest severity to lowest was head-on, angle, sideswipe (opposite direction), and sideswipe (same direction). Vehicle damage and injury severity due to traffic controls were slightly different for both models. Injury severity results show traffic signal, yield–no traffic control, two-way stop, and four-way stop to be the ordered list of severity, but the vehicle damage model shows traffic signal, two-way stop, four-way stop, and probably yield–no traffic control, which was not statistically significant.

The results of this study conclude that vehicle damage sustained from crashes can provide a different perspective on the severity of an incident. Because of the influence of crash victims, injury severity reports may vary considerably under similar highway and environmental circumstances. Therefore, in a comparison of the injury severity of similar crashes, the vehicle damage severity serves as a more objective account of the incident for highway and street designs aimed to manage kinetic energy in crashes, reaffirming the importance of the design principle of integration and separation (i.e., integrating compatible design elements and separating incompatible ones) (*4*). The vehicle damage severity does not tell the whole story, though; the collective use of injury severity makes it possible to accurately assess the influence of occupant characteristics and human factors, which helps to improve vehicle safety designs and develop effective enforcement or education programs to address the behavioral issues.

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