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RISK-BASED ADVISORY PREVENTION SYSTEM FOR COMMERCIAL TRUCKS UNDER HAZARDOUS CONDITIONS

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Disclaimer

ABSTRACT

In adverse driving conditions, such as inclement weather and complex terrain, large trucks are often involved in single-vehicle (SV) accidents in addition to multi-vehicle (MV) accidents. Although the absolute number of SV accidents is often lower than that of MV accidents, SV accidents usually result in more serious injury and fatality. Ten-year accident data involving trucks on rural highway from the Highway Safety Information System (HSIS) are studied to investigate the difference in driver-injury severity between SV and MV accidents using multinomial logit models. Injury severity from SV and MV accidents involving trucks on rural highway is modeled separately and their respective critical risk factors, such as driver, vehicle, temporal, roadway, environmental, and accident characteristics, are evaluated. The study shows that there is substantial difference between the impacts from a variety of variables on the driver-injury severity in MV and SV accidents. By conducting the injury severity study for MV and SV accidents involving trucks separately, some new or more comprehensive observations, which have not been covered in the existing studies, can be made. As a result, the complex interactions of variables and the nature of truck-driver injury are able to be disclosed in a better way. Based on the improved understanding on the severity of truck drivers from truck-involved accidents, it is expected that more rational and effective injury prevention strategy may be developed for truck drivers under different driving conditions in the future. Based on the model developed for injury studies of truck drivers, risk-based prevention strategy can be realistically developed.

TABLE OF CONTENTS

LIST OF TABLES

EXECUTIVE SUMMARY

In the United States, road accidents cause more injuries and casualties than any other natural or man-made hazard. Truck drivers receive special attention, not only because of their high numbers (approximately 2.8 million in the U.S.), but also because they face larger safety risk from traffic accidents—seven times more likely to die and 2.5 times more likely to suffer an injury than the average worker (NIOSH 2007). Each year in the United States, adverse weather alone is associated with more than 1.5 million vehicular crashes, which result in 800,000 injuries and 7,000 fatalities (The National Academies 2006). In various adverse driving conditions, such as inclement weather or complex terrain, trucks are often involved in single-vehicle (SV) accidents in addition to multi-vehicle (MV) accidents (Chen and Chen 2010; Baker 1991; Chen and Cai 2004). Although the absolute number of SV accidents is often lower than that of MV accidents, SV accidents usually result in more serious injury (The National Academies 2006). For example, SV accidents were responsible for 57.8% of all crash fatalities in 2005 (USDOT 2005). Therefore, investigations of the injury risks of both SV and MV accidents are very important.

It is known that SV and MV accidents have different mechanisms of occurrence (Chen and Chen 2010; Baker 1991), critical risk factors (Savolainen and Mannering 2007), and, accordingly, different injury mitigation strategies (NIOSH 2007). Therefore, to investigate injury severity and associated risk factors in both SV and MV accidents involving trucks is crucial to implementing more effective injury prevention strategy for truck drivers in their daily work. Moreover, the findings from such an investigation will provide scientific basis to improve the current highway design and traffic management policy, and propose next-generation safety initiatives in order to reduce the injury severity, and life and financial losses of truck-involved accidents. There exists, however, a gap between the current injury studies of truck drivers and reality. Of the limited studies that have investigated injury severity of truck-involved accidents, both SV and MV accidents were usually analyzed as a whole, and in which some important phenomena and critical risk factors unique to SV or MV accidents involving trucks cannot be identified. For thousands of truck drivers around the country, the lack of such a vital piece of knowledge may hinder efforts concerning injury prevention and traffic management on national highways.

The objective of this study is to investigate the injury severity of truck drivers by studying MV and SV accidents involving trucks on rural highways separately. By using multinomial logit models, the complex interactions between roadway characteristics, driver characteristics, accident characteristics, temporal characteristics, and environmental characteristics in both SV and MV accidents will be untangled. The model estimation results are expected to provide insightful observations of the nature of injury severities of truck drivers in SV and MV accidents. The common and unique risk factors of driver injury in SV and MV accidents will also be studied and compared.

1. INTRODUCTION

1.1 Problem statement (Chen and Chen 2011)

Existing studies on truck-involved accidents can be typically classified into two categories of topics: accident frequencies (or rates) and injury severity as well as their respective risk factor analyses. The majority of the existing works were focused on accident frequencies (or rates) (e.g., Miaou 1994, Joshua and Garber 1990), and the related risk factor analyses, including those about truck configurations (e.g. Jovanis et al. 1989, Blower et al. 1993, Braver et al. 1997), highway geometric designs, and traffic characteristics (e.g. Miaou 1994, Campbell 1991).

Different from the studies on accident frequencies (or rates), there are only limited studies specifically focused on injury severity of truck drivers or occupancies of truck-involved accidents. Golob et al. (1987) and Alassar (1988) investigated the influence of collision type, the number of involved vehicles, or road class on injury severity of truck drivers using log-linear models. Chirachavala et al. (1984) studied the factors that increase the accident severity for different truck types adopting discrete multivariate analysis. Duncan (1998) studied the injury severity of passenger occupancy caused by truck-passenger-car rear-end collisions using ordered logit models. Khorashadi et al. (2005) compared the difference of driver-injury severities from truck-involved accidents in rural and urban roads using multinomial logit models. Chang and Mannering (1999) analyzed the accident severity of occupancy in truck-involved and non-truck-involved accidents using nested logit models. The characteristics of truck-involved accidents and non-truck-involved accidents were compared, and some risk factors were found unique to truck-involved accidents. In addition to injury severity, some studies focused on the fatality of occupants related to trucks (Shibata and Fukuda 1994, Lyman and Braver 2003).

Most of the existing studies with a focus on severity of truck-involved accidents, as summarized above, covered all types of accidents as a whole without separating MV and SV accidents. During the past decade, some studies focused on the statistical difference of accident rates for SV and MV accidents (e.g., Ivan et al. 1999, Ivan et al. 2000, Lord et al. 2005, Qin et al. 2004). Recent research has found that there is significant difference on the prediction of confidence intervals between the SV and MV models using Poisson-gamma model (Geedipally and Lord, 2010). These works, however, were limited to studies of accident frequencies (or rates).

1.2 Background

A variety of statistical approaches have been applied to study injury severity. Among them, several methods have been applied to investigate the different influences of separated subsets of accident data on injury severity of drivers or occupancies. For example, earlier studies used cross-tabulation methods or χ^2 tests to compare the statistical difference between separated datasets (Brorsson et al. 1993, Holubowycz et al. 1994), such as gender groups or age groups. In the past 10 years, various disaggregate models have been widely used to compare different datasets due to the unique advantages as compared to the previous methods. These advantages include being able to test a broad range of variables that influence injury severity and capture comprehensive disaggregate information about how the injury severity is influenced by these variables (Chang and Mannering, 1999). Some studies adopted ordered logit (Duncan, 1998) or ordered probit models (Abdel-Aty, 2003) to investigate various risk factors that may influence the injury severity. For example, Abdel-Aty found the different influence of various risk factors at multiple locations. Multinomial logit models (Ulfarsson and Mannering 2004) and nested logit models (Chang and Mannering 1999) have also been frequently adopted in order to get more detailed information of the influence of variable risk factors on different injury severity levels. Ulfarsson and Mannering adopted multinomial logit models to find the difference in male and female driver-injury severity involving passenger cars, pickups, SUVs, and minivans. Chang and Mannering (1999) investigated the difference of occupancy injury severity in truck- and non-truck-involved accidents using nested logit models.

In recent years, there have been a few studies that have started investigating injury severity from SV and MV accidents separately. For example, Kockelman and Kweon (2002) used ordered probability models to investigate injury severity in two-vehicle crash and single-vehicle crash datasets separately. They found that there is a large difference of injury severity behavior for SV and MV accidents involving different vehicle types such as pickups and sport utility vehicles. In the work conducted by Ulfarsson and Mannering, single-vehicle and two-vehicle accidents were studied using separate models because it was found a single model cannot accurately tell the different characteristics of these accidents. Savolainen and Mannering estimated the probabilistic models of motorcyclists' injury severity by separating SV and MV crashes using multinomial and nested logit models. Different risk factors on the injury severity of motorcyclists in SV ad MV crashes were found. In realizing the considerably different causality mechanisms of SV and MV accidents, some other studies investigated SV accidents only (e.g., Shankar and Mannering 1996, Islam and Mannering 2006). So far, however, no study has been reported on investigating the injury severity of truck drivers in SV and MV crashes separately.

2. DATA DESCRIPTION (CHEN AND CHEN 2011)

The Highway Safety Information System (HSIS) is a database sponsored by Federal Highway Administration (FHWA) and has detailed traffic accident data from nine states across the United States that contain accident, roadway inventory, and traffic information. HSIS data have been considered to be of high quality and have the advantage of providing a comprehensive set of major risk factors (Noland and Lyoong 2004). The 10-year (1991-2000) detailed accident data on rural highways in Illinois will be utilized in this study. Illinois is an ideal location for this study because of its typical adverse driving environments, such as strong wind, ice- and snow-covered road surface and complicated terrain, etc. Besides, the HSIS database of Illinois provides comprehensive and sufficient injury data, which are critical to the present study.

According to the “roadway classification” in the collected data, three highway classes were considered as rural highways in the study: unmarked state highways (rural), controlled-access highways (rural), other state numbered highways (rural). Based on the variables of “vehicle type,” only accident records involving at least a truck will be selected in this study. Three different truck types were classified in the Illinois HSIS database: single-unit truck, tractor with semi-trailer, and tractor without semi-trailer. After removing the accident records with insufficient accident information, there were 19,741 truck-involved accidents occurring on rural highways in Illinois during the 10-year period; these include 6,891 SV accidents and 12,850 MV accidents (only count as one MV accident if there was more than one truck involved in an accident, and only the first truck involved will be considered in that case).

The variable “driver extent of injury” defined in the HSIS database of Illinois is an indicator of driver-injury severity, which is defined as a numerical scale from 1-5, representing no injury, possible injury, non-incapacitating injury, incapacitating injury, and fatal, respectively. Out of 6,891 SV accidents, 5,539 (80.4%) accidents had no injury, 214 (3.1%) accidents had possible injury, 754 (10.9%) accidents had non-incapacitating injury, 341 (5.0%) accidents had incapacitating injury and 43 (0.6%) accidents had fatal injury. Out of 12,850 MV accidents, 11,811(91.9%) accidents had no injury, 314 (2.5%) accidents had possible injury, 451 (3.5%) accidents had non-incapacitating injury, 249 (1.9%) accidents had incapacitating injury and 25 (0.2%) accidents had fatal injury.

The data showed that MV accidents have a higher percentage of no injury outcome (91.9% vs 80.4%) and lower percentages for all other injury level accidents as compared with SV accidents. It is noteworthy that such a finding from truck-involved accidents is opposite to some existing comparisons of SV and MV accidents when all types of vehicles were considered as a whole. For example, by looking into the accidents caused by all types of vehicles, Geedipally and Lord (2010) found that SV accidents have a much larger percentage of non-injury than MV accidents on four-lane highways. The different findings on injury severity of truck-involved accidents as compared with all the accidents underscore the necessity of the present study with a focus on the injury severity of truck drivers. In this study, the severity of truck drivers is grouped into three categories by merging some similar categories in the original data to ensure a sufficient number of observations are available in each category. The three categories of injury severity that will be used in the present study are (1) no injury (same as original Scale 1), (2) possible injury/non-incapacitating injury (including the original Scales 2 and 3), and (3) incapacitating injury/fatal (including original Scales 4 and 5).

The HSIS data contain very detailed information related to truck-involved accidents, which can be separated into groups such as roadway characteristics, driver characteristics, vehicle characteristics, temporal characteristics, environmental characteristics, and accident characteristics. The specifications of some selected indicators for some groups are given as follows. Driver characteristics: the young driver (≤ 25 years old) and old driver (≥ 50 years old) indicator. Vehicle characteristics: the carrying hazardous material indicator shows if the truck is carrying hazardous material or not. Temporal characteristics: the rush hour indicator refers to the accidents occurring between 6:00 am and 9:59 am. Road characteristic: the light traffic indicator and Class I designated truck route indicator. The light traffic indicator implies that the AADT divided by the number of lanes is less than or equal to 2,000. Illinois-designated truck routes include Class I designated truck route (approved for all load widths of 8½ ft. or less), Class II designated truck route (approved for all load widths of 8½ ft. or less and a wheel base no greater than 55 ft.) and Class III designated truck route (approved for all load widths of 8 foot 0 inches or less and a wheel base no greater than 55 ft.). Environmental characteristics: one example is the darkness light indicator, which shows that the light condition was dark when the accident occurred. Accident characteristics: for example, the ran off the roadway indicator suggests that the truck ran off the roadway when the accident happened. The variables shown above were selected in the present study based on the hypothesis that they would affect the injury severity of truck drivers. The hypothesis of no significant difference from zero for each parameter of severity category will be tested using the likelihood ratio χ^2 test (Kim et al. 2007) and the parameters not significantly different from zero at the 90% level will be restricted to zero.

Table 2.1 and 2.2 give the number of observations and the percentage distribution across the injury severity of truck drivers for SV and MV accidents involving at least one truck, respectively (Chen and Chen 2011). In the SV dataset (Table 2.1), there are some variables that have high percentages of incapacitating injury/fatal (more than 20%): driver trapped/extract, driver safety belt not used, and truck carrying hazardous material indicators; several variables have high percentages of possible injury/non-incapacitating injury (more than 30%): driver trapped/extract, driver safety belt not used, driver was asleep, severe crosswind, truck overturn, exceeding speed limit, and truck was merging indicators. There are also some variables with high percentages of no injury (more than 90%), such as traffic signal, truck jackknife and truck hitting animal indicators.

In the MV accident dataset, as shown in Table 2.2, 16 variables are associated with high percentages of no injury (more than 90%). In contrast, only two variables (driver trapped/extract and truck overturn) are associated with high percentages of possible injury/non-incapacitating injury (more than 30%) and incapacitating injury/fatal (more than 20%). As compared with the SV accident datasets (Table 2.1), the MV accident datasets have more indicators with percentages less than 5% for incapacitating injury/fatal (28 indicators [MV] versus 9 indicators [SV]) and possible injury/non-incapacitating injury (24 indicators [MV] versus 4 indicators [SV]). The difference of the aggregated data between the datasets of SV and MV accidents indicates possible difference in terms of driver-injury severity, which will be studied in the following sections comprehensively.

Table 2.1 Driver-injury frequency and percentage distribution for SV model

	No injury		Possible injury/non-incapacitating injury		Incapacitating injury/fatal		Total
Driver characteristics							
Young driver (age<=25)	421	77.8%	100	18.5%	20	3.7%	541
Old driver (age>=50)	1503	81.7%	225	12.2%	112	6.1%	1840
Female driver	183	76.3%	38	15.8%	19	7.9%	240
Driver trapped/extract	3	2.9%	41	40.2%	58	56.9%	102
Driver safety belt not used	48	24.1%	79	39.7%	72	36.2%	199
Driver was asleep/fainted	112	54.1%	62	30.0%	33	15.9%	207
Driver was fatigued	76	65.5%	28	24.1%	12	10.3%	116
Vehicle characteristics							
Single unit truck	710	74.4%	187	19.6%	57	6.0%	954
Truck brakes defect	64	63.4%	28	27.7%	9	8.9%	101
Truck tires defect	70	64.2%	23	21.1%	16	14.7%	109
Truck cargo defect	22	57.9%	11	29.0%	5	13.2%	38
Carrying hazardous material	67	62.6%	17	15.9%	23	21.5%	107
Temporal characteristics							
Rush hour (6:00am-9:59am)	954	75.8%	222	17.7%	82	6.5%	1258
Roadway characteristics							
Light traffic (AADT/number of lane<=2k)	1518	79.1%	291	15.2%	109	5.7%	1918
Class I designated truck route	3137	80.2%	552	14.1%	221	5.7%	3910
Stop sign/flasher	141	86.5%	17	10.4%	5	3.1%	163
Traffic signal	60	95.2%	2	3.2%	1	1.6%	63
Sharp curve (degree of curve>=5)	64	59.8%	31	29.0%	12	11.2%	107
Steep grade (Vertical curve grade>=2.2)	41	66.1%	10	16.1%	11	17.7%	62
Environmental characteristics							
Wet road surface	728	77.0%	171	18.1%	46	4.9%	945
Snow/slush road surface	399	87.5%	45	9.9%	12	2.6%	456
Ice road surface	437	84.9%	61	11.8%	17	3.3%	515
Fog/smoke/haze	128	78.1%	28	17.1%	8	4.9%	164
Severe cross wind	161	62.7%	81	31.5%	15	5.8%	257
Accident characteristics							
Truck ran off the roadway	1800	69.6%	549	21.2%	236	9.1%	2585
Truck overturn	250	57.5%	139	32.0%	46	10.6%	435
Truck jackknife	322	90.2%	34	9.5%	1	0.3%	357
Exceeding speed limit	44	58.7%	23	30.7%	8	10.7%	75
Improper lane usage	322	62.0%	137	26.4%	60	11.6%	519
Hitting animal	1538	96.6%	42	2.6%	13	0.8%	1593
Exceeding safe speed for conditions	207	72.6%	61	21.4%	17	6.0%	285
Failing to reduce speed to avoid crash	101	60.5%	41	24.6%	25	15.0%	167
Truck was passing/overtaking	38	76.0%	5	10.0%	7	14.0%	50
Truck was turning left	102	73.9%	29	21.0%	7	5.1%	138
Truck was skidding/control loss	825	69.2%	262	22.0%	106	8.9%	1193
Truck was merging	11	55.0%	8	40.0%	1	5.0%	20

Table 2.2 Driver-injury frequency and percentage distribution for MV model

	No injury		Possible injury/non-incapacitating injury		Incapacitating injury/fatal		Total
Driver characteristics							
Old driver (age>=50)	3170	91.8%	221	6.4%	61	1.8%	3452
Female driver	386	88.9%	31	7.1%	17	3.9%	434
Driver trapped/extract	4	9.3%	13	30.2%	26	60.5%	43
Driver safety belt not used	96	59.3%	37	22.8%	29	17.9%	162
Driver was asleep/fainted	18	56.3%	8	25.0%	6	18.8%	32
Driver was fatigued	29	82.9%	1	2.9%	5	14.3%	35
Vehicle characteristics							
Single unit truck	2542	89.0%	233	8.2%	81	2.8%	2856
Tractor with semi-trailer	8974	92.8%	505	5.2%	189	2.0%	9668
Truck brakes defect	167	79.2%	32	15.2%	12	5.7%	211
Truck tires defect	98	96.1%	1	1.0%	3	2.9%	102
Carrying hazardous material	115	82.1%	10	7.1%	15	10.7%	140
Roadway characteristics							
Light traffic (AADT/number of lane<=2k)	3092	89.8%	267	7.8%	86	2.5%	3445
Low truck percentage (percentage [a] <=0.1)	3061	91.8%	199	6.0%	74	2.2%	3334
Class I designated truck route	4379	93.9%	208	4.5%	78	1.7%	4665
Class II designated truck route	6367	90.9%	485	6.9%	156	2.2%	7008
Wide lane(Lane width>=13ft)	1669	92.5%	96	5.3%	39	2.2%	1804
Wide median (median width>=60ft)	1833	94.5%	70	3.6%	36	1.9%	1939
Unprotected median	4627	93.7%	220	4.5%	91	1.8%	4938
Painted median	307	88.5%	34	9.8%	6	1.7%	347
Stop sign/flasher	2015	90.1%	169	7.6%	53	2.4%	2237
No passing zone sign	254	85.2%	37	12.4%	7	2.4%	298
Environmental characteristics							
Darkness light condition	1945	90.3%	154	7.2%	56	2.6%	2155
Snow/slush road surface	1045	94.8%	48	4.4%	9	0.8%	1102
Ice road surface	591	94.1%	26	4.1%	11	1.8%	628
Accident characteristics							
Number of vehicles in accident >=3	909	86.2%	111	10.5%	34	3.2%	1054
Truck ran off the roadway	155	78.3%	29	14.7%	14	7.1%	198
Truck overturn	7	35.0%	9	45.0%	4	20.0%	20
Exceeding speed limit	190	89.6%	18	8.5%	4	1.9%	212
Failing to yield right-of-way	776	88.7%	80	9.1%	19	2.2%	875
Driving on wrong side/wrong way	110	77.5%	26	18.3%	6	4.2%	142
Driver influenced by alcohol/drugs	136	85.5%	17	10.7%	6	3.8%	159
Truck was turning left	723	93.5%	41	5.3%	9	1.2%	773
Truck was turning right	414	96.5%	12	2.8%	3	0.7%	429
Truck slowed/stopped in traffic	732	94.3%	39	5.0%	5	0.6%	776
Truck was avoiding vehicle/objects	489	85.9%	62	10.9%	18	3.2%	569
Truck was skidding/control loss	401	82.3%	54	11.1%	32	6.6%	487

[a] truck percentage is equal to commercial volume/AADT

3. STATISTICAL METHOD

3.1 Multinomial Logit Model

The injury severity in an accident is normally classified into discrete categories. When discrete outcomes are available, an ordered discrete probability model can explicitly calculate the increasing severity of each category (e.g., from no injury to fatal). Some existing studies (Ulfarsson and Mannering 2004, Kim et al. 2007) suggested that ordered models may restrict the effect of the variables across the outcomes. For example, ordered probability models may restrict variables to either increase the highest severity category or decrease the lowest, or vice versa. Thus for this study, targeting at injury severity of both SV and MV accidents, it is felt that the categorical analysis may have some advantages over the ordinal analysis, and the unordered multinomial logit model (Ulfarsson and Mannering, 2004; Khorashadi et al., 2005) will be adopted in the present study.

$P_n(i)$ is the probability of the accident n causing the injury severity category i (Ulfarsson and Mannering 2004):

$$P_n(i) = P(\beta_i \mathrm{X}_n + \varepsilon_{ni} \geq \beta_{i'} \mathrm{X}_n + \varepsilon_{ni'}) \ \ \forall i' \in I\,, \quad i' \neq i \tag{1}$$

where I is a set of all possible discrete outcomes, mutually exclusive severity categories. i and i' are different injury severity categories. β_i and $\beta_{i'}$ are vectors of estimated coefficients of severity category i and i', respectively. X_n is the vector of characteristics (e.g. driver, vehicle, roadway, and environmental) for the accident observation n that influences the injury severity category i and i'. ε_{ni} and $\varepsilon_{ni'}$ are random components (error terms) that explain the unobserved effects on injury severity of the accident observation n.

If ε_{ni} is assumed to be in a type I extreme-value distribution, a standard multinomial logit model can be expressed as (McFadden, 1981):

$$P_n(i) = \frac{e^{\beta_i \mathrm{X}_n}}{\sum_{\forall i' \in I} e^{\beta_{i'} \mathrm{X}_n}} \tag{2}$$

where the coefficients. β_i is typically estimated by the maximum likelihood method.

3.2 Elasticity

It is known that the estimated parameters of multinomial logit analysis sometimes are not sufficient to explore how changes in the explanatory variables affect the outcome probabilities because the marginal effect of a variable depends on all the parameters in the model (Kim et al. 2007). So in addition to the estimated parameters, elasticities are often used to describe the magnitude of the impact of the explanatory variables on the outcome probabilities (Ulfarsson and Mannering 2004). Elasticity $E_{x_{nk}}^{P_n(i)}$ can be obtained for observation n using the partial derivative, as described below (Chang and Mannering 1999):

$$E_{x_{nk}}^{P_n(i)} = \frac{\partial P_n(i)}{\partial x_{nk}} \frac{x_{nk}}{P_n(i)} \tag{3}$$

where $P_n(i)$ is the probability of severity outcome i on observation n and x_{nk} is the value of the variable k for the outcome n.

Because the exogenous variables we explored later are discrete instead of continuous (coded as 0 and 1 indicator values), we cannot get the standard elasticity as shown in Eq. (3). Therefore, a direct pseudo-elasticity of the probability $E_{x_{nk}}^{P_n(i)}$ has been introduced to measure the effect in percentage that a 1% change in x_{nk} (the indicator varies from 0 to 1 or from 1 to 0) has on the severity probability $P_n(i)$. This method has been used in previous studies by Ulfarsson and Mannering (2004) and Khorashadi et al. (2005):

$$E_{x_{nk}}^{P_n(i)} = \frac{P_n(i)[\text{given } x_{nk} = 1] - P_n(i)[\text{given } x_{nk} = 0]}{P_n(i)[\text{given } x_{nk} = 0]} \tag{4}$$

By combining Eqs. (2) and (4), the direct pseudo-elasticity $E_{x_{nk}}^{P_n(i)}$ can be finally expressed as (Khorashadi et al. ,2005):

$$E_{x_{nk}}^{P_n(i)} = e^{\beta_{ik}} \frac{\sum_{\forall i' \in I} [e^{\beta_{i'} x_n}]_{x_{nk=0}}}{\sum_{\forall i' \in I} [e^{\beta_{i'} x_n}]_{x_{nk=1}}} - 1 \tag{5}$$

where $E_{x_{nk}}^{P_n(i)}$ is the direct pseudo-elasticity of the k^{th} variable from the vector x_n for observation n, β_{ik} is the k^{th} component of the vector β_i of severity category i. $[e^{\beta_{i'} x_n}]_{x_{nk=0}}$ is the value of $e^{\beta_{i'} x_n}$ with the x_{nk} in x_n set to zero and $[e^{\beta_{i'} x_n}]_{x_{nk=1}}$ is the value of $e^{\beta_{i'} x_n}$ with the x_{nk} in x_n set to one.

The pseudo-elasticity of a variable to a specific severity category represents the average percentage of change in the probability for that particular injury category when the variable is changed from 0 to 1. For example, a pseudo-elasticity of 50% for a variable in the fatal severity category means that when the value of the variable in the sub-set of the observations is changed from 0 to 1, the probabilities of fatal severity outcome for these observations in the sub-set increase by 50% on average.

4. RESULTS

The data have been separated into two parts, one is the SV accident dataset and the other is the MV accident dataset. Variables were included and presented in the models if they were found to be significantly different from zero at the P=10% level (χ^2 -statistic=2.71). This is to improve the estimation efficiency for the statistically significant variables.

Tables 4.1 and 4.2 show the estimated driver-injury severity models of SV and MV accidents, which include the estimated parameters and χ^2 identified by exhibiting the maximum likelihood for each severity category. As discussed earlier, no injury category is chosen as the base case, so the estimated parameters in the tables show the difference between the results of the target category and the base case (no injury category). The tables suggest that a wide variety of variables are statistically significant on driver injury severity. The ρ^2 of the SV and MV models equal to 0.548 and 0.731, respectively, which indicate that the models fit the data satisfactorily.

Table 4.1 Multinomial logit model of driver-injury severity conditioned on SV accident for truck-involved accidents

Variable[a]	Estimated parameter	χ^2
Constant [II/F]	2.928	5.23
Constant [PI/NII]	4.004	23.42
Driver characteristics		
Young driver (age<=25) [II/F]	-0.303	5.44
Old driver (age>=50) [PI/NII]	-0.085	3.53
Female driver [II/F]	0.278	3.80
Driver trapped/extract [II/F]	2.633	73.86
Driver trapped/extract [PI/NII]	2.031	44.09
Driver safety belt not used [II/F]	1.313	141.05
Driver safety belt not used [PI/NII]	0.904	81.77
Driver was asleep/fainted [II/F]	0.430	12.59
Driver was asleep/fainted [PI/NII]	0.413	21.20
Driver was fatigued [PI/NII]	0.279	5.42
Vehicle characteristics		
Single unit truck [PI/NII]	0.263	25.17
Truck brakes defect [PI/NII]	0.230	3.17
Truck tires defect [II/F]	0.371	4.99
Truck cargo defect [PI/NII]	0.429	4.19
Carrying hazardous material [II/F]	0.623	17.32
Temporal characteristics		
Rush hour (6:00am-9:59am) [PI/NII]	0.094	4.05
Roadway characteristics		
Light traffic (AADT/number of lane<=2k) [PI/NII]	0.134	5.56
Class I designated truck route [PI/NII]	0.120	4.75
Stop sign/flasher [II/F]	-0.732	8.16
Stop sign/flasher [PI/NII]	-0.563	14.66

Traffic signal [PI/NII]	-0.771	4.33
Sharp curve (degree of curve>=5) [II/F]	0.408	4.87
Sharp curve (degree of curve>=5) [PI/NII]	0.423	11.30
Steep grade (Vertical curve grade>=2.2) [II/F]	0.928	21.44
Steep grade (Vertical curve grade>=2.2) [PI/NII]	0.334	2.96
Environmental characteristics		
Wet road surface [II/F]	-0.261	8.08
Snow/slush road surface [II/F]	-0.564	11.74
Snow/slush road surface [PI/NII]	-0.463	25.61
Ice road surface [II/F]	-0.439	9.38
Ice road surface [PI/NII]	-0.421	24.83
Fog/smoke/haze [PI/NII]	0.235	4.10
Severe cross wind [PI/NII]	0.516	40.51
Accident characteristics		
Truck ran off the roadway [II/F]	0.433	37.40
Truck ran off the roadway [PI/NII]	0.419	81.29
Truck overturn [II/F]	0.648	34.43
Truck overturn [PI/NII]	0.650	82.21
Truck jackknife [II/F]	-1.095	4.65
Exceeding speed limit [II/F]	0.497	5.70
Exceeding speed limit [PI/NII]	0.442	9.80
Improper lane usage [II/F]	0.256	8.30
Improper lane usage [PI/NII]	0.298	23.92
Hitting animal [II/F]	-0.760	24.88
Hitting animal [PI/NII]	-0.666	57.95
Exceeding safe speed for conditions [PI/NII]	0.284	10.99
Failing to reduce speed to avoid crash [II/F]	0.450	11.10
Failing to reduce speed to avoid crash [PI/NII]	0.259	6.31
Truck was passing/overtaking [II/F]	0.460	3.92
Truck was turning left [II/F]	-0.407	3.02
Truck was skidding/control loss [II/F]	0.289	16.41
Truck was skidding/control loss [PI/NII]	0.258	29.18
Truck was merging [PI/NII]	0.485	3.56
Number of observations		
Log likelihood at zero	-7570.5	
Log likelihood at convergence	-3421.6	
Number of observation used	6891	
ρ^2	0.548	

Table 4.2 Multinomial logit model of driver-injury severity conditioned on MV accident for truck-involved accidents

Variable[a]	Estimated parameter	χ^2
Constant [II/F]	5.305	25.94
Constant [PI/NII]	4.356	20.23
Driver characteristics		
Old driver (age>=50) [PI/NII]	0.080	3.58
Female driver [II/F]	0.408	8.90
Female driver [PI/NII]	0.189	3.75
Driver trapped/extract [II/F]	2.743	95.59
Driver trapped/extract [PI/NII]	1.867	40.61
Driver safety belt not used [II/F]	1.158	85.74
Driver safety belt not used [PI/NII]	0.815	61.73
Driver was asleep/fainted [II/F]	1.408	30.99
Driver was asleep/fainted [PI/NII]	1.042	21.35
Driver was fatigued [II/F]	1.036	16.05
Vehicle characteristics		
Single unit truck [II/F]	0.485	3.10
Tractor with semi-trailer [PI/NII]	-0.267	6.42
Truck brakes defect [II/F]	0.436	7.13
Truck brakes defect [PI/NII]	0.443	18.22
Truck tires defect [PI/NII]	-0.853	2.86
Carrying hazardous material [II/F]	0.750	19.65
Roadway characteristics		
Light traffic (AADT/number of lane<=2k) [PI/NII]	0.119	6.47
Low truck percentage (percentage[b] <=0.1) [II/F]	-0.139	2.73
Low truck percentage (percentage[b] <=0.1) [PI/NII]	-0.093	3.53
Class I designated truck route [II/F]	-0.941	22.22
Class II designated truck route [II/F]	-0.242	5.44
Wide lane (Lane width>=13ft) [PI/NII]	-0.158	7.09
Wide median (median width>=60ft) [PI/NII]	-0.164	4.66
Unprotected median [II/F]	0.391	6.57
Painted median [PI/NII]	0.223	5.16
Stop sign/flasher [PI/NII]	0.112	4.40
No passing zone sign [PI/NII]	0.348	13.07
Environmental characteristics		
Darkness light condition [II/F]	0.206	5.83
Darkness light condition [PI/NII]	0.203	15.59
Snow/slush road surface [II/F]	-0.496	8.01
Snow/slush road surface [PI/NII]	-0.164	4.26
Ice road surface [PI/NII]	-0.201	3.56

Accident characteristics		
Number of vehicles in accident >=3 [II/F]	0.218	4.77
Number of vehicles in accident >=3 [PI/NII]	0.323	31.99
Truck ran off the roadway [II/F]	0.426	6.89
Truck ran off the roadway [PI/NII]	0.405	13.14
Truck overturn [II/F]	1.637	22.14
Truck overturn [PI/NII]	1.576	34.60
Exceeding speed limit [PI/NII]	0.231	3.03
Failing to yield right-of-way [PI/NII]	0.207	9.13
Driving on wrong side/wrong way [II/F]	0.414	3.57
Driving on wrong side/wrong way [PI/NII]	0.605	27.33
Driver influenced by alcohol/drugs [PI/NII]	0.331	5.91
Truck was turning left [II/F]	-0.330	3.49
Truck was turning right [II/F]	-0.617	4.15
Truck was turning right [PI/NII]	-0.416	7.31
Truck slowed/stopped in traffic [II/F]	-0.531	5.35
Truck was avoiding vehicle/objects [PI/NII]	0.292	15.23
Truck was skidding/control loss [II/F]	0.639	33.08
Truck was skidding/control loss [PI/NII]	0.358	18.77
Number of observations		
Log likelihood at zero	-14117.2	
Log likelihood at convergence	-3790.6	
Number of observation used	12850	
ρ^2	0.731	

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

Following each variable name in Tables 4.1 and 4.2, the abbreviation of the corresponding severity category to which each parameter belongs is listed in brackets. They are defined as: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, and [II/F] incapacitating injury/fatal. In a multinomial logit model, the estimated parameters are not sufficient to explore the actual effect of a variable on the probability of an injury severity category. This is because the marginal effect of a variable is also related to all the other parameters of all injury severities in the model, so the sign of one variable cannot freely indicate the actual effect of a variable (Khorashadi et al. 2005). Therefore, it is important to consider the marginal effects given by the pseudo-elasticity instead of the parameter values (Ulfarsson and Mannering 2004). So we also present the average direct pseudo-elasticity for the SV and MV models in Tables 4.3 and 4.4, respectively. The detailed results in Tables 4.3 and 4.4 will be discussed by category in the following section.

Table 4.3 Average direct pseudo-elasticities of driver-injury severity of SV accidents

Variable	Elasticity (%) [a]		
	NI	PI/NII	II/F
Driver characteristics			
Young driver (age<=25)	8.9	10.1	-19.6
Old driver (age>=50)	2.8	-5.6	4.1
Female driver	-13.9	-0.2	13.7
Driver trapped/extract	-86.4	3.5	89.0
Driver safety belt not used	-58.0	3.7	56.1
Driver was asleep/fainted	-26.5	11.1	13.0
Driver was fatigued	-17.3	9.3	5.8
Vehicle characteristics			
Single unit truck	-11.5	15.0	-6.0
Truck brakes defect	-10.1	13.1	-5.6
Truck tires defect	-15.8	-5.6	22.0
Truck cargo defect	-26.6	12.7	11.1
Carrying hazardous material	-23.5	-16.2	42.6
Temporal characteristics			
Rush hour (6:00am-9:59am)	-5.5	3.7	0.9
Roadway characteristics			
Light traffic (AADT/number of lane<=2k)	-5.9	7.5	-2.9
Class I designated truck route	-6.2	5.7	-0.3
Stop sign/flasher	50.4	-14.3	-27.6
Traffic signal	51.1	-30.1	-10.6
Sharp curve (degree of curve>=5)	-26.2	12.6	10.9
Steep grade (Vertical curve grade>=2.2)	-38.4	-14.0	55.7
Environmental characteristics			
Wet road surface	9.9	5.7	-15.3
Snow/slush road surface	39.6	-12.1	-20.5
Ice road surface	32.9	-12.8	-14.3
Fog/smoke/haze	-14.1	8.7	3.4
Severe cross wind	-25.2	25.3	-4.7
Accident characteristics			
Truck ran off the roadway	-26.0	12.5	14.1
Truck overturn	-38.3	18.0	17.8
Truck jackknife	21.4	37.1	-59.4
Exceeding speed limit	-29.1	10.3	16.5
Improper lane usage	-18.1	10.3	5.7
Hitting animal	60.4	-17.6	-25.0
Exceeding safe speed for conditions	-15.8	11.9	1.5
Failing to reduce speed to avoid crash	-22.5	0.5	21.5
Truck was passing/overtaking	-9.7	-28.2	43.0
Truck was turning left	14.4	9.3	-23.8

Truck was skidding/control loss	-17.7	6.6	9.9
Truck was merging	-19.3	31.1	-17.6

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

Table 4.4 Average direct pseudo-elasticities of driver-injury severity of MV accidents

Variable	Elasticity (%) [a]		
	NI	PI/NII	II/F
Driver characteristics			
Old driver (age>=50)	-0.4	7.9	-6.8
Female driver	-19.0	-2.1	21.8
Driver trapped/extract	-86.7	-13.9	106.6
Driver safety belt not used	-52.9	6.3	49.7
Driver was asleep/fainted	-61.7	8.6	56.6
Driver was fatigued	-34.8	-48.3	83.7
Vehicle characteristics			
Single unit truck	-15.7	-17.9	37.0
Tractor with semi-trailer	-0.2	-23.6	34.4
Truck brakes defect	-26.5	14.5	13.7
Truck tires defect	13.6	-51.6	35.9
Carrying hazardous material	-28.6	-21.8	51.1
Roadway characteristics			
Light traffic (AADT/number of lane<=2k)	-2.9	9.3	-5.5
Low truck percentage (percentage[b] <=0.1)	7.9	-1.7	-6.1
Class I designated truck route	29.9	47.6	-49.3
Class II designated truck route	5.4	15.9	-17.2
Wide lane (Lane width>=13ft)	6.7	-8.9	1.9
Wide median (median width>=60ft)	2.1	-13.3	10.9
Unprotected median	-8.2	-22.2	35.7
Painted median	-0.5	24.5	-22.3
Stop sign/flasher	-5.2	6.0	-0.3
No passing zone sign	-11.8	25.0	-11.4
Environmental characteristics			
Darkness light condition	-12.8	6.8	7.1
Snow/slush road surface	22.5	4.0	-25.4
Ice road surface	14.8	-6.1	-9.0
Accident characteristics			
Number of vehicles in accident >=3	-16.8	14.9	3.5
Truck ran off the roadway	-25.2	12.1	14.5
Truck overturn	-72.2	34.4	42.9
Exceeding speed limit	-6.1	18.3	-11.0
Failing to yield right-of-way	-6.3	15.3	-7.9
Driving on wrong side/wrong way	-30.4	27.5	5.3
Driver influenced by alcohol/drugs	-19.4	12.2	8.4

Truck was turning left	14.7	3.2	-17.6
Truck was turning right	36.5	-10.0	-26.4
Truck slowed/stopped in traffic	18.9	12.7	-30.1
Truck was avoiding vehicle/objects	-15.4	13.3	3.3
Truck was skidding/control loss	-30.2	-0.2	32.2

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

[b] Truck percentage is equal to commercial volume/AADT

4.1 Driver Characteristics

The different influences of older drivers in SV and MV accidents is worth noting. Older drivers depending on whether they're involved in an SV or MV accident, have a 5.6% decrease or 7.9% increase in possible injury/non-incapacitating injury probability, respectively. This phenomenon is perhaps because of the combined effects of cautious driving behavior, more driving experience, and yet longer reaction time of older drivers. The opposite effects of older drivers on driver-injury severity of SV and MV accidents show the statistical difference of the two models, and are possibly also the reason why this indicator had not been found to be significant in the past when SV and MV accidents involving trucks were typically analyzed altogether. For older drivers, it is found that the chances of suffering severe injury and fatality increase when involved in an SV accident. Accordingly, specific mitigation strategies of severe injury for older drivers may need to be developed in the future by considering the unique characteristics of SV accidents.

There is 19.6% decrease in incapacitating injury/fatal probability in the SV model if the driver is young. However, the young driver indicator is not significant in the MV model at all. This phenomenon is perhaps because of the combined effects from cautious driving behavior, more driving experience, and yet longer reaction time of older drivers. The opposite effects of older drivers on driver-injury severity of the SV and MV accidents show the statistical difference of the two models, and are possibly also the reason why this indicator had not been found to be significant in the past when SV and MV accidents involving trucks were typically analyzed altogether. For older drivers, it is found that the chances of suffering severe injury and fatality increase when involved in an SV accident. Accordingly, specific mitigation strategies of severe injury for older drivers may need to be developed in the future by considering the unique characteristics of SV accidents.

For truck drivers, it is not uncommon to become fatigued or sometimes even fall asleep when driving (NIOSH, 2007). The probabilities of incapacitating injury/fatality in the SV and MV models both increase if the truck driver was asleep/fainted, but the probability in MV accidents is about eight times higher than that of SV accidents (56.6% vs. 13.0%). The influence of a fatigued truck driver in the SV and MV models is totally different. The difference of elasticity is more than 50% for both categories of possible injury/non-incapacitating injury (9.3% vs. -48.3%) and incapacitating injury/fatality (5.8% vs. 83.7%). This interesting observation implies that severe injury will likely happen if a fatigued truck driver is involved in an MV accident. In contrast, less severe injury is likely expected if a fatigued driver experiences an SV accident. The detailed reasons behind the observation are not straightforward and require further studies. Possible explanations may include a different crash nature between SV and MV accidents, as well as the fact that a fatigued or asleep truck driver can otherwise do much more to avoid an MV accident than to avoid an SV accident. Based on the results illustrated above, to effectively reduce the probability of severe injury or fatality of truck drivers due to fatigue or falling asleep, both types of accidents are important, but the focus should be put on preventing the occurrence of MV accidents.

The SV and MV models give similar findings about incapacitating injury/fatal probability if the driver was trapped/extract (89% vs. 106.6%) or the driver did not use a safety belt (56.1% vs. 49.7%). These findings reflect that using a safety belt can reduce incapacitating injury/fatality probability in both SV and MV accidents. Similar observations have been made by Chang and Mannering (1999) among other researchers.

4.2 Vehicle Characteristics

Opposite effects on the driver-injury severity were found between the SV and MV accidents if the truck is single-unit. For example, if the truck is single-unit, the probability of incapacitating injury/fatality increases by 37% in an MV accident while decreases by 6% in an SV accident as compared with trucks that are not single-unit. Also a tractor with a semi-trailer indicator is significant in the MV model by increasing the probability of incapacitating injury/fatality by 34.4%, but not significant in the SV model. So from the perspective of lowering the injury severity of the driver, a single-unit truck is better than other non-single-unit trucks in an SV accident, but usually becomes worse than other non-single-unit trucks in an MV accident.

If a truck has a brake or tire defect, there is a considerable difference of incapacitating injury/fatality probability between the SV and MV models (-5.6% vs. 13.7% for brake defect, 22.0% vs. 35.9% for tire defect). Comparatively, tire defect is found to be more critical than brake defect in terms of causing severe injury of truck drivers. This finding may help the trucking industry develop safer maintenance processes and highway patrol improve law enforcement. The probabilities of incapacitating injury/fatality in both SV and MV accidents will increase significantly if the truck is carrying hazardous material (42.6% and 51.1% for the SV and MV accidents, respectively). This result highlights the significantly elevated threats to HazMat truck drivers' lives no matter what kind of accident is involved.

4.3 Temporal Characteristics

In this study, only one temporal characteristic variable was found to be statistically significant. The rush hour indicator slightly increases the possible injury/non-incapacitating injury probability in the SV model while it has no significant effect in the MV model. Although high traffic volume has a large impact on accident frequency of MV accidents, it doesn't seem to be critical from the perspective of injury severity of truck drivers.

4.4 Roadway Characteristics

Roadway characteristics affect driver injury severity in SV and MV accidents in a rather complex manner. In MV accidents, both Class I and II designated truck routes increase the probability of possible injury/non-incapacitating injury (47.6% vs. 49.3%), while they decrease the probability of incapacitating injury/fatality (49.3% vs. 17.2%) at the same time. Because of the trade-offs, Class I and II designated truck routes may not have considerable impacts on the two injury levels as a whole, but they both significantly decrease the probability of severe injury and fatality, which are usually very critical to policymaking. Comparatively, Class I designated truck routes are more effective than Class II designated truck routes. Since this study is only based on the data in Illinois, it is advisable for transportation agencies to evaluate the effectiveness of the designated truck routes by considering the site-specific accident and injury data. It is believed that studies on optimizing the strategy of designated truck routes may need to be conducted on a case-by-case basis for different highways, especially those that are historically the site of severe truck driver injury.

There are some variables that are found to be significant only for one type of accident. For example, wide lane, wide median, and unprotected median indicators decrease the probability of possible injury/non-incapacitating injury by 8.9%, 13.3%, and 22.2% while they increase the probability of incapacitating injury/fatal by 1.9%, 10.9%, and 35.7% in the MV model, respectively. All these indicators, however, are found to be not significant in the SV model. Obviously, the impacts from wide lanes, wide medians, or unprotected medians on the injury severity of truck drivers in MV accidents are complex in nature: these roadway design features help reduce the probability of moderate injury, but increase the probability of severe injury and fatality at the same time. This is probably the outcome from the trade-offs between the provided physical protection and the affected driving behavior due to either a “safer” or “more dangerous” feeling by the drivers. For example, on one hand, wide lanes and wide medians do provide more physical safety margins for truck drivers. On the other hand, the “safer” feeling may also encourage unsafe driving behavior by the truck drivers. In contrast, an unprotected median may pose higher risks of injury during accidents, but it may also alert truck drivers to drive more cautiously. The results imply the need to evaluate the impacts of some roadway design features on traffic safety more comprehensively by traffic agencies and the research community, from both engineering and psychological perspectives simultaneously.

The low truck percentage indicator decreases the probability of both possible injury/non-incapacitating injury and incapacitating injury/fatal for the MV model, and is found to be not significant for the SV model. Class II designated truck route, painted median, and no passing traffic control indicators increase the possible injury/non-incapacitating injury probability by 15.9%, 24.5%, and 25.0%, respectively, in the MV model although they were not found to be significant in the SV model. Different from Class II designated truck route, Class I designated truck route will decrease the probability of incapacitating injury/fatality in both the MV and SV models, but with a substantial difference (49.3% [MV] vs. 0.3% [SV]). These findings can help transportation agencies evaluate the related roadway feature designs and further identify those features that are helpful in effectively reducing traffic injury severity.

Similar to those variables as summarized above, which are only significant in the MV model, there are also some variables that are only significant in the SV model. For example, if a highway has sharp curves, the probability of possible injury/non-incapacitating injury or incapacitating injury/fatality increase by 12.6% or 10.9% in the SV model, respectively, but no significant impact was observed in the MV model. The steep grade indicator will increase the probability of incapacitating injury/fatality by more than 50% in the SV model but has no influence in the MV model. These findings underscore the substantial effects of complex terrains on injury severity in SV accidents. It is known that SV accidents are common in areas with complex terrains (e.g., mountainous states). The results suggest that highways should be designed very carefully, given that optimizing the terrain may potentially save many lives and avoid injuries of many truck drivers each day.

4.5 Environmental Characteristics

If an accident happens on an icy road, the probabilities of possible injury/non-incapacitating injury and incapacitating injury/fatality in both the SV and MV models are found to decrease, which can be partly because people often drive slower and more carefully on icy roads than normal road conditions. The results for both the SV and MV accidents are generally similar if the accidents occur on a snow-covered road, except for one situation: the probability of possible injury/non-incapacitating injury in the MV model slightly increases by 4% while that in the SV model decreases by 12.1%.

The darkness indicator was found to be significant in the MV model, but not in the SV model. The probability of severe injury increasing at night has also been found by a study on truck-involved accidents as a whole (Chang and Mannering, 1999). But the different impacts on SV and MV accidents, as introduced above, have not been discussed previously. Contrary to the darkness indicator, the wet road surface indicator was found to be significant in the SV model, but not in the MV model. Another interesting finding is that inclement weather like fog or windy weather increases the possible injury/non-incapacitating injury probability in the SV model while these weather conditions were found to be not significant in the MV model. So depending on the specific adverse environmental condition, more effective injury mitigation technology for truck drivers can be developed accordingly with an emphasis on SV accidents based on the findings summarized above.

4.6 Accident Characteristics

Many variables of accident characteristics were also found to have totally different influence on SV and MV accidents. There are many characteristic indicators that only have significant impacts on the truck driver injury severity in either MV or SV accidents, but not both. For example, six accident characteristic indicators (e.g., failing to yield right-of-way indicator) were found to be significant in the MV model but not in the SV model. Seven other accident characteristics indicators (e.g., improper lane usage indicator) were found to be significant in the SV model but not in the MV model. Details of these variables are summarized in Tables 4.5 and 4.6.

Even for those indicators that were found to be significant in both models, there is still some considerable difference. For example, if a truck is overturned, the probabilities of both possible injury/non-incapacitating injury and incapacitating injury/fatality in the MV model increase more significantly than in the SV model (34.3% versus 18% and 42.9% versus 17.8%, respectively). When a truck loses control, there is also large difference between the increasing probability of incapacitating injury/fatality in the SV and MV models (9.9% versus 32.2%). Considerably higher probabilities of experiencing severe injury in MV accidents than SV accidents are possibly related to the difference in the crash nature of SV and MV accidents.

It is known that the influence of alcohol or drugs can increase the probability of severe injury (Khorashadi et al., 2005). In addition to having the same observation as Khorashadi et al. (2005), the present study further shows there is a different influence of these variables on SV and MV accidents: the driver influenced by alcohol or drugs increases the probability of both possible injury/non-incapacitating injury and incapacitating injury/fatality in the MV model, but the same indicator is found to be not significant in the SV model.

It can be found from the above results that there is substantial difference between the impacts from a variety of variables on the driver-injury severity in MV and SV accidents. For clarity, Tables 4.5 and 4.6 summarize all the indicators that have different influences in the SV and MV models, including those only significant to one type of accident, with opposite trends, and with the same trend but significantly different elasticity to both types of accidents. By conducting the injury severity study for MV and SV accidents involving trucks separately, some new or more comprehensive observations, which have not been covered in the existing studies, can be made. As a result, the complex interactions of various indicators and the nature of truck-driver injury are able to be disclosed in a better way.

Table 4.5 Summary of indicators by influence types

Indicators only significant to SV model	Indicators only significant to MV model
(1)-Young driver (age<=25) **(2)-**Truck cargo defect **(3)-** Rush hour (6:00am-9:59am) **(4)-**Traffic signal **(4)-**Sharp curve (degree of curve>=5) **(4)-**Steep grade (Vertical curve grade>=2.2) **(5)-**wet road surface **(5)-** Fog/smoke/haze **(5)-** Severe cross wind **(6)-**Truck jackknife **(6)-**Improper lane usage **(6)-**Hitting animal **(6)-**Exceeding safe speed for conditions **(6)-**Failing to reduce speed to avoid crash **(6)-**Truck was passing/overtaking **(6)-**Truck was merging	**(2)-**Tractor with semi-trailer **(4)-**Low truck percentage (percentage^b <=0.1) **(4)-**Class II designated truck route **(4)-**Wide lane(Lane width>=13ft) **(4)-**Wide median (median width>=60ft) **(4)-**Unprotected median **(4)-**Painted median **(4)-**No passing zone sign **(5)-** Darkness light condition **(6)-**Number of vehicles in accident >=3 **(6)-**Failing to yield right-of-way **(6)-**Driving on wrong side/wrong way **(6)-**Driver influenced by alcohol/drugs **(6)-**Truck was turning right **(6)-**Truck slowed/stopped in traffic **(6)-**Truck was avoiding vehicle/objects
Indicators having influence on SV and MV models with the same trend and the difference of elasticity is small (smaller than 10% for both PI/NII and II/F)	Indicators having influence on SV and MV models with the same trend but the difference of elasticity is large (bigger than 20% for either of PI/NII and II/F)
(1)-Female driver **(1)-**Driver safety belt not used **(2)-**Carrying hazardous material **(4)-**Light traffic (AADT/number of lane<=2k) **(5)-** Ice road surface **(6)-**Truck ran off the roadway **(6)-**Truck was turning left	**(1)-**Driver was asleep/fainted (II/F) **(2)-**Truck tires defect (PI/NII and II/F**)** **(4)-**Class I designated truck route (PI/NII and II/F**)** **(6)-**Truck overturn (II/F**)**

The numbers in brackets before indicators are defined as: (1) driver characteristics (2) vehicle characteristics (3) temporal characteristics (4) roadway characteristics (5) environmental characteristics (6) accident characteristics

Table 4.6 Indicators which have opposite influence on SV and MV models

	SV		MV	
Variables	possible injury/non-incapacitating injury	incapacitating injury/fatal	possible injury/non-incapacitating injury	incapacitating injury/fatal
(1)-Old driver (age>=50)	⇩	⬆	⬆	⇩
(1)-Driver trapped/extract	⬆	⬆	⇩	⬆
(1)-Driver was fatigued	⬆	⬆	⇩	⬆
(2)-Single unit truck	⬆	⇩	⇩	⬆
(2)-Truck brakes defect	⬆	⇩	⬆	⬆
(4)-Stop sign/flasher	⇩	⇩	⬆	⇩
(5)-Snow/slush road surface	⇩	⇩	⬆	⇩
(6)-Exceeding speed limit	⬆	⬆	⬆	⇩
(6)-Truck was skidding/control loss	⬆	⬆	⇩	⬆

Arrows show increase (up) or decrease (down) in elasticity. The numbers in brackets before indicators are defined in the same way as Table 4.5.

5. MODEL SPECIFICATION TESTS

Different alternate nested models have been tested to validate the multinomial logit models by checking whether they are statistically sound (Khorashadi et al. 2005). In the present study, five nested logit models as alternate model structures have been tested. The first one is (1) no injury, (2) possible injury, and (3) non-incapacitating injury/incapacitating injury/fatality. The second one is (1) no injury, (2) possible injury, (3) non-incapacitating injury, and (4) incapacitating injury/fatality. The third one is (1) no injury/possible injury, (2) non-incapacitating injury, and (3) incapacitating injury/ fatality. The fourth one is (1) no injury, (2) possible injury/non-incapacitating injury/incapacitating injury, and (3) fatality. The final one is (1) no injury/possible injury, (2) non-incapacitating injury, (3) incapacitating injury, and (4) fatality. In these five models, there is no reasonable level of confidence to reject the validity of the multinomial logit model used in this study for both the SV and MV datasets.

The likelihood ratio test is also conducted to verify the statistical justification of estimating SV and MV accidents separately in the present study. The method is conducted to check the significance of the combined model for all vehicle accidents (both SV and MV accidents) and two separate models for SV and MV only. The following formula is adopted to apply the likelihood ratio test (Ulfarsson and Mannering, 2004):

$$-2\left[L_N(\beta) - L_{N_s}(\beta^s) - L_{N_m}(\beta^m)\right] \tag{6}$$

where $L_N(\beta)$ is the log-likelihood at convergence of the all data model, with a coefficient β , $L_{N_s}(\beta^s)$ is the log-likelihood at convergence of the model estimated on the SV data subset, and $L_{N_m}(\beta^m)$ is the log-likelihood at convergence of the model estimated on the MV data subset. The test adopts χ^2 distribution with the degrees of freedom equal to the sum of the number of estimated coefficient in the SV and MV models minus the number of coefficients estimated on all data models.

With a P<0.001, the result of the test indicates that significant difference of severity likelihood exists between SV and MV accidents, which justifies the choice of modeling SV and MV accidents separately in the present study.

6. CONCLUSIONS AND RECOMMENDATIONS

In this study, ten-year detailed HSIS accident data on major interstate highways, U.S. highways, and state highways in Illinois were studied to disclose the safety risk nature of large trucks. The multinomial logit model was adopted to analyze the driver-injury severity of accidents involving trucks on rural highways. The result of the likelihood ratio test indicates that the injury mechanisms of SV and MV accidents involving trucks are clearly distinct. A comprehensive collection of different risk factors, including driver characteristics, vehicle characteristics, temporal characteristics, roadway characteristics, environmental characteristics, and accident characteristics, were included in the multinomial logit models. For the first time, single- and multi-vehicle accidents involving trucks were studied separately to identify those risk factors that have significant influence on driver-injury severity.

It is expected that the findings on risk factors in MV and SV accidents will add to the existing knowledge of injury studies about truck drivers. With the improved understanding of the injury severity of truck drivers, it is expected that more rational and effective injury prevention strategies may be developed for truck drivers by the trucking industry and related agencies, such as occupational safety and transportation agencies. In the meantime, some findings may be helpful for transportation agencies to evaluate and improve the existing designs of transportation infrastructure and traffic management systems. Finally, the present study can also help develop training and educational courses for truck drivers, state patrols, engineers, and the public.

The major findings in terms of different influences on injury severity in MV and SV accidents are summarized in the following.

(a) Some variables are only significant in the single-vehicle accident model but not in the multi-vehicle model and vice versa. According to the results of the present study, there are 16 variables that are only significant in the SV model while not in the MV model. Also, there are 16 variables that were found significant in the MV model only.

(b) Even if some variables were found significant in both SV and MV models, there is considerable difference of marginal effects on these two models. Some of them can have opposite effects for SV and MV accidents. There are also some variables that have significant difference of magnitudes even with the same trend. All the variables that have different influences on the injury severity in SV and MV accidents as discussed above are summarized in Tables 4.5 and 4.6.

The ultimate goal of any injury study is to provide scientific basis to potentially reduce injury severity through advancing the state-of-the-art of modeling, manufacturing, and policymaking. Therefore, among a large number of risk factors being investigated in the present study, it may be helpful to summarize those critical risk factors that have been rarely reported before, while causing more or less severe injury in truck-involved accidents. Depending on the impacts, these risk factors should be considered strategically in any future injury mitigation strategy, transportation design, or management.

(1) As shown in Tables 4.5 and 4.6, there are some risk factors that were found to be significant to the severity of truck-related accidents in the present study, but were rarely reported in the existing studies of truck-involved accidents. These risk factors include older driver, driver trapped/extract, driver was asleep/fainted, driver was fatigued, carrying hazardous material, light traffic, low truck percentage, Class I and II designated truck route, wide lane, wide median, no passing zone sign, stop sign/flasher, traffic signal, sharp curve, fog/smoke/haze, severe cross wind, hitting animal, truck overturn, truck jackknife, improper lane usage, driving on wrong side/wrong way, failing to reduce speed to avoid crash, truck was avoiding vehicle/objects, truck was passing/overtaking,

and truck was skidding/control loss indicators. In fact, some of these variables that are significant to the severity of SV or MV accidents would not have been identified if only the analysis of the data from all the accidents as a whole was conducted.

(2) Among those factors summarized above, which were rarely reported before, the injury severity analysis presented in this study revealed that several risk factors may lead to more severe injuries (higher probability of incapacitating injury/fatal) of truck drivers. These factors include older driver (SV accident), driver trapped/extract (both SV and MV accidents), driver was asleep/fainted (both SV and MV accidents), driver was fatigued (MV accidents), carrying hazardous material (both SV and MV accidents), wide lane (MV accidents), wide median (MV accidents), truck overturn (both SV and MV accidents), improper lane usage (SV accidents), failing to reduce speed to avoid crash (SV accidents), truck was avoiding vehicle/objects (MV accidents), truck was passing/overtaking (SV accidents), and truck was skidding/control loss indicators (both SV and MV accidents). These risk factors deserve special consideration in future transportation design, management, and policymaking.

(3) The injury of truck drivers was found less severe (lower possibility of incapacitating injury/fatality) under the following conditions: older driver (MV accidents), light traffic (both SV and MV accidents), low truck percentage (MV accidents), Class I designated truck route (both SV and MV accidents), Class II designated truck route (MV accidents), stop sign/flasher (SV accidents), traffic signal (SV accidents), no passing zone sign (MV accidents), severe cross wind (SV accidents), hitting animal (SV accidents), and truck jackknife (SV accidents). Some risk factors become helpful to reduce the probability of severe injury through complex interactions between driver behavior and measureable factors such as driving environment, which can play a significant role in truck driver injury severity.

Similar to most studies, the present study also has some limitations, such as the fact that data reflect information from a single US state, were obtained from a single database, and the fact that the truck types investigated are limited by the available types from the database. Future studies with multiple states, data from different databases, and more comprehensive truck types may be conducted, which may provide more comprehensive insights.

7. REFERENCES

Abdel-Aty, M., 2003. “Analysis of driver injury severity levels at multiple locations using ordered logit models.” *J. Safety Res.* 34 (5), 597–603.

Alassar, L., 1988. “Analysis of heavy large-truck accident severity.” *J. Adv. Transport.* 22 (1), 77–91.

Baker, C.J., 1991. “Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system.” *J. of Fluids and Structures* 5, 221–241.

Blower, D., K.L. Campbell, and P.E. Green, 1993. “Accident rates for heavy truck-tractors in Michigan.” *Accident Anal. Prevent.* 25, 307-321.

Brorsson, B., H. Rydgren, J. Ifver, 1993. “Single-vehicle accidents in Sweden: a comparative study of risk and risk factors by age.” *J. Safety Res.* 24, 55–65.

Campbell, K.L., 1991. “Fatal accident involvement rates by driver age for large large-trucks.” *Accident Anal. Prev.* 23 (4), 287–295.

Chang, L.-Y. and F. Mannering, 1999. “Analysis of injury severity and vehicle occupancy in truck- and non-truck-involved accidents.” *Accident Anal. Prevent.* 31 (5), 579–592.

Chen, S.R. and C.S. Cai, 2004. “Accident assessment of vehicles on long-span bridges in windy environments.” *Journal of Wind Engineering and Industrial Aerodynamics*, 92(12), 991-1024.

Chen, S.R. and F. Chen, 2010. “Simulation-based assessment of vehicle safety behavior under hazardous driving conditions.” *J. of Transportation Engineering*, ASCE. 136(4), 304-315.

Chen, F. and S.R. Chen (2011). “Injury severities of truck drivers in singe- and multiple-vehicle accidents on rural highway.” *Accident Analysis and Prevention*, 43, 1677-1688.

Chirachavala, T., D. Cleveland, L.P. Kostyniuk, 1984. “Severity of large-truck and combination-vehicle accidents in over-the-road service: a discrete multivariate analysis.” *Transport. Res. Rec*. 975, 23–36.

Daniel J. and S.I.J. Chien, 2004. “Truck safety factors on urban arterials.” *J. of Transportation Engineering*, ASCE. 130(6), 742-752.

Duncan, C., A. Khattak, F. Council, 1998. “Applying the ordered logit model to injury severity in truck-passenger car rear-end collisions.” *Transport. Res. Rec*. 1635, 63–71.

Geedipally S.R. and D. Lord, 2010, “Investigating the effect of modeling single-vehicle and multi-vehicle crashes separately on confidence intervals of Poisson gamma models.” *Accident Anal. Prevent*. 42(4), 1273-1282.

Golob T., W. Recker, and J. Leonard, 1987. “An analysis of the severity and incident duration of truck-involved freeway accidents.” *Accident Anal. Prevent*. 19(5), 375-396.

Holubowycz, O.T., C.N. Kloeden, and J.A. McLean, 1994. “Age, sex, and blood alcohol concentration of killed and injured drivers, riders, and passengers.” *Accident Anal. Prevent*. 26 (4), 483–492.

Islam, S. and F. Mannering, 2006. “Driver aging and its effect on male and female single-vehicle accident injuries: some additional evidence.” *Journal J. Safety Res*. 37 (3), 267–276.

Ivan, J.N., R.K. Pasupathy, and P.J. Ossenbruggen, 1999. “Differences in causality factors for single and multi-vehicles crashes on two-lane roads.” *Accident Anal. Prevent*. 31, 695–704.

Ivan, J.N., C. Wang, and N.R. Bernardo, 2000. “Explaining two-lane highway crash rates using land use and hourly exposure.” *Accident Anal. Prevent*. 32 (6), 787–795.

Joshua, S. and N. Garber, 1990. “Estimating truck accident rate and involvements using linear and Poisson regression model.” *Transportation Planning and Technology* 15, 41–58.

Jovanis, P., H. Chang, and I. Zabaneh, 1989. “Comparison of accident rates for two truck configurations.” *Transport. Res. Rec*. 1249, 18–29.

Jung, S., X. Qin, and D.A. Noyce, 2010. “Rainfall effect on single-vehicle crash severities using polychotomous response models.” *Accident Anal. Prevent*. 42, 213-224,

Khorashadi, A., D. Niemeier, V. Shankar, and F. Mannering, 2005. “Differences in rural and urban driver-injury severities in accidents involving large trucks: an exploratory analysis.” *Accident Anal. Prevent*. 37 (5), 910–921.

Kim J.K., S. Kim, G.F. Ulfarsson, and L.A. Porrello, 2007. “Bicyclist injury severities in bicycle-motor vehicle accidents.” *Accident Anal. Prevent*. 39(2), 238-251.

Kockelman, K. and Y. Kweon, 2002. “Driver injury severity: an application of ordered probit models.” *Accident Anal. Prev*. 34 (3), 313-321.

Lee, J. and F. Mannering, 2002. “Impact of roadside features on the frequency and severity of run-off-roadway accidents: an empirical analysis.” *Accident Anal. Prev*. 34 (2), 149–161.

Lord, D., S.P. Washington, and J.N. Ivan, 2005. “Poisson, Poisson-gamma and Zero Inflated regression models of motor vehicle crashes: balancing statistical fit and theory.” *Accident Anal. Prevent*. 37 (1), 35–46.

Lyman, S. and E.R. Braver, 2003. “Occupant deaths in large truck crashes in the United States: 25 years of experience.” *Accident Anal. Prevent*. 35(5), 731-739.

Malyshkina, N.V. and F.L. Mannering, 2009. “Markov switching multinomial logit model: an application to accident-injury severities.” *Accident Anal. Prevent*. 41(4), 829–838.

McFadden, D., 1981. In: C. Manski and D. McFadden (Eds.). *Econometric models of probabilistic choice. In Structural Analysis of Discrete Data with Econometric Applications.* MIT Press, Cambridge, MA.

Miaou, S.P., 1994. “The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions.” *Accident Anal. Prevent*. 26 (4), 471–482.

Miaou, S.P. and H. Lum, 1993. « Modeling vehicle accidents and highway geometric design relationships.” *Accident Anal. Prevent*. 25 (6), 689-709.

National Institute for Occupational Safety and Health (NIOSH) 2007. Truck driver occupational safety and health, 2003 conference report and selective literature review, Centers for Disease Control and Prevention, Department of Health and Human Services.

Noland R.B. and L. Oh, 2004. "The effect of infrastructure and demographic change on traffic-related fatalities and crashes: a case study of Illinois county-level data." *Accident Anal. Prevent*. 36 (4) , 525-532.

Qin, X., J.N. Ivan, and N. Ravishanker, 2004. "Selecting exposure measures in crash rate prediction for two-lane highway segments." *Accident Anal. Prevent*. 36 (2), 183–191.

Savolainen, P. and F. Mannering, 2007. "Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes." *Accident Anal. Prevent*. 39, 955–963.

Shankar, V.N. and F.L. Mannering, 1996. "An exploratory multinomial logit analysis of single-vehicle motorcycle accident severity." *J. Safety Res*. 27 (3), 183–194.

Shao, S.P., 1987. "Estimating passenger-vehicle driver injury severity in car/tractor-trailer collisions." *Accident Anal. Prev*. 19 (3), 207–217.

Shibata, A. and K. Fukuda, 1994. "Risk factors of fatality in motor vehicle traffic accidents." *Accident Anal. Prevent*. 26 (3), 391–397.

The National Academies, 2006. Where the weather meets the road – a research agenda for improving road weather system, Report in Brief, The National Academies.

Ulfarsson, G. and F. Mannering, 2004. "Differences in male and female injury severities in sport-utility vehicle, minivan, pickup and passenger car accidents." *Accident Anal. Prevent*. 36 (2), 135–147.

U.S. Department of Transportation (USDOT), 2005. Report to Congress on the Large Truck Crash Causation Study. Federal Motor Carrier Safety Administration, U.S. Department of Transportation.

Wahlberg A.E., 2008. "Meta-analysis of the difference in accident risk between long and short truck configurations." *J. of Risk Research*. 11(3), 315-333.