Factors Contributing to the Severity of Heavy Truck Crashes: A Comparative Study of Jiangxi and Shaanxi, China

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ABSTRACT

To understand heavy truck crash severity, a total of 1,818 sample crashes occurring over a six-year period (2011-2016) were recorded on four typical expressway segments in mountainous regions of Jiangxi and Shaanxi, China. The crashes were investigated using an ordered logit approach to determine the significant variables contributing to truck crash severity. Elasticity analysis was then used to measure the pseudoelasticity of each independent variable. A total of 12 explanatory variables, including less than three years driving experience of truck driver, type of commercial transport task of the vehicle, brake failure, speeding behavior, overloading condition, steep downhill grade of the road and slippery surface condition, hours between midnight and dawn, winter season, adverse weather, and head-on and rear-end collision types, were found to be statistically significantly correlated with the severity of truck crashes occurring on Jiangxi and Shaanxi mountainous expressways. Only truck drivers older than 55 years of age, presence of tunnel and runoff collision type were identified to have a significant and positive effect on the severity of truck crashes on Shaanxi expressways. Taken together, these findings provide useful guidance to develop safer design standards, stricter regulations and more efficient technical countermeasures in order to reduce or prevent the occurrence of serious heavy-truck crashes on mountainous expressways in China.

KEYWORDS: Truck crash, Injury severity, Mountainous expressway, Ordered logit model, Pseudoelasticity.

INTRODUCTION

Over the last two decades, the transportation industry in China has experienced an enormous growth in the use of large/oversized motor vehicles. The total number of mini, light, medium and heavy-duty trucks registered for use in China has increased from about 5.09 million in 2001 to more than 25.7 million in 2018 (China Statistical Yearbook, 2019). Similarly, the number of road traffic crashes has also increased, a large majority of which involved heavy-duty trucks (Chen and Zhang, 2016; Wang and Prato, 2019; Wang et al., 2019b), especially for those occurring in mountainous regions. In the United States, commercial heavy truck-related fatal crashes accounted for about 10% of all road traffic crashes from 2009-2011 and resulted in a total property loss of almost $250 billion (Chen and Xie, 2014). The commercial trucking situation is far more serious in China, as trucks comprise a larger share of the overall traffic flow (Chen and Zhang, 2016). In short, a number of alarming statistics reveal that heavy-duty trucks are a major contributing factor to serious road traffic crashes in China.

Given the human, social and economic costs and the consequences of truck crashes worldwide, it is necessary to determine the potential risk factors associated with these crashes, so as to gain a better understanding of their causes and suggest suitable countermeasures (Al-Khateeb, 2010). Considerable research efforts have been devoted to investigate the demographic characteristics of truck drivers (i.e., age, sex,

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educational background,… *etc.*) that may contribute to the occurrence of truck crashes (Zheng et al., 2018; Balakrishnan et al., 2019; Naghawi and Bannoura, 2019). For example, young, inexperienced male truck drivers have been identified to be at high risk for being involved in crashes (Chen and Zhang, 2016). The occupation of the driver is another potential risk factor for work-related crashes and injuries (Wang and Prato, 2019; Wang et al., 2019a; Wang et al., 2019b; Balakrishnan et al., 2019). Truck drivers, particularly those involved in long-distance commercial transport, are often exposed to extremely stressful conditions, including long working hours and irregular shifts (Chen and Zhang, 2016; Wang and Prato, 2019; Wang et al., 2019b). Additionally, they may be required to perform challenging, non-driving-related physical tasks, such as loading, unloading or heavy lifting. The combination of stress and lack of rest can deteriorate driving performance and increase the likelihood of a crash (Meng et al., 2015; Wang et al., 2019a).

There is a wealth of factors that affect the attributes of the driver besides driver fatigue, such as vehicle defects, environmental conditions and roadway geometry, which are associated with truck injury severity. Sameen and Pradhan (2016) found that the geometric design elements of the expressway (i.e., length of road segments, number of vertical curves in a road section, horizontal curve and distance to the nearest access point) and the annual average daily traffic (AADT) are significantly correlated with the crash frequency rate. Also, Qu *et al.* (2020) reported that the percentage of trucks and roadway access point density significantly affect the frequency of occurrence of traffic crashes. In addition, Wang *et al.* (2019) found that overspeeding and unsafe following behavior by the truck driver, roadway horizontal and vertical elements, external factors (i.e., time of the crash, day of the week, season) and weather conditions significantly affect the severity of the truck crash. Also, Ahmed *et al.* (2018) showed that the severity of heavy-truck crashes was significantly increased when the visibility was greatly reduced or during icy and snowy weather conditions.

However, despite numerous efforts, many problems associated with heavy-truck crashes remain unsolved today. Few studies over the past several years have focused on conducting an impact analysis to quantify various potential factors that contribute to truck crashes in China, especially those occurring on rural mountain expressways, where driver behaviors, geometric design elements and environmental conditions are quite different from those in other areas. The main purpose of this study was to quantify the potential risk factors associated with: i) the severity of truck crashes and ii) the pseudoelasticity of each contributing factor, using the truck crash data from four mountain expressways in Jiangxi and Shaanxi, China, reported over a recent 6-year timeframe. We anticipate that the findings of this study can serve as a guide in the development of safer design standards and effective management regulations for heavy-duty truck safety performance on expressways in mountainous regions of China.

METHODOLOGY

Data Preparation

We used crash statistics from a six-year timeframe (2011-2016) obtained from both the Traffic Accident Database (TADS) of the Department of Transportation of Shaanxi Province, China and the Department of Transport of Shaanxi Province, China. A total of 1,818 original crashes, comprising 806 cases from three segments in Jiangxi province and 1,012 from one segment in Shaanxi province, as shown in Figure 1, resulted in fatal and non-fatal injuries associated with at least one at-fault truck driver and were included in the final data analysis. Table 1 presents the independent variables characterizing driver, vehicle, roadway, environment and crash characteristics.

Table 1. Four mountainous expressway segments of crash data collection

Province	Segment	National expressway	Mileage (km)	Design speed (km/h)
Jiangxi	Changfu – Jinyushi	Shanghai – Kunming (G60)	168	100
	Liyuan – Wenjiazhen	Shanghai – Kunming (G60)	245	100
	Taihe – Ganzhou	Daqing – Guangzhou (G45)	128	100
Shaanxi	Laoyukou – Mianxian	Beijing – Kunming (G5)	254	60-100

Table 2. Variable description

Variable	Code	Jiangxi (*N*=806)		Shaanxi (*N*=1012)	
		Frequency	%	Frequency	%
Driver factors					
Gender	1 = Male	794	98.51	1001	98.91
	0 = Female	12	1.49	11	1.09
Age	1 = Less than 30	83	10.30	79	7.81
	2 = 30–55	687	85.24	892	88.14
	3 = More than 55	36	4.47	41	4.05
Driving experience	1 = Less than 3	296	36.72	397	39.23
	2 = 3-5	224	27.79	314	31.03
	3 = 5-15	167	20.72	177	17.49
	4 = More than 15	119	14.76	124	12.25
Alcohol consumption	1 = Yes	59	7.32	55	5.43
	0 = No	747	92.68	957	94.57
Seatbelt usage	1 = Yes	713	88.46	857	84.68
	0 = No	93	11.54	155	15.32
Vehicle factors					
Commercial transport	1 = Yes	760	94.29	877	86.66
	0 = No	46	5.71	135	13.34
Vehicle insurance	1 = Yes	709	87.97	917	90.61
	0 = No	97	12.03	95	9.39
Brake failure	1 = Yes	344	42.68	631	62.35
	0 = No	462	57.32	381	37.65
Speeding	1 = Yes	674	83.62	721	71.25
	0 = No	132	16.38	291	28.75
Overloading	1 = Yes	743	92.18	937	92.59
	0 = No	63	7.82	75	7.41
Roadway factors					
Roadway grade	0 = Level	161	19.98	133	13.14
	1 = Uphill	76	9.43	84	8.30
	2 = Downhill	569	70.60	795	78.56
Alignment	0 = Straight	599	74.32	663	65.51
	1 = Curve	207	25.68	349	34.49
Tunnel	1 = Yes	71	8.81	235	23.22
	0 = No	735	91.19	777	76.78
Roadway surface	1 = Slippery	464	57.57	465	45.95
	0 = Dry	342	42.43	547	54.05
Environment factors					
Time of day	1 = 0:00-6:00	388	48.14	451	44.57
	2 = 6:00-20:00	149	18.49	286	28.26
	3 = 20:00-24:00	269	33.37	275	27.17
Day of week*	1 = Holidays	108	13.40	116	11.46
	0 = Working days	698	86.60	896	88.54
Seasons*	1 = Spring	103	12.78	160	15.81
	2 = Summer	221	27.42	367	36.26

	3 = Autumn	114	14.14	104	10.28
	4 = Winter	368	45.66	381	37.65
Weather condition	1 = Adverse	559	69.35	578	57.11
	0 = Fine	247	30.65	434	42.89
Crash characteristics					
Collision outcome	1 = Slight injury	153	18.98	113	11.17
	2 = Severe injury	426	52.85	568	56.13
	3 = Fatal injury	227	28.16	331	32.71
Collision type	1 = Head-on	52	6.45	66	6.52
	2 = Sideswipe	139	17.25	140	13.83
	3 = Rear-end	264	32.75	308	30.43
	4 = Angle	183	22.70	158	15.61
	5 = Runoff	103	12.78	208	20.55
	6 = Rollover	65	8.06	132	13.04

* See references in (Wang and Prato, 2019) and (Wang et al., 2019b).

The injury severity in each crash sample was measured using a 3-point ordinal scale: slight, severe and fatal. Fatal injury referred to the cases when vehicle occupants sustained injuries leading to death, immediately or within 30 days of the crash; severe injury referred to the cases when vehicle occupants sustained injuries requiring hospitalization; and slight injury referred to the cases when vehicle occupants sustained minor injuries requiring no hospitalization. The distribution of injury severity levels in the Jiangxi and Shaanxi provinces was as follows: slight injury = 18.98 and 11.17%, severe injury = 52.85 and 56.13% and fatal injury = 28.16 and 32.71%, respectively.

Analytical Model

This study aimed to identify the effect of several contributing factors, including driver, vehicle, roadway, environmental conditions and collision type, on the injury severity in traffic crashes involving heavy trucks. Since the severity y_i of such a crash had three ordinal levels; namely, 1 = slight, 2 = severe and 3 = fatal, an ordered logit approach was proposed to model the linear relationship between the observed variables x_i affecting the injury severity and the latent injury level y_i^* as follows:

$$y_i^* = x_i^T \beta + \varepsilon_i \tag{1}$$

where $x_i = \{1, x_{i1}, x_{i2}, \ldots, x_{in}\}^T$ was a vector that represented the values of the i^{th} crash on the set of n independent variables, $\beta = \{\beta_0, \beta_1, \beta_2, \ldots, \beta_n\}^T$ was a vector of the regression coefficient to be determined and ε_i was a random error term that was normally distributed.

The relationship between the observed levels of the dependent injury severity y_i and the latent injury risk y_i^* was expressed by introducing the thresholds μ_1 and μ_2 as follows:

$$y_i = \begin{cases} 1 \text{ (slight injury)}, & if\ -\infty < y_i^* \le \mu_1 \\ 2 \text{ (severe injury)}, & if\, \mu_1 < y_i^* \le \mu_2 \\ 3 \text{ (fatal injury)}, & if\, \mu_2 \le y_i^* < +\infty \end{cases} \tag{2}$$

Thus, the probability P of the dependent variable was:

$$\mathrm{P}(y_i > j) = g(x_i^T \beta_j) = \frac{\exp(\mu_j - x_i^T \beta_j)}{1 + \exp(\mu_j - x_i^T \beta_j)}, j = 1,2 \tag{3}$$

where μ_j was a cutoff point (threshold) for the cumulative logit j.

Equivalently, Eq. (3) was rewritten using the cumulative probability distribution:

$$P\ (y_i = 1) = F(\mu_1 - x_i^T \beta_1) \tag{4a}$$

$$P(y_i = 2) = F(\mu_2 - x_i^T \beta_2) - F(\mu_1 - x_i^T \beta_1) \tag{4b}$$

$$P(y_i = 3) = 1 - F(\mu_2 - x_i^T \beta_2) \tag{4c}$$

where β parameters were estimated using the maximum likelihood method; these parameters represented the effects of each independent variable on injury severity, where positive β meant greater severity with the increase in the value of the corresponding variables. The following goodness-of-fit measure was also introduced:

$$\rho^2 = 1 - \frac{LL(\beta)}{LL(0)} \quad (5)$$

where $LL(\beta)$ was the log-likelihood value at convergence, $LL(0)$ was the log likelihood value at zero and ρ^2 varied between 0 and 1 with a higher value suggesting a better model fit. For a 95% confidence level, a p-value or probability less than 0.05 was considered statistically significant.

Elasticity Analysis

Pseudoelasticity approach was proposed to determine the effect of the m^{th} independent variable on the probability of the severity level k for truck crash i. The independent variables x_{kim} correlated with severity level k for crash i were considered to be 0 or 1, the direct pseudoelasticity values were represented as the percent change in probability, while the variable x_{kim} switched from 1 to 0 or from 0 to 1 (Washington et al., 2010):

$$E_{x_{kim}}^{P_{ki}(y_i>j)} = \frac{P_{ki}(y_i>j)[given\ x_{kim}=1] - P_{ki}(y_i>j)[given\ x_{kim}=0]}{P_{ki}(y_i>j)[given\ x_{kim}=0]}. \quad (6)$$

Ultimately, the pseudoelasticity value was calculated for each severity level and each crash record. An average direct pseudoelasticity value for each severity level was considered the average over the entire sample of truck crashes (Washington et al., 2010).

RESULTS

The results of model estimation in STATA 15 (StataCorp LLC, College Station, Texas, USA) are shown in Table 3, in which the significance of each independent variable was determined at the 0.05 significance level. A total of 12 independent factors exhibited significant association with truck crashes on two representative expressway segments in the mountainous regions of Jiangxi and Shaanxi provinces: inexperienced drive, commercial vehicle operation, brake failure, speeding behaviors, overloading condition, steep downhill grade, slippery pavement condition, hours between midnight and dawn, winter season, adverse weather and head-on and rear-end collision types. Old truck drivers of more than 55 years, presence of long tunnels and runoff collision type significantly affected the expressway truck crashes in Shaanxi. The goodness-of-fit test ρ^2 values were 0.336 and 0.378, respectively, indicating that the proposed models adequately predicted the likelihood of severe injuries in truck crashes in the Jiangxi and Shaanxi provinces of China. The pseudoelasticity of each independent variable at the 95% confidence level is shown in Table 4.

Table 3. Model estimation results

Variable	**Jiangxi**			**Shaanxi**		
	Coef.	**Std. Err.**	***p*-value**	**Coef.**	**Std. Err.**	***p*-value**
Driver characteristics						
Male	4.872	0.317	0.117	3.451	0.335	0.094
Age (base: less than 30 years)						
30–55 years	-2.360	0.445	0.072	-3.064	0.477	0.138
More than 55 years	-2.429	0.363	0.055	2.860	0.354	0.019
Driving experience (base: more than 15 years)						
Less than 3 years	-5.339	0.527	<0.001	-4.371	0.490	<0.001
3-5 years	-2.762	0.459	0.053	-2.933	0.426	0.091
6-15 years	-2.479	0.309	0.171	-2.617	0.339	0.066
Alcohol consumption	-3.082	0.356	0.067	-2.887	0.317	0.103
Failure to use seatbelt	4.764	0.441	0.114	5.393	0.514	0.089

Vehicle factors						
Commercial transport	1.976	0.294	0.009	-2.335	0.369	<0.001
Vehicle insurance	-2.267	0.377	0.227	-3.194	0.391	0.084
Brake failure	11.375	0.560	<0.001	15.667	0.684	<0.001
Speeding	6.761	0.542	<0.001	8.373	0.578	<0.001
Overloading	9.033	0.293	<0.001	12.633	0.336	<0.001
Roadway factors						
Roadway grade (base: level)						
Uphill	-1.362	0.233	0.151	-2.390	0.167	0.061
Downhill	5.809	0.515	0.031	7.762	0.646	0.016
Curve	-2.910	0.286	0.086	-2.995	0.265	0.063
Tunnel	-0.994	0.194	0.174	6.461	0.184	0.013
Slippery roadway surface	6.737	0.663	<0.001	11.044	0.717	<0.001
Environment factors						
Time of day (base: 6:00-20:00*)*						
0:00-6:00	6.669	0.447	0.027	5.316	0.535	0.006
20:00-24:00	-2.374	0.206	0.112	-3.087	0.410	0.175
Holidays	-1.677	0.191	0.239	-2.224	0.317	0.080
Seasons (base: Spring)						
Summer	-4.870	0.405	0.044	-5.264	0.473	0.017
Autumn	-1.603	0.133	0.266	-1.079	0.264	0.106
Winter	5.761	0.484	0.019	7.443	0.555	0.007
Adverse weather	8.775	0.570	<0.001	12.917	0.676	<0.001
Crash characteristics						
Collision type (base: sideswipe*)*						
Head-on	1.769	0.233	<0.001	1.660	0.144	<0.001
Rear-end	3.775	0.440	<0.001	4.022	0.423	<0.001
Angle	-2.861	0.367	0.067	-4.351	0.459	0.115
Runoff	-3.515	0.384	0.091	6.719	0.565	0.003
Rollover	4.030	0.561	0.108	4.863	0.470	0.074
Threshold parameters						
μ_1	-8.296	0.542	<0.001	-8.749	0.626	<0.001
μ_2	-6.857	0.467	<0.001	-7.335	0.508	<0.001
Model goodness-of-fit statistics						
Number of observations	806			1012		
$LL(\beta)$	-371.864			-455.918		
$LL(0)$	-247.069			-283.655		
ρ^2	0.336			0.378		

Table 4. Pseudoelasticity for explanatory variables

Variable	Jiangxi /%			Shaanxi /%		
	Slight injury	Severe injury	Fatal injury	Slight injury	Severe injury	Fatal injury
Driver characteristics						
Male	6.39	4.76	-2.16	7.27	3.37	-1.59
Age (base: less than 30)						
30–55	5.11	3.35	-1.04	5.71	3.57	-3.90
More than 55	-5.31	3.07	1.86	-3.17	4.93	6.24
Driving experience (base: more than 15)						
Less than 3	5.76	2.97	1.88	4.94	3.76	6.29
3-5	2.57	-1.49	0.63	1.66	-2.22	1.31
6-15	-1.52	-0.76	-0.59	-3.61	-3.28	-2.66
Alcohol consumed	1.23	-3.26	2.18	0.90	1.43	1.22
Failure to use seatbelt	-0.49	1.67	1.92	-0.94	1.77	1.89

Vehicle factors						
Commercial transport	4.07	-5.45	5.03	3.16	5.84	7.56
Vehicle insurance	2.19	-1.55	-1.07	1.93	-2.17	-0.84
Brake failure	-6.89	14.86	18.84	-8.49	19.37	25.46
Speeding	-2.45	5.49	6.76	-4.55	7.67	9.11
Overloading	-1.46	3.73	5.89	-2.27	4.19	7.44
Roadway factors						
Roadway grade (base: level)						
Uphill	1.52	-2.17	1.76	0.66	-1.63	0.87
Downhill	-2.37	3.61	4.55	-2.20	5.14	6.38
Curve	-2.77	1.65	2.24	1.88	-2.76	1.22
Tunnel	2.16	1.48	-0.77	3.85	-3.51	4.83
Slippery roadway surface	2.17	-3.62	2.85	-6.04	5.57	4.39
Environment factors						
Time of day (base: 6:00-20:00*)*						
0:00-6:00	-2.76	3.59	5.51	-3.22	5.77	3.64
20:00-24:00	1.25	-2.34	-1.75	-1.83	2.51	3.81
Holidays	-2.31	1.76	1.38	1.80	1.22	-1.77
Seasons (base: Spring)						
Summer	0.77	0.83	1.62	1.15	-1.67	2.87
Autumn	-0.33	-0.67	-0.41	-0.55	-1.02	-0.69
Winter	4.89	-3.76	2.68	-3.71	2.55	3.86
Adverse weather	-7.63	9.77	6.49	-6.16	10.49	14.62
Crash characteristics						
Collision type (base: sideswipe*)*						
Head-on	-4.78	11.26	10.87	-5.44	9.79	12.12
Rear-end	-10.72	7.03	11.49	-9.79	7.66	12.17
Angle	2.97	-8.66	-7.67	3.69	6.32	-10.75
Runoff	3.87	2.31	-1.76	-8.20	11.98	8.33
Rollover	-5.14	3.15	2.32	-4.73	4.29	4.31

The driving experience of the drivers was divided into four categories; namely, less than 3 years, 3-5 years, 6-15 years and more than 15 years. The driving experience of more than 15 years was considered as a reference. Significant difference was observed between truck drivers with less than 3 years and those with more than 15 years of driving experience (see Table 3). Driving experience of less than 3 years did not violate the assumption and had a negative coefficient (Jiangxi: coef. = -5.339, p-value < 0.001; Shaanxi: coef. = -4.371, p-value < 0.001). These findings indicate that truck drivers with less than 3 years of truck driving experience are more likely to sustain severe physical injuries in traffic crashes than those with more than 15 years of driving experience. A larger increase in injury severity probabilities was identified in truck crashes involving drivers with less than 3 years of driving experience in both Jiangxi (slight injury: 5.76%; severe injury: 2.97%; fatal injury: 1.88%) and Shaanxi (slight injury: 4.94%; severe injury: 3.76%; fatal injury: 6.29%) provinces, as shown in Table 3. Drivers aged 55 years and older in Shaanxi were more likely than younger drivers to sustain severe injuries (coef. = 2.860, p-value = 0.019), showing an increase of 4.93% and 6.24% in severe and fatal injury probabilities and a decrease of 3.17% in slight injury probability.

Among vehicular factors, brake failure had a significantly positive correlation with injury severity (Jiangxi: coef. = 11.375, p-value < 0.001; Shaanxi: coef.= 15.667, p-value < 0.001). In fact, truck drivers involved in a crash caused or affected by brake failure are more likely to result in serious injuries (see Table 3). Also, due to brake failure, increases of 14.86% and 19.37% in severe injury probabilities and 18.84% and 25.46% in fatal injury probabilities and decreases of 6.89% and 8.49% in slight injury probabilities were observed in truck crashes in Jiangxi and Shaanxi provinces (see Table 4), respectively. The commercial conditions of the truck clearly had significant effects on injury severity (Jiangxi: coef. = -1.976, p-value = 0.009; Shaanxi: coef. = 2.335, p-value < 0.001), as shown in Table 3. A decrease of 5.45% in severe injury probability and an increase of 4.07% and 5.03% in slight and fatal injury probabilities were identified in crashes involving commercial truck in Jiangxi province (see Table 4). In Shaanxi province, commercial vehicle operation decreased slight injury probability by 3.16%, but increased severe and fatal injury probabilities by 5.84% and 7.56%, respectively.

As anticipated, speeding (Jiangxi: coef. = 11.375, *p*-value < 0.001; Shaanxi: coef. = 15.667, *p*-value<0.001) and overloading (Jiangxi: coef. = 6.761, *p*-value < 0.001; Shaanxi: coef. = 8.373, *p*-value < 0.001) behaviors were also found to be positively associated with crash injury severities (see Table 3). In Jiangxi province, a larger change in injury severity probabilities was observed for truck drivers with speeding (slight injury: -2.45%; severe injury: 5.49%; fatal injury: 6.76%) and overloading (slight injury: 1.46%; severe injury: 53.73%; fatal injury: 5.89%) behaviors (see Table 4). Similar results were found among truck drivers involved in crashes in Shaanxi province.

Regarding road factors, wet road surface conditions had a positive influence on the severity of the truck crash (Jiangxi: coef. = 6.737, *p*-value = 0.005; Shaanxi: coef. = 11.044, *p*-value < 0.001) and increased the slight (2.17%) and fatal (2.85%) injury probabilities, but decreased the severe (3.62%) injury probability in Jiangxi province, as shown in Table 4. Wet roads greatly increased the severe (5.57%) and fatal (4.39%) injury probabilities and decreased the slight (6.04%) injury probability in Shaanxi province. The presence of tunnels had a significantly positive effect on injury severity for crashes in Shaanxi province (coef.=6.461, *p*-value = 0.013), increasing slight and fatal injury probabilities by 3.85% and 4.83% while decreasing severe injury probability by 3.51%.

There were three categories of roadway grades; namely, level, uphill and downhill and the level category was considered as the reference. As shown in Table 2, there was a significant difference between level and downhill roads, but none between level and uphill roads. The downhill roadway grade violated the assumption and had a positive coefficient (Jiangxi: coef. = 5.809, *p*-value = 0.031; Shaanxi: coef. = 7.7762, *p*-value = 0.016), indicating that drivers involved in a truck crash in a downhill segment are more likely to result in serious injuries than those in a level segment. A decrease in slight injury probabilities of 2.37% and 2.20% and an increase in severe injury probabilities of 3.61% and 5.14% and fatal injury probabilities of 4.55% and 6.38% were observed in Jiangxi and Shaanxi provinces (see Table 4), respectively.

Regarding environmental factors, adverse weather was positively correlated with injury severity (Jiangxi: coef. = 8.775, *p*-value < 0.001; Shaanxi: coef. = 12.917, *p*-value<0.001). According to the data shown in Table 3, adverse weather conditions reduced the slight (Jiangxi: 9.77%; Shaanxi: 6.16%) injury probabilities and increased the severe (Jiangxi: 7.63%; Shaanxi: 6.49%) and fatal (Jiangxi: 10.49%; Shaanxi: 14.62%) injury probabilities. The time of the day was split into three time-period categories: 0:00 ~ 6:00, 6:00 ~ 20:00 and 20:00 ~ 24:00 using the 6:00 ~ 20:00 period as the reference category. Significant difference was found between the 0:00 ~ 6:00 and 6:00 ~ 20:00 periods, but not between the 6:00 ~ 20:00 and 6:00 ~ 20:00 periods (see Table 3). The specific 0:00 ~ 6:00 period violated the proportional odds assumption with a positive coefficient (Jiangxi: coef. = 6.669, *p*-value = 0.027; Shaanxi: coef. = 5.316, *p*-value = 0.006), thus it can be inferred that drivers involved in a truck crash occurring between midnight and 6:00 a.m. are more likely to sustain serious injuries than those involved in crashes at other times of the day. The 0:00~6:00 period decreased slight injury probabilities by 2.76% and 3.22%, but increased severe injury probabilities by 3.59% and 5.77% and fatal injury probabilities by 5.51% and 3.64% in Jiangxi and Shaanxi provinces (see Table 4), respectively.

Seasons were, naturally, split into four categories; namely, spring, summer, autumn and winter, using spring as the reference. The modeling results showed a significant difference between summer and spring as well as between winter and spring, but none between autumn and spring (see Table 3). Summer did not violate the assumption and had a negative coefficient (Jiangxi: coef.= - 4.870, *p*-value = 0.044; Shaanxi: coef. = -5.264, *p*-value = 0.017), indicating that drivers involved in a truck crash on a summer day are not likely to sustain serious injuries compared to those involved in crashes occurring on a spring day. A larger change in injury severity probabilities was observed in samples of crashes occurring on summer days in Shaanxi province (slight injury: 1.15%; severe injury: -1.67%; fatal injury: 2.87%) than those in Jiangxi province (slight injury:

0.77%; severe injury: 0.83%; fatal injury: -1.62%), as shown in Table 4. Winter season violated the assumption with a positive coefficient (Jiangxi: coef. = 5.761, *p*-value = 0.019; Shaanxi: coef. = 7.443, *p*-value = 0.007) and considerably changed the probability of certain injury severity level in the Jiangxi (slight injury: 4.89%%; severe injury: -3.76%; fatal injury: 2.68%) and Shaanxi (slight injury: -3.71%; severe injury: 2.55%; fatal injury: 3.86%) provinces.

Collision types were divided into six categories: head-on, rear-end, sideswipe, angle, runoff and rollover; sideswipe was used as the reference. Significant differences were found between head-on and sideswipe, rear-end and sideswipe and rollover and sideswipe, but not between angle and sideswipe or rollover and sideswipe. The rear-end collision type did not violate the assumption and had a negative coefficient (Jiangxi: coef. = -3.775, *p*-value < 0.001; Shaanxi: coef. = - 4.022, *p*-value < 0.001), indicating that truck drivers involved in a rear-end collision are unlikely to sustain serious injuries compared to those who are involved in a sideswipe collision. Truck drivers involved in a real-end collision were associated with a reduction of 10.72% and 9.79% in slight injury probabilities and an increase of 7.03% and 7.66% in severe injury probabilities and 11.49% and 12.17% in fatal injury probabilities in Jiangxi and Shaanxi provinces (see Table 4), respectively.

The head-on collision type also violated the assumption and had a positive coefficient (Jiangxi: coef. = 1.769, *p*-value < 0.001; Shaanxi: coef. = 1.660, *p*-value < 0.001), indicating that head-on collision is more likely to result in serious injuries to the drivers involved. An increase of 11.26% and 9.79% in severe injury probabilities and 10.87% and 12.12% in fatal injury probabilities and a decrease of 4.78% and 5.44% in slight injury probabilities were identified for head-on collisions. Interestingly, the runoff collision type was positively associated with collision severity in Shaanxi province (coef. = 6.719, *p*-value = 0.003), but not in Jiangxi province (see Table 3). An increase of 11.98% and 8.33% in severe and fatal injury probabilities and a reduction of 8.20% in slight injury probability were found in runoff truck crashes in Shaanxi province (see Table 4).

DISCUSSION

The results of the statistical analysis performed in this study indicated that commercial truck drivers with less driving experience have a significantly higher propensity to crash than the others with more experience. These drivers also need to be more frequently behind the wheel and for longer time than their more experienced co-workers and often at night. As a result, they are generally more susceptible to loneliness, boredom, stress and high workloads which exhaust them more quickly and make them less responsive to emergency situations in the long run (Moonaghi et al., 2015; Wang et al., 2019a). Additionally, these drivers more often exhibit violations or high-risk driving behaviors, such as speeding and overloading, all of which in turn increase the probability of a severe crash involvement (Chen and Zhang, 2016; Naghawi and Bannoura, 2019; Wang and Prato, 2019; Wang et al., 2019b; Filtness et al., 2020).

Therefore, it is urgently needed to take effective action to improve the overall safety level of commercial truck driving. Stricter regulations should be implemented to limit the maximum continuous driving duration of commercial truck driver per shift and require a minimum rest period between shifts, as well as maximum daily, weekly and fortnightly driving hours. Additionally, measures should be taken to prohibit risky driving behaviors, especially for drivers with less experience. Employers should be required to reduce the heavy burden on specific truck drivers undertaking long-distance transport tasks. More importantly, these results strongly suggest that it is imperative to cut down the high-toll charge in order to reduce the transport cost as well as the propensity of drivers to overload their vehicles. In addition, it is necessary to provide larger parking facilities and services at rest stations to make breaks more attractive and convenient for truck drivers.

Moreover, the results showed that brake failure is a major risk factor associated with truck accidents on mountainous expressways in China. Accordingly, truck drivers should be strongly required to follow the speed signs, road markings and load restrictions and to check the brake system before entering a long downhill grade. The modeling results also showed that segments with sharp curves and steep slopes significantly increase the potential risk of heavy-truck crashes in mountainous regions, in line with previous studies (Dong et al., 2015; Sameen and Pradhan, 2017; Wang and Prato, 2019; Wang et al., 2019b). Interestingly, this study revealed that 20.55% of the total accident samples from the Xi'an-Hanzhong Expressway segment, in Shaanxi province, belong to single-vehicle, runoff crashes related to poor geometric design factors, such as steep grades and sharp horizontal curves. Therefore, it should be strongly required to avoid such high-risk elements in designing new mountainous expressways. If possible, climbing lanes can be installed to help heavy trucks travel up the gradient safely and efficiently (Shihabi, 2017). Specially, the presence of long tunnels is associated with increased severity of crash injuries in Shaanxi province. Thus, it is worthwhile to help truck drivers adapt to sudden changes in lighting inside and outside long tunnels to prevent crashes. Drivers should also be alerted to icing conditions at the exit of lengthy tunnels in isolated, high-altitude areas.

Among the environmental factors evaluated in this study, the time of the day was shown to affect the probability of occurrence of a crash most negatively. In particular, midnight to 6 a.m. is the period with the highest risk for long-distance commercial truck drivers to be involved in a crash, most likely due to driver fatigue. During this period, commercial drivers often use alcohol, caffeine or music to keep themselves awake, but these measures can sometimes impair their driving ability and thus increase the injury severity (Sharwood et al., 2013; Brodsky and Slor, 2013; Marquis and Wang, 2015; Wang and Prato, 2019; Wang et al., 2019b; Filtness et al., 2020). However, in this study, alcohol consumption was not found to be a statistically significant factor contributing to the injury severity in heavy-truck crashes and the possible explanation lies in the small percentage of the sample (Jiangxi: 7.32%; Shaanxi: 5.43%) in the total crash observation. This finding, to a large extent, reflects that China has been rigorously enforcing drunk driving laws and has achieved good results in recent years. As anticipated, bad weather can also severely impact driver visibility and the braking distance of trucks (Lan et al., 2019). The expressway management office should provisionally remind truck drivers to slow down or close specific entrance ramps as necessary.

CONCLUSIONS

This study collected a crash sample of 1,818 crashes involving at least one at-fault heavy truck from four representative expressway segments in mountainous regions of the provinces of Jiangxi and Shaanxi, China. The collected data was used to compare the risk factors contributing to traffic injury severity as well as the average pseudoelasticity of each independent factor in these two provinces. Less experienced truck drivers (less than three years), commercial transport task of the vehicle, brake failure, traffic offences, such as speeding and overloading, steep downhill grade on roadway, slippery pavement condition, time period from midnight to early morning, winter season, adverse weather and head-on and rear end collision types, were identified as having a significant impact on the injury severity in truck crashes occurring in these two provinces. Only old truck drivers (55 years or older), presence of tunnels and runoff collision type were found to have significant influence on the severity of the truck crashes in Shaanxi province. These important findings can eventually help improve the safety level in the design of mountainous expressway and operation management process in China.

This study has several technical limitations that should be considered. First, the original crash data from 2011 to 2016 was obtained from four mountainous expressways in two provinces of China, which may be not generalizable to the whole country. Second, the influence of affecting parameters on the injury severity outcomes may have temporal instability across different time periods. Thus, temporal stability and unobserved heterogeneity problems should be seriously considered in future investigation. Finally, it is important to comprehensibly analyze the influence in more depth, such as individual-level socioeconomic factors, driving behavior variables and detailed environmental contributors, on the probability of occurrence and injury severity using advanced statistical modeling approaches.

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