Title: The effect of fatigue driving on injury severity considering the endogeneity

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Abstract

Introduction: Fatigue driving is one of the most risky driving-related behaviors and represented a significant social and economic cost to the community. Several studies have already examined the relationship between fatigue driving behavior and traffic injury severity from different aspects. However, fatigue driving and injury severity in traffic crash may share some common influential factors. Ignoring the impact of these common factors will lead to endogeneity problem and result in biased parameter estimation. *Method:* Based on 38,564 crash records during 2006-2011 in Guangdong province, China, we apply a bivariate endogenous binary-ordered probit model to examine the relationship between fatigue driving and injury severity considering

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endogeneity of fatigue driving. We also explore the difference of influential factors between commercial and non-commercial vehicle drivers. *Results:* This study identifies several common observed influential factors of fatigue driving propensity and fatal injury propensity and reveals a substantial and significant negative correlation of unobserved factors between them. *Conclusions:* The influence of fatigue driving on injury severity is significantly underestimated if the endogeneity of fatigue driving on fatal injury propensity is ignored. Factors such as vehicle insurance and road types not only affect fatal injury propensity, but also fatigue driving propensity. *Practical applications:* The findings in this study can help better understand how those factors affect fatigue driving and injury severity, and contributes to more efficient policy for preventing the harmfulness of fatigue-related crashes.

Keywords: Fatigue driving, Endogeneity, Injury severity, Commercial vehicle driver

1. Introduction

Road safety has already become a great threat to human being all around the world. According to *Global Status Report on Road Safety 2015* by World Health Organization (World Health Organization, WHO, 2015), more than 1.2 million people die each year, with millions more sustaining serious injuries and living with long-term adverse health consequences. In low- and middle-income countries, traffic injuries have become one of the leading causes of death and cost approximately 3% of their GDP as a result of traffic crashes (WHO, 2015).

Fatigue driving was identified as one of the four most risky driving-related behaviors, especially in fatal traffic crashes (Fernandes et al., 2010) and represented a significant social and economic cost to the community. Approximately 20% of fatal crashes in Canada involved driver fatigue, eliminating the influence of alcohol, speeding and unsafe passing (Canadian Council of Motor Transport Administrator, CCMTA, 2010). In Australia, 20-30% of all fatal traffic crashes were found due to fatigue driving (Australian Transport Council, ATC, 2010). However, this situation could be worse in developing countries since those countries include most of traffic crashes worldwide (WHO, 2015). A questionnaire-based research among commercial bus drivers in Malaysia found that the prevalence of fatigue among commercial bus drivers was 37.7% (Fadhli et al., 2008). Statistics from China also showed that 1,271 (0.83% of total number of crashes due to any cause) crashes were caused by fatigue driving in 2013, with 677 (1.16% of total number of people killed in the crashes due to any cause) people killed, 1,600 (0.75% of total number of people injured in crashes due to any cause) people injured, and over RMB 37 million in property losses (Traffic Management Bureau, Ministry of Public Security, PRC, 2013). China seems to have lower fatal fatigue-related crash rate than Canada and Australia. The reason for this contrast may be related to their criterion for calculating the "crash rate". The fatigue crash rate in the statistics of Canada and Australia is calculated using the number of crash which "fatigue is one of the contributing factors". However, the fatigue-related crash rate for China is calculated by the number of crashes which "fatigue is the major cause of crash". In this case, China is applying a much narrower concept in calculating fatigue-related crash rate than Canada and Australia. Applying the similar criteria, UK estimated the fatigue-related crash rate should be around 2% of all crashes in 2015 (Department for Transport, UK, 2016), which the fatigue-related rate is much closer to China. Although the reported fatigue-related crash rate of China is not so high, we can still speculate that the crash rate for "fatigue is one of the contributors of crash" would be much higher.

Despite extensive body of research addressing the harmfulness of fatigue driving on road safety, it has not attracted enough attention. Drivers were less concerned about fatigued driving than other traffic safety issues (Vanlaar et al., 2008). Studies from different countries showed that many people still drove when they felt fatigue (Beirness et al., 2005; Nordbakke & Sagberg, 2007; Tefft, 2010). Besides drivers, public are also not fully aware of the potential risk of fatigue driving because it is difficult to evaluate its effect accurately. For example, fatigue could be resolved after a period of rest (Karrer et al., 2004), this feature made it hard to detect and identify after crashes occurred. When other risky driving behaviors are involved, it is even harder to tell what the major contributor is and may lead to misclassification of the cause of crash (Horne & Reyner, 1995; Philip et al., 2005; Armstrong et al., 2008). In addition, police also tended to assign the cause of crash to current interest (Ogden & Moskowitz, 2004).

Several studies have examined the relationship between fatigue driving and traffic injury severity from different aspects. However, fatigue driving and injury severity in traffic crashes may share some observed common influential factors (e.g. road types). There are also some unobserved factors between fatigue driving and injury severity. The connection between sleep disorder, fatigue and traffic injury severity were discussed by many researchers (Akerstedt et al., 2001; Horne & Reyner, 2001; Philip et al., 2003; Stutts et al., 2003). Ignoring the impact of these common factors will lead to endogeneity problem and incorrect conclusion. This study contributes toward current fatigue driving research by applying a bivariate endogenous binary-ordered probit model framework to examine the relationship between fatigue driving propensity and fatal injury propensity in a crash considering the potential endogeneity of fatigue driving. Considering the potential systematic differences between commercial and non-commercial vehicle drivers, this model also identifies the observed common factors of fatigue driving and injury severity for two groups of drivers and makes a comparison. This result may help better understand how those factors affect fatigue driving propensity and injury severity, and contributes to more efficient policy for preventing the harmfulness of fatigue-related crashes. The analysis includes several types of factors, including driver characteristics, vehicle characteristics, road characteristics, environmental characteristics, and collision characteristics.

The rest of this paper is arranged as follows: In section 2, we review related literature of factors affecting fatigue driving propensity and injury severity in a crash. We present the methodology in section 3, and data source and sample descriptive statistics in section 4. Empirical analysis and discussion of estimation results are presented in section 5. Conclusions and practical applications are provided in section 6.

2. Literature Review

Fatigue is a gradual and cumulative process closely related to deterioration of performance efficiency like driving performance (Haworth, 1998; Rajaratnam & Arendt ,2001; Philip et al., 2005), and could be induced by repetitive and monotonous activities like driving long distances (Stutts et al., 1999). Research pointed out that fatigue was not a strictly monotone decreased progress (Karrer et al., 2004), but an interaction between deactivation and compensation processes, resulting in variability of performance (Dinges & Kribbs, 1991).

As for the influential factors related to fatigue driving, prior studies basically focused on four categories: driver characteristics, road characteristics, environmental characteristics and vehicle characteristics. Considering driver characteristics, male drivers were at high risk of fatigue driving for the reason that males were more likely to drive for a longer time (Fernandes et al., 2010; Amstrong et al., 2011). In Amstrong et al. (2008)'s study, it was found that drivers aged 17-24 years were more likely to be involved in a fatigue-related crash. However, the influence of age is much more complicated and there exist different behavior patterns between young drivers and elder drivers. Young drivers frequently committed their fatigue-related offenses during early morning and night-time hours (Horne & Reyner, 1995; Pack et al., 1995; Maycock, 1996; Horne & Reyner, 2001) while elder drivers mostly in the afternoon (Summala & Mikkola, 1994). In addition, the motivation for driving while fatigue for young drivers might be their overestimation of capabilities (Gregersen & Bjurulf, 1996) and miscalculation of the cost of consequence (Fernandes et al., 2010).

For road characteristics and environmental characteristics, driving on different types of road can lead to similar consequence. Both high-demand and low-demand road condition could induce driver fatigue (Oron-Gilad et al., 2008; Zhao & Rong, 2013). Dyani (2007) divided driver fatigue into two groups: passive fatigue and active fatigue. Passive fatigue was defined closely related to underload, which has been confirmed by simulated driving studies in monotonous condition (Desmond & Hancock, 2001; Thiffault & Bergeron, 2003). Active fatigue was defined related to overload of driver. For example, poor road condition (Arnold et al., 1997), complex traffic conditions and road environments (Pilcher & Huffcutt, 1996) required more attention and could easily induce physical and mental fatigue. Time of day was mentioned by several fatigue-related studies. Folkard (1997) has reviewed several researches that studied the relationship between road safety and time of day. It was widely believed that time of day were closely related to human rhythms, which was identified as an important factor affecting driver fatigue (Haworth, 1998; Philip et al., 2005). Horne and Reyner (2001) found that 02:00-06:00 and 14:00-16:00 is time period associated with higher probability of fatigue. Haworth (1998) also pointed out that nighttime is significant contributor of fatigue-related crashes. Light level (Sullivan & Flannagan, 2002) and season were also identified to play important role (Radun & Radun, 2009).

Nevertheless, fatigue-related crashes are severe among commercial vehicle drivers. Statistics from Europe pointed out that approximately 20% of commercial vehicle crashes were related to driver fatigue (European Transport Safety Council, ETSC, 2001). The causes of fatigue varied since fatigue could be developed while on the job with regular sleep patterns or arrived at work already fatigued with irregular sleep patterns (Young & Hashemi, 1996). Commercial vehicle drivers suffered from sleep restriction (Hanowski et al., 2007) and were under great work pressure, which made them vulnerable to fatigue-related crashes. Specifically, drivers in developing countries are more likely to drive while fatigue for financial reasons (Mock et al., 1999; Nantulya & Muli-Musiime, 2001). Surveys conducted among truck and taxi drivers in Beijing, China, showed that driver fatigue was prevalent and the most important reason was prolonged driving time (Meng et al., 2015).

Even though it is not in agreement, fatigue driving and injury severity in the crash may share some common influential factors, including observed and unobserved factors. Radun and Radun (2009) claimed that there was no connection between crash severity and whether the driver was judged to have been fatigued. However, more studies believed there existed some kind of connection (Haworth, 1998; Zhang et al., 2016). Fatigue-related crashes were often severe that drivers could not take evasive action under fatigue (Haworth, 1998). Some factors related to fatigue driving may impair driver performance, then affect injury severity. For example, some unobserved factors related to the driver's internal state and circadian cycle can also affect both fatigue propensity and driving performance (Williamson et al. (2011) has given a detail review on that). Unfortunately, these information was almost impossible to collect due to traumatic effects and emotional state change after the crash (Radun & Radun, 2009). Some drivers might not admit fatigue or falling asleep during driving concerning about insurance and legal consequences (Corfitsen, 1999). Therefore, those common factors were often neglected, which may lead to endogeneity problem and biased estimation when analyzing the relationship between fatigue driving and injury severity.

3. Econometric Framework

3.1. Model structure

In fatigue-related crashes, drivers who are more likely to be involved in fatigue-related crashes and injury severity can be correlated, which may cause endogenous problem. In econometrics, endogeneity problem is said to occur if the independent variable is correlated with the error term. This correlation can be caused by several reasons: omitted variables, measurement error, and simultaneity in simultaneous equations models. Endogeneity induces estimation bias in statistical models and may eventually lead to mistaken conclusions. To take into account the potential endogeneity of fatigue driving, we apply a bivariate endogenous binary-ordered probit model in the current paper. Bivariate endogenous binary-ordered probit model is a hierarchical model system of two equations that can be used to model two response variables simultaneously, and addresses endogeneity problem. This model addresses endogeneity by considering error correlations among two equations that capture the relationships among endogenous variable, exogenous variables and error term (for further discussion, see Greene, 2007; Fernandez-Antolin et al., 2014).

Let i ($i = 1, 2, ..., N$) be an index representing drivers and k ($k = 1, 2, ..., K$) be indices representing ordinal categories of injury severity sustained by driver i in the crash. Suppose y_i is the observed injury severity level and y_i^* represents latent injury severity propensity of driver i in the crash. Thus, the latent propensity y_i^* is mapped to the actual injury severity level y_i by threshold ψ_k ($\psi_0 = -\infty$ and $\psi_K = \infty$, $\psi_0 < \psi_1 < \cdots < \psi_K$) as the following equations:

$$y_i^* = \alpha' x_i + \theta\, fatig_i + v_i, \tag{1}$$

$$y_i = k, \ \text{ if } \psi_{k-1} \le y_i^* < \psi_k \tag{2}$$

where x_i is an M×1 column vector of variables that influences y_i^* (not including a constant) and $fatig_i$ is a dummy variable indicating whether driver i is convicted as fatigue driving or not. α represents an M×1 coefficient vector of x_i and θ is the coefficient of $fatig_i$. v_i is the error term assumed to be identically and independently across driver i.

However, $fatig_i$ included in Eq. (1) may be endogenous. Therefore, we specify here:

$$fatig_i^* = \beta' z_i + \omega_i, \tag{3}$$

$$fatig_i = \begin{cases} 1, & \text{if } fatig_i^* \ge 0 \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

This equation represents the latent fatigue driving propensity $fatig_i^*$ of driver i. $fatig_i$ is the actual observed fatigue driving behavior by driver i, and z_i is an L×1 column vector of independent variables (including a constant) influencing fatigue driving propensity $fatig_i^*$. β is an L×1 coefficient vector of z_i. x_i and z_i can share some common variables, representing the common observed influential factors between fatigue driving propensity and fatal injured propensity. ω_i represents the random components that capture all unobserved factors.

Still, there could be unobserved correlation between injury severity and fatigue driving. To capture the unobserved correlation, without losing generality we assume that v_i and ω_i form a bivariate normal distribution. In particular, the probability is given as:

$$
\begin{aligned}
&\text{Prob}\left(y_i = k,\ fatig_i = j \mid x_i, z_i\right) \\
&= \text{Prob}\left(\psi_{k-1} \le y_i^* < \psi_k,\ \tau_{j-1} \le fatig_i^* < \tau_j\right) \\
&= \begin{pmatrix}
\Phi_2\left(\psi_k - (\alpha' x_i + \theta\, fatig_i),\ \ \tau_j - \beta' z_i; \rho\right) \\
-\ \Phi_2\left(\psi_{k-1} - (\alpha' x_i + \theta\, fatig_i),\ \ \tau_j - \beta' z_i;\ \rho\right) \\
-\ \Phi_2\left(\psi_k - (\alpha' x_i + \theta\, fatig_i),\ \ \tau_{j-1} - \beta' z_i;\ \rho\right) \\
+\ \Phi_2\left(\psi_{k-1} - (\alpha' x_i + \theta\, fatig_i),\ \ \tau_{j-1} - \beta' z_i;\ \rho\right)
\end{pmatrix}
\end{aligned}
\tag{5}
$$

where $\Phi_2(\cdot)$ is the standard bivariate normal cumulative distribution function. τ_j and τ_{j-1} $(j = 0,1)$ represent thresholds for mapping the latent variable $fatig_i^*$ to the observed variable $fatig_i$ in Eq. (4). Specifically, in the binary probit model we set $\tau_{-1} = -\infty$, $\tau_0 = 0$, and $\tau_1 = \infty$. ρ measures the correlation between disturbances in the equations, which measures correlation between injury severity and fatigue driving propensity after the influence of fatigue is accounted in injury severity function. If this correlation between fatigue driving propensity and fatal injury propensity is ignored when actually exists, it could lead to inconsistent estimation of the effect of fatigue on injury severity. We also introduce a univariate endogenous binary-ordered probit model in which we assume $\rho = 0$, neglecting the correlation between v_i and w_i for comparison purpose.

3.2. Model estimation

The log-likelihood function is given by:

$$LL = \sum_{i=1}^{N} \ln \begin{pmatrix} \Phi_2\left(\psi_k - \left(\alpha' x_i + \theta\, fatig_i\right),\ \tau_j - \left(\beta' z_i\right); \rho\right) \\ - \Phi_2\left(\psi_{k-1} - \left(\alpha' x_i + \theta\, fatig_i\right),\ \tau_j - \left(\beta' z_i\right); \rho\right) \\ - \Phi_2\left(\psi_k - \left(\alpha' x_i + \theta\, fatig_i\right),\ \tau_{j-1} - \left(\beta' z_i\right); \rho\right) \\ + \Phi_2\left(\psi_{k-1} - \left(\alpha' x_i + \theta\, fatig_i\right),\ \tau_{j-1} - \left(\beta' z_i\right); \rho\right) \end{pmatrix} \tag{6}$$

The corresponding parameters α, β, θ, ψ_k, and ρ are estimated simultaneously by maximizing the log-likelihood function of Equation (6). R software (version 3.3.1) is used for estimation in this study.

4. Data

4.1. Data source

The Guangdong Traffic Accident Dataset (GTAD) is sourced from the Traffic Management Sector Specific Incident Case Data Report, the Road Traffic Accident Database of China's Public Security Department. A total of 38,564 crash records during 2006-2011 are applied in this study. The data we used in this study were drawn from police-reported crashes in 21 cities across Guangdong Province, and compiled from a sample of crashes that involve at least one motor vehicle and resulting in property damage, injury, or death.

Several crash-related attributes are collected for each record in GTAD, including driver characteristics, vehicle characteristics, road characteristics, environmental characteristics, and crash characteristics. The injury severity of each individual involved in the crash is categorized into four ordinal levels: (1) No injury, (2) Minor injury, (3) Serious injury, and (4) Fatal injury.

This study mainly focuses on drivers who were chiefly responsible for the occurrence of crash that was convicted to be fatigue-related. The reason is that crash and personal information is better recorded. The definition for fatigue driving in GTAD is defined as fulfilling one of the following conditions: (a) Driving cars more than eight hours a day, (b) Engaging in other work with excessive physical exertion, (c) Lacking of sleep which results in sleepy or weakness of limbs, so that the driver is having difficulty in assessing traffic conditions immediately and reacting accurately. Normally, the police officer would interview the involved parties and witnesses, and check the driving records to identify the cause of crash. Technical reconstruction is also helpful for determining the cause of crash by studying testimony of witnesses and physical evidence, especially in serious crashes. Fatigue-related crashes defined by this definition constitute 6.5% of all crashes in GTAD dataset. The distribution of fatigue driving and injury severity across observations is presented in Table 1. Overall, the descriptive statistics in Table 1 indicate a substantially higher percentage of fatal fatigue-related crashes (13.2%) than non-fatigue-related crashes (6.5%).

Table 1: Number of Fatigue Related Crashes by Injury Level

Injury Severity	Fatigue Driving		All (%)
	No (%)	Yes (%)	
All			
No Injury	25070	173	25243
	(65.5)	(56.9)	(65.5)
Minor Injury	8156	64	8220
	(21.3)	(21.0)	(21.3)
Serious Injury	2559	27	2586
	(6.7)	(8.9)	(6.7)
Fatal Injury	2475	40	2515
	(6.5)	(13.2)	(6.5)
Total	38260	304	38564
	(100)	(100)	(100)
Commercial			
No Injury	8297	96	8393
	(86.0)	(57.5)	(85.5)
Minor Injury	725	34	759
	(7.5)	(20.3)	(7.7)
Serious Injury	227	15	242
	(2.4)	(9.0)	(2.5)
Fatal Injury	400	22	422
	(4.1)	(13.2)	(4.3)
Total	9650	167	9817
	(100)	(100)	(100)
Non-commercial			
No Injury	16773	77	16850
	(58.6)	(56.2)	(58.6)
Minor Injury	7431	30	7461
	(26.0)	(21.9)	(25.9)
Serious Injury	2332	12	2344
	(8.1)	(8.8)	(8.2)
Fatal Injury	2075	18	2093
	(7.3)	(13.1)	(7.3)
Total	28610	137	28747
	(100)	(100)	(100)

4.2. Variables

Five types of variables were considered in the empirical analysis. ***Driver characteristics*** include: driver's age (≤25, 26-35, 36-45, 46-55, 56-65, and ≥66 years old), driver's gender, driving experience (≤2 years), and whether the driver has a valid driving license. ***Vehicle characteristics*** include: whether the vehicle has insurance. Other vehicle characteristics, such as vehicle speed just before collision, could not be included because of the absence of data in the GTDA. ***Road characteristics*** include: road type (whether the crash occurred on express way or urban roads), isolated lanes (whether the road has separated lanes for motorized and non-motorized vehicles), and terrain (mountain area). ***Environmental characteristics*** include: time of day represented in three categories (early morning (00:00-06:59), morning peak hours (07:00-08:59), and afternoon peak hours (17:00-19:59)) and lighting conditions (dark with street lights and dark without street lights). ***Crash characteristics*** include: collision type (head-on collision, rear-end collision, sideway collision). Variable description is presented in Table 2.

Firstly, a general model including all the variables suggested by prior studies and intuitiveness considerations are applied. Then, variables are chosen based on a systematic process of removing statistically insignificant variables and combining variables when their effects were not significantly different. Furthermore, continuous variables, such as driver' age and time of day, were converted into dummy variables and different ranges are also tested.

Table 2: Variable Description

Variables	Description	Mean
Driver characteristics		
Driver's gender		
Male	Male=1 ; Female=0	0.947
Driver's age		
≤25	≤ 25=1; Others=0	0.209
26-35	26-35=1; Others=0	0.355
36-45	36-45=1; Others=0	0.296
46-55	46-55=1; Others=0	0.106
56-65	56-65=1; Others=0	0.028
≥66	≥66=1; Others=0	0.006
Driving experience		
≤2 years	≤2 years=1; Others=0	0.135
Driving license		
Not valid	Not valid=1; Others=0	0.280
Vehicle characteristics		
Insurance		
Yes	Insurance=1; Others=0	0.779
Road characteristics		
Road type		
Express way	Express way=1; Others=0	0.046
Urban road	Urban road=1; Others=0	0.409
Isolated lanes		
Yes	Isolated lanes=1; Others=0	0.397
Terrain		
Mountain	Mountain=1; Others=0	0.600
Environmental characteristics		
Lighting condition		
Dark with street light	Dark with street light=1; Others=0	0.261
Dark without street light	Dark without street light=1; Others=0	0.173
Time of day		
00:00-06:59	00:00-06:59=1; Others=0	0.155
07:00-08:59	07:00-08:59=1; Others=0	0.087
17:00-19:59	17:00-19:59=1; Others=0	0.171
Crash characteristics		
Head-on	Head-on collision=1; Others=0	0.224
Sideway	Sideway collision=1; Others=0	0.421
Rear-end	Rear-end collision=1; Others=0	0.119

5. Estimation Results and Discussion

In this study, two different models were estimated: (1) Bivariate Endogenous Binary-Ordered Probit model, and (2) Univariate Endogenous Binary-Ordered Probit model (by assuming $\rho = 0$ as noted earlier). There could be potential systematic differences between commercial and non-commercial vehicle drivers (i.e. driving skill, driving time), we compare the factors associated with fatigue driving propensity and fatal injury propensity between them. Variables considered in the models at the very beginning of fatigue and injury severity function are listed in Table 3, and all the variables that were included in fatigue function also being included in injury severity function. In Table 4 and Table 5, we present the results of both models for commercial and non-commercial vehicle drivers, and only significant variables (at 95% significant level) will be listed and discussed in the following parts.

Table 3: Variable Selection for Fatigue Model and Injury Severity Model

Variable	Fatigue		Injury severity	
	Commercial	Non-commercial	Commercial	Non-commercial
Driver characteristics				
Driver's gender	√	√	√	√
Driver's age	√	√	√	√
Driving experience	√	√	√	√
Driving license	√	√	√	√
Vehicle characteristics				
Vehicle type	√	√	√	√
Insurance	√	√	√	√
Road characteristics				
Road type	√	√	√	√
Isolated lanes	√	√	√	√
Terrain	√	√	√	√
Environmental characteristics				
Lighting condition	√	√	√	√
Time of day	√	√	√	√
Crash characteristics				
Collision type			√	√

5.1. Measures of fit

Before discussing the estimation results, likelihood ratio test is conducted to compare bivariate and univariate model. The test statistic is given as

$$LR = -2\times\left(llk_{nc} - llk_{c}\right) \quad (7)$$

where llk_{nc} is the log-likelihood at convergence of bivariate model, and llk_{c} is the log-likelihood at convergence of the models estimated on univariate model. The LR statistic for commercial and non-commercial vehicle drivers is 4.38 and 3.66, which reject the null hypothesis of $\rho = 0$ at $p < 0.05$ and $p < 0.1$, respectively. It should be noted that, in this case, ρ is conservatively retained in non-commercial vehicle driver sample since the correlation does significantly change the coefficient of fatigue in the model. This result indicates that correlation due to unobserved factors between injury severity and fatigue driving propensity is significant, and model estimation without considering these correlation may result in inefficient parameter estimates (Yamamoto & Shankar, 2004).

We also conduct information criteria to compare model performance. Both of the value of Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) decline for commercial and non-commercial vehicle drivers by including the correlation, which also suggests that the proposed model is more efficient.

5.2. Estimation results

The results in Table 4 and Table 5 indicate that fatigue has significant impacts on fatal injury propensity for both commercial and non-commercial vehicle drivers. The coefficient of fatigue in the bivariate endogenous model is larger than in univariate model. The estimated coefficient of fatigue driving among commercial drivers is 0.984 in bivariate model and 0.291 in univariate model. The impact of fatigue driving on fatal injury propensity is underestimated by 0.693 in the latter. For non-commercial vehicle drivers, the coefficient of fatigue driving in bivariate model is 0.895 while in univariate model is 0.234 and the gap is 0.661. The impact of fatigue driving on injury severity in a crash on both groups are underestimated and the gaps between these two groups are similar. Larger coefficient of fatigue driving indicates higher risk of involving in fatal injured crash. Results suggest that commercial vehicle drivers are somewhat more risky when driving under fatigue than non-commercial vehicle drivers. Commercial vehicle drivers often drove a high number of miles (National Sleep Foundation, 2009), and some of them tend to break the rules about duty and rest hours for pursuing more profit (Radun & Radun, 2009). Thus, they are more likely to lose focus or even fall asleep at the wheel, which may lead to severe crashes.

This study also identifies the observed common factors of fatigue driving propensity and fatal injury propensity. In summary, the observed common factors for commercial vehicle drivers are: insurance, road types, and terrain. For non-commercial vehicle drivers, the observed common factors are: insurance and road types. More detail discussions of estimation results by groups are as following:

Driver characteristics: although gender, age and driving experience do not show significant impact on fatigue driving propensity, they do influence the driver's propensity of fatal injury in the crash. Non-commercial vehicle drivers who is over 45 years old are more likely to be fatal injured in the crash while male, young non-commercial vehicle drivers are found less likely. This result is consistent with previous findings (Hatfield et al., 2005; McConnell, 2003). Less experienced drivers ($\leq$2 years) are found more likely to be more severe injured than those with more driving experienced. Less experienced drivers with dynamic driving style are with more risk in the monotonous setting than experienced and calm drivers (Stutts et al., 2003; Karrer et al., 2004). However, these effects are not significant for commercial vehicle drivers due to small variation in commercial driver group. Drivers without a valid driving license are significantly more likely to be severe injured for both commercial and non-commercial vehicle drivers.

Vehicle characteristics: the impact of factors associated with vehicle itself shows contrast effects on fatigue driving propensity and fatal injury propensity. For both groups of drivers, driving vehicles with insurance are less likely to be fatally injured in the crash. Insurance lowers the monetary loss of crashes. Nevertheless, monetary compensation can never compensate for losing one's life. Therefore, drivers will pay enough attention to preventing themselves from fatal crashes. On the other hand, they might let their defenses down under the circumstances which they thought to be not serious. Thus, light-injured crashes are more likely to happen. In addition, non-commercial vehicle with insurance presents higher risk of fatigue driving while the impact for commercial vehicle is not significant. This finding may be related to different penalties for commercial drivers and non-commercial vehicle drivers when conducting fatigue driving. According to the Road Traffic Safety Law of the People's Republic of China and local traffic regulations, commercial vehicle drivers will have their driving licenses endorsed with at least six penalty points even lose their driving licenses once caught fatigue driving. However, for non-commercial vehicle drivers, fatigue driving will only incur traffic tickets without losing any points on their driving license.

Road characteristics: driving on express way is at high risk of fatigue driving and fatal injury for commercial and non-commercial vehicle drivers. Express ways are mostly monotonous and of high speed. Driving on them can be regarded as a repetitive activity which requires sustained attention and can easily lead to fatigue (McCartt et al., 2000; Thiffault & Bergeron, 2003). On the contrast, driving on urban road or mountain area is less likely to fatigue driving as well as sustain fatal injured. The lower propensity of fatigue driving may be the result of high rate of environmental stimulation and continuous changes in the driving scenery (Mavjee & Horne, 1994; Horne & Reyner, 1999), which help to maintain driver's attention persistently. The impact of driving in mountain area on fatigue driving propensity is not significant for non-commercial vehicle drivers. Isolated lanes show no significant impact on fatigue driving propensity, however, its impact on injury severity differs between commercial and non-commercial vehicle drivers. For commercial vehicle drivers, driving on isolated lanes is less likely to sustain fatal injury, but is more likely for non-commercial vehicle drivers.

Environmental characteristics: The effect of time period on fatigue driving propensity also shows different patterns. During midnight to early morning (00:00-06:59), both commercial and non-commercial vehicle drivers are more likely to fatigue driving compared to other time period in a day. For example, 75% of fatigue-related crashes occurred between 02:00 and 08:00 in 107 heavy truck crashes reviewed (National Transportation Safety Board, U.S., 1995). Morning peak hour (07:00-08:59) only affects the fatigue driving propensity of commercial drivers. It is still not clear whether this result is due to sleep loss or other reasons. Driving at night significantly contributes to more severe injury crashes for both commercial and non-commercial vehicle drivers, but the propensity of fatal injured crashes declines following the installation of street lights. This finding is also consistent with several previous studies (Elvik, 1995; Owens & Sivak, 1996; Plainis et al., 2006).

Crash characteristics: since collision type does not affect fatigue driving behavior, this variable is only considered in injury severity function. The result indicates that commercial vehicle drivers are more likely to fatal injured when involved in rear-end collision while sideway collision and head-on collision is less likely to fatal injured. Some commercial vehicles have larger size and are heavier than the other passenger vehicles with which they share the roads, and the stopping distance for them is much longer. Thus, large and heavy commercial vehicles involving in rear-end crashes may be due to their inability to stop immediately, and cause severe injuries. For sideway and head-on collision, commercial vehicle drivers can reduce the harmfulness of collision by taking sudden turns or other protecting behaviors based on their experience. However, for non-commercial vehicle drivers, both head-on and rear-end collision have higher propensity of fatal injury, which may be related to lacking experience in handling emergencies on road compared to commercial vehicle drivers. The impact of side collision is not significant for non-commercial vehicle drivers.

Table 4: Estimation Result of Commercial Vehicle Driver Sample

	Correlated		**Uncorrelated**	
Variables	Coef.	SE	Coef.	SE
	Fatigue Driving Propensity			
Road type				
Express way	0.368^{***}	0.080	0.400^{***}	0.079
Urban road	-0.718^{***}	0.152	-0.702^{***}	0.151
Terrain				
Mountain	-0.179^{**}	0.072	-0.178^{**}	0.072
Time of day				
00:00-06:59	0.771^{***}	0.079	0.740^{***}	0.079
07:00-08:59	0.466^{***}	0.114	0.457^{***}	0.114
Intercept	-2.379^{***}	0.068	-2.381^{***}	0.068
	Injury Severity Propensity			

Fatigue	0.984***	0.312	0.291***	0.097
Driving license				
Not valid	0.291***	0.064	0.293***	0.065
Insurance				
Yes	-0.192***	0.064	-0.193***	0.064
Road type				
Express way	0.850***	0.056	0.883***	0.054
Urban road	-0.129***	0.044	-0.133***	0.044
Isolated lanes				
Yes	-0.085**	0.040	-0.084**	0.040
Terrain				
Mountain	-0.217***	0.034	-0.223***	0.034
Lighting condition				
Dark with street light	0.131***	0.048	0.136***	0.048
Dark without street light	0.243***	0.040	0.252***	0.040
Collision type				
Head-on	-0.142***	0.050	-0.140***	0.051
Side	-0.377***	0.047	-0.376***	0.047
Rear-end	0.276***	0.044	0.280***	0.044
ρ	-0.313**	0.132		
Cut1	0.925***	0.071	0.921***	0.071
Cut2	1.450***	0.072	1.449***	0.072
Cut3	1.719***	0.074	1.720***	0.074
log-likelihood	-5491		-5493	
AIC	11025		11028	
BIC	11057		11059	
N	9816		9816	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Estimation Result of Non-commercial Vehicle Driver Sample

	Correlated		**Uncorrelated**	
Variables	Coef.	SE	Coef.	SE
	Fatigue Driving Propensity			
Insurance				
Yes	0.351***	0.090	0.351***	0.089
Road type				
Express way	0.595***	0.108	0.604***	0.108
Urban road	-0.267***	0.068	-0.268***	0.068
Time of day				
00:00-06:59	0.419***	0.071	0.384***	0.070

Intercept	-2.896***	0.086	-2.891***	0.086
	Injury Severity Propensity			
Fatigue	0.895**	0.364	0.234**	0.101
Driver's gender				
Male	-0.200***	0.028	-0.199***	0.028
Driver's age				
26-35	-0.170***	0.016	-0.170***	0.016
46-55	0.238***	0.023	0.238***	0.023
56-65	0.500***	0.037	0.500***	0.037
⩾65	0.606***	0.075	0.606***	0.075
Driving experience				
≤ 2 years	0.153***	0.022	0.153***	0.022
Driving license				
Not valid	0.703***	0.017	0.703***	0.017
Insurance				
Yes	-0.281***	0.017	-0.280***	0.017
Road type				
Express way	0.370***	0.050	0.388***	0.050
Urban road	-0.250***	0.015	-0.251***	0.015
Isolated lanes				
Yes	0.060***	0.016	0.060***	0.016
Terrain				
Mountain	-0.135***	0.015	-0.135***	0.015
Lighting condition				
Dark with street light	0.076***	0.017	0.077***	0.017
Dark without street light	0.181***	0.020	0.182***	0.020
Collision type				
Head-on	0.140***	0.017	0.140***	0.017
Rear-end	0.180***	0.024	0.180***	0.024
ρ	-0.234*	0.122		
Cut1	0.053	0.036	0.052	0.036
Cut2	0.960***	0.036	0.960***	0.036
Cut3	1.442***	0.037	1.442***	0.037
log-likelihood	-28726		-28728	
AIC	57504		57506	
BIC	57541		57541	
N	28748		28748	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5.3. Marginal effects

The coefficient estimates do not provide the magnitude of impacts on probability in each injury level. Thus, we calculate the marginal effect of variables, which directly influence fatal injury propensity, on each injury level for both commercial and non-commercial vehicle drivers. Considering all variables in this model are dummy variables, we compute probabilities by setting the variable to one and then zero, and take the difference. That is,

$$ME = \text{Prob}(y_i = k \mid m_i = 1) - \text{Prob}(y_i = k \mid m_i = 0) \quad (7)$$

where ME is the marginal effect of dummy m_i on injury level k. The marginal effect can be interpreted as the change of probability due to the change in variable from zero to one. The results of bivariate and univariate models for commercial and non-commercial vehicle drivers are presented in Table 6 and Table 7. (These tables only present the marginal effect for significant variables identified in earlier discussion).

Some important features should be addressed here. First, this study shows that the marginal effect of fatigue driving on fatal injury for commercial vehicle driver and non-commercial driver is 12.9% and 17.9%. That is, the occurrence of fatigue driving will increase the probability of fatal injury in a crash by 12.9% for commercial vehicle driver and 17.9% for non-commercial vehicle drivers. Moreover, comparing marginal effect in bivariate and univariate model, we find that the estimated impact of fatigue are much lower without considering correlation. Ignoring the correlation of unobserved factors may lead to underestimation of the harmfulness of fatigue driving behavior. In our study, the harmfulness of fatigue is underestimated by 10.5% and 14.6% for commercial and non-commercial vehicle driver, respectively. Second, for commercial vehicle drivers, other major risk factors of fatal injury include express way, not valid driving license, and rear-end collision. For non-commercial vehicle, elder driver (aged ≥66 years old and 56-65 years old), not valid driving license, and express way are the most significant contributors. Third, side collision, driving in mountain area, and insurance are recognized as the three most influencing factors for commercial vehicle drivers to survive in a crash while for non-commercial vehicle drivers are insurance, urban road, and male.

Table 6: Marginal Effect for Commercial Vehicle Driver Sample

	Bivariate Binary-Ordered Probit				Univariate Binary-Ordered Probit			
	Y = 1	**Y = 2**	**Y = 3**	**Y = 4**	**Y = 1**	**Y = 2**	**Y = 3**	**Y = 4**
Fatigue Driving	-0.256	0.086	0.041	0.129	-0.060	0.025	0.010	0.024
Driving License								
Not valid	-0.058	0.025	0.010	0.023	-0.060	0.025	0.010	0.024
Insurance								
Yes	0.037	-0.016	-0.006	-0.014	0.038	-0.016	-0.006	-0.015
Road type								
Express way	-0.225	0.084	0.037	0.087	-0.237	0.087	0.039	0.094
Urban road	0.037	-0.009	-0.004	-0.008	0.036	-0.009	-0.003	-0.007
Isolated lanes								
Yes	0.015	-0.007	-0.003	-0.006	0.015	-0.007	-0.003	-0.006
Terrain								
Mountain	0.054	-0.022	-0.008	-0.018	0.046	-0.018	-0.007	-0.015
Lighting condition								
Dark with street light	-0.024	0.011	0.004	0.009	-0.026	0.011	0.004	0.010
Dark without street light	-0.046	0.021	0.008	0.017	-0.049	0.022	0.009	0.019
Collision type								
Head-on	0.024	-0.011	-0.004	-0.009	0.024	-0.011	-0.004	-0.009
Sideway	0.063	-0.031	-0.011	-0.022	0.065	-0.031	-0.011	-0.022
Rear-end	-0.054	0.024	0.009	0.020	-0.056	0.025	0.010	0.021

Table 7: Marginal Effect for Non-commercial Vehicle Driver Sample

	Bivariate Binary-Ordered Probit				Univariate Binary-Ordered Probit			
	Y = 1	**Y = 2**	**Y = 3**	**Y = 4**	**Y = 1**	**Y = 2**	**Y = 3**	**Y = 4**
Fatigue Driving	-0.303	0.051	0.073	0.179	-0.081	0.028	0.020	0.033
Driver's gender								
Male	0.069	-0.025	-0.017	-0.027	0.069	-0.025	-0.017	-0.027
Driver's age								
26-35	0.058	-0.024	-0.014	-0.020	0.058	-0.024	-0.014	-0.020
46-55	-0.083	0.030	0.021	0.032	-0.083	0.030	0.021	0.032
56-65	-0.175	0.051	0.044	0.080	-0.175	0.051	0.044	0.080
≥65	-0.211	0.054	0.053	0.105	-0.211	0.054	0.053	0.105
Driving experience								
Less than 2 years	-0.053	0.020	0.013	0.020	-0.052	0.020	0.013	0.020
Driving License								
Not valid	-0.259	0.098	0.067	0.093	-0.258	0.098	0.067	0.093
Insurance								
Yes	0.097	-0.039	-0.025	-0.036	0.097	-0.039	-0.025	-0.037
Road type								
Express way	-0.140	0.038	0.031	0.055	-0.143	0.038	0.032	0.057
Urban road	0.089	-0.035	-0.021	-0.029	0.089	-0.035	-0.021	-0.029
Isolated lanes								
Yes	-0.021	0.008	0.005	0.007	-0.020	0.008	0.005	0.007
Terrain								
Mountain	0.046	-0.018	-0.011	-0.017	0.046	-0.018	-0.011	-0.017
Lighting condition								

Dark with street light	-0.026	0.010	0.006	0.009	-0.026	0.010	0.006	0.010
Dark without street light	-0.063	0.024	0.016	0.024	-0.063	0.024	0.016	0.024
Collision type								
Head-on	-0.048	0.019	0.012	0.018	-0.049	0.019	0.012	0.018
Rear-end	-0.062	0.023	0.015	0.024	-0.063	0.023	0.016	0.024

6. Conclusions and practical applications

Several studies have examined the relationship between driver fatigue and traffic injury severity from different aspects. However, some of factors that affect driver's fatigue propensity also have influence on driver's injury severity in a crash, including observed and unobserved factors. Ignoring the impact of these common factors will lead to endogeneity problem and incorrect conclusion. Based on 38,564 crash records during 2006-2011, we conduct an empirical analysis to examine the relationship between fatigue driving propensity and fatal injury severity by comparing bivariate and univariate endogenous binary-ordered probit model. Five types of factors are included. It is essential to quantify the impact of these characteristics on injury severity by calculating marginal effect, so that measures to prevent or reduce harmfulness of fatigue driving can be identified and implemented.

The result reveals a substantial and significant negative error correlation between fatigue driving propensity and fatal injury propensity, which lends strong support for endogeneity of fatigue driving propensity. The influence of fatigue driving on injury severity is significantly underestimated if ignoring the unobserved correlation between fatigue driving behavior and crash injury severity propensity. This study also compares the difference in risk factors of fatigue driving behavior and crash-related injury between commercial vehicle drivers and non-commercial drivers. Some common observed influential factors are identified. For instance, driving on express way not only contribute to higher fatal injury propensity but also high fatigue driving propensity.

Measures aiming at preventing driver fatigue such as light signals or signs may also help to reduce injury severity in the crash. It is also found in the paper that factors show different impacts on them. Driver's gender and age has significant influence on fatigue driving propensity of non-commercial vehicle driver, but this influence is not significant on commercial vehicle driver.

It should arouse the attention of researchers that the harmfulness of driver fatigue on traffic crash injury severity is larger than expected due to neglecting of the endogeneity of fatigue. Furthermore, correctly understanding the impact of fatigue-related crash is considered to be essential to the development and design of countermeasures aimed at reducing the hazard of fatigue crash. Different impact factors identified between commercial and non-commercial vehicle drivers in this study should be addressed. Some factors have similar impacts for both commercial and non-commercial vehicle drivers (e.g. road types and lighting conditions), but some factors have not (e.g. collision types). Thus, developing effective measures to reduce fatigue-related crash occurrence and its injury severity should take into account those differences. Moreover, according to our findings, police makers should also consider installing driver fatigue prevention devices (e.g. deceleration strip or warning signs) on express ways since those devices help reducing driver fatigue as well as injury severity.

With respect to fatigue driving behavior, our results suggest that fatigue is important in reducing the likelihood of fatal injury. However, one of the major limitations of this research is the sparseness of fatigue-related crash in this dataset for the reason that small sample size may influence model estimation. It is essential to address endogenous in the model since endogeneity would cause inconsistent estimation. And this model can apply for any crash type when there is potential endogenous dependent variable. Therefore, it is reasonable to introduce this model in our analysis given the data limitation. In addition, the number of observations of some variables are small that may also limit the ability of determining effects precisely. And the vague and broad definition of fatigue may also cause misclassification problem and reduce the accuracy of our data analysis. This paper also does not consider the potential confounding effects of driving mileage, driver's health condition, drug use, which could affect both fatigue and risk of crash (Connor et al., 2001), due to the limitation of data. To deal with this problem, more detail and complete data are needed. Interaction effects or non-linear effects of variables and heterogeneity of drivers, which may also have significant impacts on injury severity and fatigue driving propensity, are not considered in this study for the first attempt since the focus is on the endogeneity of fatigue driving. Those problems will be discussed in our future studies.

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