

Analysis of bicyclist-vehicle crash at intersection area considering behavior prior to crash: A random parameter ordinal probit approach

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Abstract: In order to analyze the risky factors that affect vehicle-cyclist crash injury severity at the intersection area, especially the factors relating to the road users' behaviors, an empirical study was conducted by collecting accident records from 2011 to 2015 from the General Estimates System. After preliminary screening, the variables were classified into 5 main categories including cyclists' characteristic and behavior, drivers' characteristic and behavior, vehicle characteristic, intersection condition, and time. The random parameter ordinal probit (RPOP) was used to study the significant influencing factors and corresponding heterogeneity. The results show that failing to obey traffic signals, failing to yield to right-of-way, dash and drinking before cycling can increase the injury severity for cyclists, and the corresponding fatal injury likelihoods increase by 53.2%, 40.0%, 86.3%, and 211.5%, respectively. Moreover, drivers' inattention, speeding, going straight and left turning increase the risk of crashing for cyclists. The corresponding fatal injury likelihoods increase by 134.5%, 186.5%, 69.3%, and 22.7%, respectively. Other indicators such as age, gender, vehicle type, traffic signal and intersection type can also affect injury severity.

Key words: traffic safety; injury severity; cyclist crash; intersection; random parameter ordinal probit (RPOP)

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In recent years, the governments in the North American area have been actively devoted to increasing investment in bicycle facilities to encourage bicycling^[1-2]. But quite a few researchers regard cycling as dangerous mode of transportation^[3-4]. According to the reports from the National Highway Traffic Safety Administration (NHTSA)^[5-7], the number of cyclists killed in cyclist-motor vehicle crashes have increased from 729 (2014) to 857

(2018) during the past years. The problem of cycling safety in the U. S. seems to become more and more serious. At least there's no downward trend in deaths.

An intersection is one of the most complex parts in a transportation system^[8-9]. Bicycling through intersections may significantly increase the risk of traffic accidents^[10]. Many studies have confirmed the factors which affect the frequency and injury severity of cyclist related crashes at intersections. Most of them focused on inherent characteristics of the environment (e. g. green space, light condition, etc.), road (e. g. number of cycle lanes, intersection type, etc.) and road users (e. g. age, gender, race, etc.)^[11-15]. A few took cyclists and vehicles' movements (e. g. turning direction, riding with/against traffic, etc.) into account^[14,16]. Wang et al.^[15] and Rodgers^[17] pointed out that the risks for cyclists aged 18 to 24 and over age 64 were significantly higher than those aged 25 to 65. In terms of gender, women seemed to be more likely to be hit by vehicles than men^[18]. Volume is another important influencing factor. Strauss et al.^[8] pointed out that a 1.0% increase in bicycle flows would result in a 0.87% increase in the number of injuries. For movement, wrong-way bicycling is dangerous for all bicyclists^[14]. Regarding lighting, street lighting can decrease the severity of injury^[12]. Roundabouts improved motor vehicle safety, but a similar safety effect was not found for bicycles^[19]. Crash risk may greatly increase when people cycle around roundabouts^[20].

Actually, drivers' and cyclists' behaviors prior to crashes are the most direct cause of accidents. But as far as it is concerned, there are few studies in this area. The objective of this study is to analyze the risk factors of cyclists' injury severity in intersection-related cyclist-vehicle crashes. But in a departure from previous studies, cyclists' and drivers' behaviors are taken into account. The data source are accident records from 5 years (2011—2015) from the General Estimates System (GES). The random parameter ordinal probit (RPOP) is adopted to identify the significant factors and corresponding random effects.

1 Materials and Methods

1.1 Data source and variable processing

The datasets of crash records from GES are used for an-

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alyzing cyclist-related crash. Data for GES comes from nationally representative samples of police reported motor vehicle crashes of all types^[21]. These accident reports are chosen weekly from approximately 400 police jurisdictions in 60 areas across the U. S. Approximately 90 data elements are coded into a common format^[21].

The records for cyclist crash occurring at intersections from 2011 to 2015 are filtered out. The final dataset includes 6 383 observations. The injury severity in the dataset is described by the KABCO scale, shown in Tab. 1. This scale was developed by the National Safety Council (NSC) and is frequently used by law enforcement for classifying injuries^[22].

Tab. 1 KABCO scale

Representative symbol	Injury classification
K	Fatal
A	Incapacitating injury
B	Non-incapacitating injury
C	Possible injury
O	No injury

There are few observations for some injury level. So the injury severity indicators are regrouped, as shown in Tab. 2.

Tab. 2 Injury level and code

Level	Code	Injury classification
S1	0	No injury/possible injury
S2	1	Non-incapacitating injury
S3	2	Incapacitating injury
S4	3	Fatal

Then the possible correlated indicators are classified into 5 main categories including cyclists' characteristics and behavior, drivers' characteristics and behavior, vehicle characteristics, road condition, and time. All of them are discontinuous categorical variables, so they are processed into dummy variables. Some of the variables were classified detailedly in origin datasets, so the observations for some sub-classifications of them are few. In sight of this, some detailed classifications are merged into upper classifications. The age of cyclists is divided into 4 types (<25, 25 to 45, 45 to 65, and >65). Vehicles are merged into 5 main types including automobiles, buses, heavy trucks, light trucks, and motorcycles. The volume was not provided in the GES datasets. But this information is partly included in the time indicator. Therefore, time is divided into 3 types including peak time (7:00 a. m.—10:00 a. m. , 4:00 p. m.—7:00 p. m.), off peak time (10:00 a. m.—4:00 p. m.) and night time (7:00 p. m.—12:00 p. m. , 0:00 a. m.—7:00 a. m.). Considering the correlation between time and lighting, the lighting indicator is excluded. For some sub-classification of few observations (<5%), which cannot be merged into other categories, are merged into the “other” type.

1.2 Methodology

Random parameter discrete choices models which accommodate unobserved heterogeneity across observations by adding a random effect to the parameters of the utility function are widely used to analyze accident severity^[23]. In this study, the RPOP is adopted to investigate the influencing factors for injury severity.

There are 4 levels of injury severity. The utility function of injury severity for the i -th cyclist can be expressed as

$$Y_i^* = \beta X_i + \varepsilon_i = Z_i + \varepsilon_i \quad (1)$$

where Y_i^* is the i -th cyclist's utility; β is the coefficient vector; X_i is the vector of explanatory variables that affect the injury severity of the i -th cyclist; ε_i is an error term that is to be normally distributed; Z_i is the dot product of β and X_i . Let Y_i denote the injury severity that is an ordered variable. The classification of Y_i is determined by 3 thresholds: δ_1 , δ_2 and δ_3 ^[24]. Then the probability of Y_i can be computed by

$$\Pr(Y_i = 0) = \Pr(Z_i + \varepsilon_i < \delta_1) = \Phi(\delta_1 - Z_i) \quad (2)$$

$$\Pr(Y_i = 1) = \Pr(\delta_1 < Z_i + \varepsilon_i < \delta_2) = \Phi(\delta_2 - Z_i) - \Phi(\delta_1 - Z_i) \quad (3)$$

$$\Pr(Y_i = 2) = \Pr(\delta_2 < Z_i + \varepsilon_i < \delta_3) = \Phi(\delta_3 - Z_i) - \Phi(\delta_2 - Z_i) \quad (4)$$

$$\Pr(Y_i = 3) = \Pr(Z_i + \varepsilon_i > \delta_3) = 1 - \Phi(\delta_3 - Z_i) \quad (5)$$

where Φ is the probability function of ε_i . There may be certain random effects for each influencing factor. In order to detect unobserved heterogeneity of each explanatory variable, a random error term, also normally distributed, is added to each coefficient.

$$\beta' = \beta + \sigma_i \quad (6)$$

where β' is the random coefficient vector; σ_i is the random error term. β' , δ_1 , δ_2 and δ_3 are estimated by the maximum likelihood method. The likelihood function of the i -th cyclist suffers level m injury may be written as

$$P_{i,m} = \begin{cases} \int [\Phi(\delta_{m+1} - Z_i)] f(\beta' | w) d\beta' & m = 0 \\ \int [\Phi(\delta_{m+1} - Z_i) - \Phi(\delta_m - Z_i)] f(\beta' | w) d\beta' & 1 \leq m \leq 2 \\ \int [1 - \Phi(\delta_m - Z_i)] f(\beta' | w) d\beta' & m = 3 \end{cases} \quad (7)$$

Then, the corresponding log-likelihood function is

$$L = \sum_i \sum_m d_{i,m} \ln(P_{i,m}) \quad (8)$$

where $f(\beta' | w)$ is the probability density function of β' ;

w is the distribution parameter of β' ; $d_{i,m}$ is equal to 1 if the i -th cyclist suffers level m injury and is zero otherwise. Each coefficient in β' of the probit model does not reflect the quantitative effects of the explanatory variables. Therefore, the elasticity is reported. It indicates the change rate for the likelihood of each injury level^[25].

$$E_{i,n} = \frac{\partial \Pr(Y_i)}{\partial X_{i,n}} \frac{X_{i,n}}{\Pr(Y_i)} \quad (9)$$

where $X_{i,n}$ is the n -th explanatory variable in X_i ; $E_{i,n}$ is the elasticity of $X_{i,n}$.

2 Results

The backward elimination method is used to exclude non-significant variables. Then, 23 dummy significant variables are obtained. The p -value of Wald χ^2 test is smaller than 0.01. The value of the Akaike information criterion (AIC) for the RPOP is 10 038.6, which shows improvement compared with the AIC(10 114.5) for the fixed parameter model, so the RPOP shows a better fit performance in this study. The results of the RPOP and the elasticities are shown in Tab. 3.

Tab. 3 The results of the RPOP and elasticities

Classification	Dummy variable	Coefficient		Elasticity/%			
		Mean	Standard error	S1	S2	S3	S4
Cyclist	45 to 65 ^a	0.140 ***	0.417 ***	-30.6	-3.3	19.8	42.3
	> 65 ^a	0.295 ***	0.614 ***	-55.3	-8.2	44.8	115.4
	Female	0.083 **		-19.0	-1.9	11.6	23.7
	Alcohol involved ^a	0.434 ***	0.176 **	-71.3	-13.5	69.2	211.5
	Dart-out/dash ^a	0.236 ***	0.570 ***	-46.0	-6.4	35.3	86.3
	Fail to yield right-of-way ^a	0.132 ***	0.198 ***	-28.9	-3.2	18.8	40.0
	Fail to obey traffic signals	0.162 ***		-33.7	-4.1	23.6	53.2
Driver	Exceeding speed limit	0.396 ***		-66.3	-12.2	62.8	186.5
	Vision obscured by other vehicles	0.321 ***		-57.5	-9.3	49.7	134.9
	Inattentive/careless	0.324 ***		-58.6	-9.4	50.0	134.5
	Alcohol involved ^a	0.350 ***	1.036 ***	-60.9	-10.4	54.7	154.2
	Going straight ^a	0.237 ***	0.437 ***	-53.7	-5.5	33.2	69.3
	Turning left	0.079 *		-17.9	-1.8	11.1	22.7
Vehicle	Automobile ^a	0.471 ***	0.183 ***	-141.3	-7.0	56.6	91.9
	Bus ^a	0.710 ***	0.611 ***	-90.7	-25.8	121.3	532.2
	Heavy truck ^a	1.094 ***	1.255 ***	-106.0	-44.4	191.4	1 373.8
	Light truck ^a	0.622 ***	0.480 ***	-104.9	-19.1	98.5	315.9
	Contact point at front side ^a	0.074 **	0.202 ***	-18.0	-1.6	10.0	19.1
Road	2-3 Lanes	0.207 ***		-48.1	-4.6	28.6	57.7
	Stop/yield/warning sign	-0.176 ***		44.9	3.5	-23.2	-42.1
	Roundabout	0.475 **		-73.4	-15.4	77.2	254.5
Time	Tuesday ^a	-0.129 ***	0.386 ***	32.6	2.5	-17.0	-30.8
	Nighttime ^a	0.108 **	0.664 ***	-23.9	-2.6	15.3	32.2

Note: ***, ** and * indicate 1%, 5% and 10% level of significance, respectively; ^a denotes the random parameters of variables.

3 Discussion

3.1 Cyclist characteristics and behavior

3.1.1 Age

The 45 to 65 years old indicator and beyond 65 years old indicator are positively significant. The elasticity for cyclists aged 45 to 65 for incapacitating injury is 19.8% and for fatal injury is 42.3%. It means that compared with younger cyclists (age < 45), the likelihood for incapacitating injury will increase by 19.8% and for fatal injury will increase by 42.3%. The parameter of this dummy variable is normally distributed with a mean of 0.14 and a standard deviation of 0.42. It means that 63.1% of them tend to sustain a greater injury. Similarly, compared with younger people (age < 45), the likelihood for 68.4% of the older cyclists (age > 65) will increase by 44.8% for an incapacitating injury and 115.4% for a fa-

tal injury, respectively. The results indicate that older cyclists are prone to greater injury compared with younger cyclists, which is consistent with previous studies^[23,26]. In fact, the proportion of older cyclists (age > 45) in the total number of commuting cyclists is smaller than 15% in the U. S.^[27]. A recent official report from the National Highway Traffic Safety Administration (NHTSA) shows that the average age of cyclists killed in crashes has increased from 41 to 47 during the past 10 years^[28]. The phenomenon could be explained by the fact that the perceptual skill and reaction of the older people may be lower. Consequently, they may not have enough flexibility to yield and respond to emergencies^[14,23,26]. In addition, some of the older cyclists' own health conditions also increase the degree of injury in crashes^[23,26]. Therefore, given the alarming issue, it is recommended that older people should pay more attention to their safety during

daily cycle travelling.

3.1.2 Gender

The dummy indicator of being a female is positively significant. The elasticity for incapacitating injury is 11.6% and that for fatal injury is 23.7%. It means that women are more vulnerable to serious injuries than men at intersections. However, females generally do not prefer commuting by bicycle and only 24% of commuting cyclists are female in the U. S. ^[27]. This finding is consistent with previous studies ^[18]. Male cyclists are less likely to have dangerous conflicts at intersections than women, and they can calmly adopt the right maneuvers in conflicts ^[18]. This might be attributed to the higher long-term accumulated experience and skills in cycling commuting of males. Nevertheless, other studies show that males could have a much higher risk of fatal injury than females ^[17-18, 28-29]. This could be attributed to higher average speed of male cyclists, which increases the severity of potential collision risks ^[18].

3.1.3 Alcohol-intoxicated

In many states of the U. S., bicycles are classified as vehicles. Therefore, cyclists are subject to the same legal restrictions on alcohol as drivers. Compared with cyclists who are not drunk, 99.3% alcohol-intoxicated cyclists tend to suffer higher injury (the coefficient is normally distributed with a mean of 0.43 and a standard deviation of 0.18). The likelihoods for incapacitating injury and for fatal injury will increase by 69.2% and 211.5%, respectively. Drinking will not only reduce their flexibility to take evasive maneuvers ^[23], but also reduce the use of helmets ^[26]. Therefore, it is highly recommended that drink-driving or cycling should be prohibited by explicit order.

3.1.4 Behavior prior to crash

Three types of cyclists' violation including fail to obey traffic signals, dashing and fail to yield right-of-way are significant, which may cause more serious injury. Among them, dashing is the most dangerous factor of which the elasticity for incapacitating injury is 35.3% and that for fatal injury is 86.3%, followed by failing to obey traffic signals of which the elasticity for incapacitating injury is 23.6% and that for fatal injury is 53.2%. Moreover, the likelihood for fatal injury tends to increase by 40.0% if cyclists fail to yield right-of-way in crashes. Cycling at a high speed increases the risk of serious conflict with motor vehicles, which commonly occurs among male cyclists ^[18]. This may be attributed to their self-identified riding skills and risk-taking tendency. Previous studies have shown that red-light running could lead to serious injuries ^[26]. It is quite common in many western countries, and at least 50% of the cyclists have different degrees of red-light running behavior ^[30-32]. It is particularly prevalent among young and middle-aged cyclists, and there is also gender difference ^[31]. This may also be the reasons

for the high mortality of male cyclists. However, studies also indicate that females are becoming more risk-taking regarding violation behaviors ^[18]. In addition, drivers are often not willing to share right-of-way with cyclists ^[33], which also increase the risk of collisions.

3.2 Driver characteristics and behaviors

3.2.1 Speeding

Exceeding speed limit is significant for increasing injury severity. The likelihood for incapacitating injury tends to increase by 62.8% and that for fatal injury increases by 186.5%. This result is logical and consistent with expectations. Speeding can increase the momentum of the collision intensely, which also reflects the driver's aggressive personality ^[26].

3.2.2 Alcohol intoxicated

Alcohol intoxicated drivers caused 63.2% of the cyclists' incurring higher injury. The likelihood for incapacitating injury tends to increase by 54.7% and that for fatal injury increases by 154.2%. Under the influence of alcohol, drivers' reaction ability is reduced and they drive more recklessly. The heterogeneity of this variable may be explained by different kinds of responses from the cyclists interacting.

3.2.3 Vision obstacle and inattention

When drivers' vision is blocked by other vehicles at intersections, their perception of risk will be weakened and their reaction time will be longer. The elasticity for incapacitating injury is 49.7% and that for fatal injury is 134.9%. Meanwhile, inattention can easily cause failing to be evasive, which would lead to a higher speed before incident. The elasticity for incapacitating injury is 50.0% and that for fatal injury is 134.5%.

3.2.4 Movement

Movement indicates the moving direction of drivers before the collision occurs. Consistent with the previous research, both going straight and turning left are significant for increasing the injury severity relative to turning right and other movements ^[16]. The elasticity for going straight for incapacitating injury is 33.2% and that for fatal injury is 69.3%. The coefficient is heterogeneous with a mean of 0.24 and a standard deviation of 0.44. It means that 70.3% cyclists sustain higher injury if they are hit by a going-straight vehicle. The possible reason is that the speed of straight cars is higher. But some of the risks are compensated for because it is easier for drivers to see cyclists when going straight than turning. The elasticity for turning left for incapacitating injury is 11.1% and that for fatal injury is 22.7%. This is because vehicles may have potential conflicts with the existing traffic flow ^[2].

3.3 Vehicle characteristics

3.3.1 Body type

Compared with motorcycles, all other types of vehicles

will increase the injury severity for cyclists. In general, the injury severity is positively correlated with the mass of the vehicle body^[12]. The elasticities of vehicle types for fatal injury are 91.9% (automobiles), 532.2% (buses), 1373.8% (heavy trucks), 315.9% (light trucks), respectively. This finding is consistent with previous studies^[34–35] that stated heavy vehicles have a higher risk of impact. Significantly, heavy trucks contribute the most to the likelihood of fatal injury, because they generally have higher bumpers, which can cause severe upper body or head injuries to cyclists in collisions^[34–35]. All the coefficients of vehicle types are heterogeneous and the standard deviations are also positively correlated with vehicle mass. It is probably due to the lower speed of heavy vehicles at the intersection area.

3.3.2 Initial contact point

64.3% head-on crashes cause higher injury than other impacting patterns. The likelihood for incurring an incapacitating injury and that of a fatal injury tend to increase by 10.0% and 19.1%, respectively. This finding is consistent with previous reports^[23,26] because the energy of a head-on collision is higher. The significant normal distribution of the coefficient of the dummy variable can be explained by cyclists who can be easily seen by the driver when they appear in front of the vehicle. Drivers often have enough time to take effective evasive maneuvers. So, not all the cyclists involved in head-on collision are seriously injured.

3.4 Intersection condition

3.4.1 Roadway width

The dummy variable “2-3 lanes” is significant. The elasticity for an incapacitating injury is 26.8% and that for a fatal injury is 57.7%. It means that the likelihood for an incapacitating injury and that for a fatal injury increase by 26.8% and 57.7%, respectively, on a 2-3 lanes roadway. However, some previous studies have shown that the increase in the roadway width can increase the injury severity in crashes^[36]. One possible explanation is that in the non-crossroad sections, the wide road leads to a higher vehicle speed. While at intersections, the speed is generally lower than those at other sections. Wide roadways increase drivers’ visibility and reaction ability, and also provide enough time and space for cyclists to react and yield. Meanwhile, a narrower roadway means that the mixed traffic flow of motor vehicles and bicycles is relatively dense, which increases the potential conflicts. In particular, if there are other vehicles blocking drivers’ vision, the blind area of drivers can be larger, which can lead to a dangerous conflict.

3.4.2 Intersection type

A roundabout is a dangerous form of intersection for cyclists, which has been confirmed by previous studies^[19–20,37]. Especially in built-up areas, both the number

of accidents and the severity of injuries is increased^[20]. The possible reason is that they reduce the risk perception of cyclists^[19]. The result in this study accords with the former’s. Compared with the intersections of other types (four-way intersection, T-shape, etc.), the likelihood for an incapacitating injury will increase by 77.2% and that for a fatal injury will increase by 254.5%.

3.4.3 Traffic control device

The stop/yield/warning sign indicator is negatively correlated to crash severity. Compared with the intersection without control devices and with other devices, the likelihood for incurring an incapacitating injury will decrease by 23.2% and that for a fatal injury will decrease by 42.1%. This result indicates that controlled intersections are related to less severe injuries because they can reduce vehicle speeds and improve the risk perception level^[15,36]. Thus, the conflicts between bicycles and motor vehicles can be reduced accordingly.

3.5 Time

The nighttime indicator is significant. The result shows that 56.5% cyclists suffer higher injuries at night. The likelihood for incurring an incapacitating injury will increase by 15.3% and that for fatal injury will increase by 32.2% compared with the daytime. This finding is consistent with Eluru’s report^[23]. Lower visibility at night reduces the driver’s reaction ability, hence increasing collision energy^[23]. In addition, the factor Tuesday is also significant. The reason for this interesting phenomenon is unknown and further study is needed.

4 Conclusions

1) In the U. S., commuting by bicycle is quite dangerous for older cyclists and women. Therefore, more attention must be paid to them. Reinforcing safety education and adding safety facilities are effective ways to reduce collision risk.

2) Considering the behavioral factors, the main causes of higher injury severity in vehicle-cyclist collision include high speed (racing, dashing, etc.), insufficient reaction time (racing, drinking, etc.) and increased chance of conflict (turning left, red-light running, etc.). Therefore, it is important to strengthen the law enforcement for both drivers and cyclists.

3) Improving road environment can effectively reduce the risk of collision. Lighting facilities should be improved to increase visibility at night and signs can be expended to limit speed and enhance the vigilance of road users.

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考虑碰撞前行为的交叉口自行车碰撞事故分析： 随机参数次序 Probit 方法

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摘要:为了分析交叉路口自行车与机动车碰撞事故严重程度的风险因素,尤其是与道路使用者行为相关的因素,以综合评估系统中收集的 2011—2015 年的事故记录为依据,进行实证型研究. 经过初步筛选,解释变量被分为骑车人的特征和行为、驾驶员的特征和行为、车辆特征、交叉路口条件和时间 5 个主要类别. 采用 RPOP 模型探索显著的影响因素和相应的异质性. 结果表明,骑车人不遵守交通信号、不分享路权、突然冲出和骑车前饮酒都会增加骑车人的伤害严重度,致死伤害的可能性分别增加 53.2%、40.0%、86.3%、211.5%. 此外,驾驶员注意力不集中、超速、直行和左转弯增加了骑车人的撞车风险,致死伤害的可能性分别增加 134.5%、186.5%、69.3%、22.7%. 其他指标如年龄、性别、车辆类型、交通信号和交叉路口类型也会影响伤害的严重程度.

关键词:交通安全;伤害严重程度;自行车事故;交叉口;RPOP

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