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IDENTIFYING THE FACTORS THAT INCREASE THE SEVERITY OF PEDESTRIANS' INJURIES WHEN STRUCK BY VEHICLES

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Abstract: This research focuses on identifying the factors that correlate with the increase in the severity of pedestrian injuries when struck by motorized vehicles. Using a dataset of all collisions involving pedestrians from Washington State, the objective of this research is to identify demographic attributes of at-risk drivers who are more likely to be involved in collisions resulting in death or serious injuries to pedestrians. Other factors being investigated include environmental conditions, visibility, urban/rural location, and the type of the roadway. A multinomial logit model was estimated to identify the most significant factors associated with death or serious injuries for pedestrians. This paper finds young, male, and impaired drivers are more likely to be involved in collisions resulting in death of or serious injuries to pedestrians. Poor visibility and overcast conditions are also associated with higher odds for pedestrian injury or death. Similarly, rural locations and interstate facilities also found to be associated with higher odds. A key limitation of this paper is the lack of demographic attributes of pedestrians.

1 INTRODUCTION

In 2015, the National Highway Traffic Safety Administration reported 5,376 pedestrian deaths from traffic crashes in the U.S., a 9.5% increase from pedestrian fatalities in 2014, and is the highest number of pedestrians killed annually since 1996 (National Highway Traffic Safety Administration [NHTSA], 2017). Although overall traffic fatalities in USA have largely declined over the past two decades, the percentage of total fatalities involving pedestrians has risen from 11% in 2006 to 15% in 2015, with no single year in decline (NHTSA, 2017).

Vehicle-pedestrian collisions typically have a high degree of severity. In 2015, 15% of all traffic fatalities and nearly 3% of injuries in traffic crashes were pedestrians (NHTSA, 2017). This suggests that vehicle-pedestrian collisions are generally more severe for injury severity than single-vehicle or multivehicle collisions. Injury severity is related to both collision speed and vehicle type. For high-speed collisions, pedestrian death is by far the most likely outcome. Further, at low speeds, pedestrians struck by a large sports-utility vehicle (SUV) or a pick-up truck are more likely to have higher odds of injury severity and death compared to those struck by a smaller passenger car (Ballesteros et al. 2004). Pedestrians struck by vehicles other than passenger cars at low speeds were twice as likely to endure traumatic brain, thoracic, and abdominal injuries, although at higher speeds there is a significantly higher chance of death overall (Ballesteros et al. 2004).

A collision involves first a potential situation, and if a conflict exists, then either an evasive action could be taken, which may or may not ultimately prevent a collision (Allen et al. 1978). In two-party situations, it is often the unpredictability of one of the parties that contributes to a collision, and a greater unpredictability typically correlates with a lower window of reaction time available to each party to evade (Allen et al., 1978). Further, the failure of any party to notice a potential hazard or delayed responses to hazards in general can result in traffic collisions (Ewing & Dumbaugh, 2009).

Results from population regression models across 21 countries show that a reduction in urban speed limits from 60 km/h to 50 km/h could reduce pedestrian fatalities by 25% (Fieldwick & Brown, 1987). Other studies have demonstrated that since the stopping distance for a vehicle is proportional to the square of the initial speed, even small reductions in the speed can greatly lower the severity of injury and probability of death (Anderson, et al., 1997).

In 2015, 74% of all pedestrian fatalities in traffic collisions occurred at night, with the highest total percentage (26%) occurring from 6pm to 9pm, and the next highest total percentage (23%) occurring from 9pm to 12am (NHTSA, 2017). It was also found that providing continuous roadway lighting reduces the risk of collisions and severity of injuries more than partial lighting, and similarly partial lighting more than no lighting (Dewar, 2007).

When drinking was a contributing factor, the probability of a severe injury greatly increased overall, with fatal injury probability increasing by 73%, and the probability of a complain of pain or no injury decreasing by 37% (Kim, et al., 2013). The authors also note that because drinking is correlated with risk-taking behaviour, and that driver intoxication may be endogenous (Kim, et al., 2013).

Infrastructure design that incorporates effective safety engineering has been addressed in the literature. At the neighbourhood level, road and zoning layouts such as cul-de-sac conventional networks, grid networks, and offset networks provide different advantages and disadvantages for both drivers and pedestrians (Wei & Lovegrove, 2012). In particular, 3-way offset layouts, a Dutch initiative, encouraged mode split (i.e. increased walking, bicycling, and transit) and improved road safety, at the cost of a small reduction in vehicular accessibility (Wei & Lovegrove, 2012).

The objective of this paper is to identify the significant factors contributing to the injury severity of pedestrian when struck by vehicles. Several explanatory variables are investigated, including those related to the driver (such as driver's gender, age, and state of intoxication) and those related to the environment (such as lighting and weather conditions).

2 DATA COLLECTION

All pedestrian-related collisions were extracted from aggregate datasets on traffic collisions maintained in the Highway Safety Information System (HSIS) data files for Washington State between 2003 and 2013 (Nujjetty & Mohamedshah; HSIS, 2014). For every analysis year, accident files and vehicle files were merged together to obtain the relevant variables for each incident. The recorded incident number, which is unique to each collision, was used to link the two files together for each year.

Between 2003 and 2013 there were 492,676 total traffic collisions reported in Washington State. The accident reporting threshold at the time of data collection was a minimum of $750 in property damage or personal injury. After eliminating incomplete records, there were 6,797 traffic collisions involving pedestrians. The data were then further filtered to remove collisions in which a pedestrian was not struck by a vehicle (2,115), injury severity was unstated (41), driver's gender was unstated (1,005), driver's age was unstated (110), driver's intoxication condition was unstated (651), lighting conditions were unstated (21), weather conditions were unstated (12) and road surface condition was unstated (5). The final dataset used for analysis comprised 2,837 records of collisions where vehicles collided with pedestrians. We estimated multinomial logit models using R software.

Within the Accident sub-file of the HSIS data, the severity variable is of primary interest for the scope of this research. For injury severity, the HSIS files denote a range of categorical values including unstated, no injury, possible injury, non-disabling injury, disabling injury, died at hospital, dead on arrival, and dead at scene. A limitation of this dataset is the HSIS definition of the severity variable, which it explains as the injury of greatest severity in a crash. While pedestrians involved in vehicle collisions are much more likely to sustain serious injuries compared to the driver, it is possible for scenarios to exist in which the driver is more seriously injured than the pedestrian. For example, a significantly older driver may incur more serious injuries than a younger pedestrian during low-speed collisions as will be discussed later in a subsequent section of this paper. However, these cases likely represent a small minority of cases overall. Indeed, for the adjusted dataset which includes only collisions involving pedestrians, there are 5 instances of driver death, all of which were reported to have the same severity as the involved pedestrian. It is therefore assumed that severity in general refers to pedestrian injuries.

3 MODEL

Statistical models for injury severity in motor-vehicle crashes are usually conditioned on both observable and unobservable factors that affect the probability of a particular injury severity category (J-K. Kim, Ulfarsson, Shankar, & S. Kim, 2008). The literature on injury severity mentions several empirical methods for modelling injury severity. These methods include logistic regression, multinomial logit models, and ordered probit models (Ballesteros, et al., 2004; Ulfarsson and Mannering, 2004; Kockelman and Kweon, 2002). Since HSIS categorises *injury severity* into mutually exclusive categories, we use multinomial logit models to determine the determinants of injury severity. Logit modeling allows for the estimation of the *k*-1 logit equations for nominal dependent variables with *k* categories, and follows a logit distribution. The approach designates one response category as a reference and reports the log-odds of the linear function generated by the predictors as per the following formula (Rodriguez, 2007):

[1] $logit(Y_i) \;=\; \eta_{ij} \;=\; \log\left(\frac{\pi_{ij}}{\pi_{iJ}}\right) \;=\; \alpha_j + x_i'\beta_j$

Where α_j is a constant and β_j is a vector of regression coefficients, for $j = 1, 2, \ldots, J - 1$. In this case, we also have:

[2] $\pi_{ij} \;=\; \Pr\{Y_i = j\}$

The log-odds generated by the multinomial logit model may also be written in terms of their original probabilities, π_{ij}, such that:

[3] $\pi_{ij} \;=\; \frac{\exp\{\eta_{ij}\}}{\sum_{k=1}^{J}\exp\{\eta_{ik}\}}$

for $j = 1, \ldots, J$. Equation 3 will yield probabilities that sum to 1 for each *i* (adapted from Rodriguez, 2007).

4 EMPIRICAL RESULTS

As mentioned earlier, our dependent variable is *injury severity*, captured as five categories ranging from no injry to death. Injury severity tabulations are presented in Table 1. Of the 2,837 collisions in the data set, approximately 7% collisions reported no injury, approximately 7.9% of the collisions resulted in death, and another 85.1% of the collisions involved some form of injury. This research estimated multinomial logistic regression models using the *multinom* function from the *nnet* package in R (Ripley and Venables, 2016). Results of the multinomial logit regression are summarized in Table 2. It should be noted that driver's age was not analyzed as a continuous variable. This is due to the high crash rates at both young age (from lack of experience) and old age (due to physiological reasons) as found by McCartt and Teoh (2015). Therefore, driver's age was analyzed as categorial variable, as shown in Table 2. The coefficient values represent the log-odds for comparing a baseline value of a predictor (e.g. for driver gender, the baseline is male) to another categorical value for the same predictor (for driver gender, this would be female), which is then further compared to the dependent categorical variable severity (adjusted) instances, as they relate to the reference of "No Injury". For comparison purposes, all coefficients were found to be statistically significant at the 0.01 confidence level except where stated.

Estimates presented in Table 3 show that male drivers are 1.70 times more likely to cause a pedestrian death from collision than female drivers. However, compared to male drivers, female drivers are 1.20 times as likely to cause disabling injury to a pedestrian from a collision, 1.47 times as likely to cause non-disabling injury, and 1.51 times as likely to cause possible injury. These results are statistically significant at the 1% confidence level. Further, drivers under 25 were significantly more likely to be involved in a collision causing severe injury or death of pedestrians when compared to drivers aged 25-74. However, drivers aged 75 and over were most likely to be involved in crashes causing fatal injury compared to all other drivers, with approximately a 1.13 odds ratio compared to drivers under 25. This held also for disabling injury (1.47 times as likely), non-disabling injury (1.74 times as likely), and possible injury (1.62 times as likely). For non-disabling and possible injury severities, there was no other statistically significant finding for age groups, the closest being possible injury for drivers 65-74, at the 10% confidence level.

Impaired driving was found to have increased odds ratios for both fatal injury (1.60 times) and disabling injury (1.26 times), and decreased odds ratios for non-disabling injury (0.87 times) and possible injury (0.68 times).

For fatal injury, the most significant odds ratio compared to daylight was the scenario with the lowest likelihood of adequate visual acuity. Drivers who collided with pedestrians in the dark (with no streetlights) were 10.21 times as likely to cause fatal injury than compared to collisions in the daytime, all other factors remaining constant. Increased odds compared to daytime driving were also found for disabling injury. No statistical significance was found for non-disabling injury due to dark driving conditions (without streetlights) compared to daytime driving. Further, dark driving conditions with streetlights (both on and off) also saw increased odds ratios for fatal injury, with lights on at 3.67 times more likely, and lights off at 3.19 times more likely. Compared to daylight lighting conditions, both dusk and dawn saw increases in all odds ratios for all severities except for fatal injury at dawn. For fatal injury, daylight saw an increased odds ratio of 1.59 compared to dawn. Dusk was the only lighting condition that was found to have increased odds ratios for all severities compared to daylight, with fatal injury specifically being 2.05 times more likely. All weather types compared to reference (clear/partly cloudy), except for overcast were found to have decreased odds ratios for fatal injury. Snowy weather was found to have the largest reduction in odds ratio for fatal injury severity compared to clear weather, at 0.53 times as likely. However, increases in odds ratios from snowy weather for disabling injury (1.71 times) and possible injury (1.14 times) were found to be statistically significant. Although rainy weather showed a small (but statistically significant) decrease in odds for fatal injury compared to clear weather (0.94 times as likely), there were statistically significant increases in odds for disabling injury (1.26 times), non-disabling injury (1.25 times), and possible injury (1.57 times). Overcast weather was found to have increased odds ratios for all severity types compared to clear weather, but only fatal injury (1.24 times) and possible injury (1.27 times) were significant.

Table 1**:** Adjusted summary counts for *severity* categorical variable

Injury Severity	Count (*N*)	% of TOTAL
Death from injury	223	7.9%
Disabling injury	528	18.6%
Non-disabling injury	1,005	35.4%
Possible injury	883	31.1%
No injury	198	7.0%
TOTAL	6,752	100%

Table 2**:** Pedestrian injury severity model estimation results

Independent Variable		Dependent Variable			
		Death From Injury	Disabling Injury	Non-Disabling Injury	Possible Injury
Driver Age (Ref: Under 25)	25-54	-0.322*** (0.079)	-0.257*** (0.067)	-0.013 (0.061)	-0.052 (0.063)
	55-64	-0.103** (0.047)	-0.442*** (0.080)	-0.058 (0.075)	-0.029 (0.075)

	65-74	-0.183*** (0.009)	0.045 (0.058)	0.060 (0.080)	0.145* (0.075)
	75+	0.118*** (0.004)	0.386*** (0.016)	0.553*** (0.068)	0.484*** (0.060)
Driver Gender (Ref: Male)	Female	-0.530*** (0.012)	0.188*** (0.067)	0.386*** (0.058)	0.411*** (0.060)
Lighting Condition (Ref: Daylight)	Dawn	-0.464*** (0.0003)	0.300*** (0.003)	0.170*** (0.003)	0.091*** (0.003)
	Dusk	0.717*** (0.001)	0.605*** (0.005)	0.373*** (0.006)	0.472*** (0.006)
	Dark, street lights on	1.299*** (0.062)	0.747*** (0.070)	0.292*** (0.065)	0.096 (0.068)
	Dark, street lights off	1.160*** (0.001)	-0.925*** (0.001)	-0.608*** (0.002)	-0.793*** (0.002)
	Dark, no street lights	2.324*** (0.051)	0.905*** (0.044)	0.050 (0.044)	-0.228*** (0.027)
Weather (Ref: Clear)	Overcast	0.211*** (0.008)	0.044 (0.086)	0.095 (0.073)	0.235*** (0.075)
	Raining	-0.061*** (0.014)	0.229*** (0.082)	0.219*** (0.073)	0.448*** (0.075)
	Snowing	-0.635*** (0.001)	0.539*** (0.003)	0.135*** (0.002)	0.692*** (0.003)
	Other	-0.116*** (0.002)	-0.052*** (0.004)	-0.012** (0.005)	-1.153*** (0.002)
Day of Week (Ref: Weekday)	Weekend	0.145*** (0.012)	-0.171** (0.079)	-0.167** (0.071)	-0.360*** (0.075)
Driver Intoxication (Ref: Not Impaired)	Impaired	0.471*** (0.005)	0.229*** (0.007)	-0.145*** (0.007)	-0.385*** (0.004)
Environment Location (Ref: Rural)	Urban	-1.125*** (0.033)	-0.974*** (0.071)	-0.486*** (0.084)	0.025 (0.065)
Road Type (Ref: Interstate)	Arterial	-1.048*** (0.018)	0.107 (0.071)	0.428*** (0.095)	0.549*** (0.066)
	Collector	-1.057*** (0.005)	0.128*** (0.023)	0.747*** (0.023)	1.424*** (0.027)
Vehicle Year (Continuous)	-	-0.020*** (0.0001)	-0.012*** (0.0001)	-0.017*** (0.0001)	-0.007*** (0.0001)
Constant	-	42.225*** (0.0003)	25.304*** (0.0001)	35.254*** (0.0001)	14.196*** (0.0001)

*p<0.1; **p<0.05; ***p<0.01, McFadden R^2 = 0.052, Log-likelihood = -3846.0, “Ref” = Reference value for categorical variables, Standard errors are in parentheses.

Weekends (Saturdays and Sundays) were found to have a significant impact on increased odds for fatal injury compared to weekdays, at 1.16 times more likely, at the 1% confidence level. However, weekends also were found to have decreased odds ratios for disabling, non-disabling, and possible injury severities, at 0.84, 0.85, and 0.70 times those of weekdays, respectively. The confidence intervals are at the 5% level for disabling and non-disabling injury, and 1% for possible injury.

Compared to rural areas, urban areas were found to have statistically significant reductions in odds ratios for fatal injury (0.33 times), disabling injury (0.38 times), and non-disabling injury (0.62 times). A small increase in odds ratio was found for urban areas compared to rural areas for possible injury (1.03 times), but it was not significant. Compared to interstate roads, both arterial and collector roads were found to have statistically significant decreases in odds ratios for fatal injury, at 0.35 times and 0.34 times, respectively. It is noted that in general, pedestrians are not permitted on interstate roads, which suggest that other factors exist (such as intoxication levels). However, both arterial and collector roads were found to have increases in odds ratios for all other severity types, with statistical significance at the 1% level for all cases except for arterial roads and disabling injury, which was not significant at the $P < 0.1$ level. In particular, collector roads had the highest odd ratio increases for disabling injury (1.14 times), non-disabling injury (2.11 times), and possible injury (4.12 times), compared to interstate roads.

Vehicle year (a continuous variable) representing the age of the vehicle was found to have a small but statistically significant impact on injury severity. A one unit (year) increase in vehicle year was found to correlate with a small decrease in odds ratio (0.997 times) for fatal injury and non-disabling injury (0.994 times). Small odds ratio increases were found for disabling injury and possible injury (both less than a 1% increase). The complete odds ratios are given in *Table 3*.

5 DISCUSSION

Injury severity is found in the literature to be most affected by pedestrians' physical condition (age, alcohol use), vehicle speed, driver and pedestrian perception and reaction (weather, lighting), and area of impact (vehicle type) (Lee & Abdel-Aty, 2005). We found that an increase in injury severity to fatal injury is likely correlated with driver age, driver gender, light condition, weather condition, temporal conditions, driver intoxication, road functional class and setting, and vehicle year. Using the model presented, it was found that the log-odds ratios for fatal injury increased for younger driver age groups (under 25), as reported in Table 2. These results are similar to findings by McCartt and Teoh (2015) and Kim et al. (2008), where young drivers (under 25) were found to have significantly higher rates of fatal injury overall compared to other age groups (McCartt & Teoh, 2015). The model outlined in this paper suggests that elderly drivers (75+) are more likely to inflict severe or fatal injury on pedestrians compared to all other driver ages. Conversely, McCartt & Teoh (2015) report a model in which elderly drivers were found to have a lower incidence rate of fatal injury and incapacitation injury to pedestrians, despite a higher rate of crash incidence overall (McCartt & Teoh, 2015; Kim et al., 2008). Furthermore, the model in this paper suggests that male drivers are more likely to fatally injure pedestrians than females. Conversely, female drivers were found to be more likely to injure pedestrians in a non-fatal fashion compared to males, all other factors remaining constant. This could be due to a number of contributing factors, such as risk aversion proportion of driver gender, but similar findings were reported by McCartt & Teoh (McCartt & Teoh, 2015). This skew towards males as contributing to more severe injuries is also found on the pedestrian side of the equation within the literature.

While males in general contribute to a larger share of traffic collisions overall behind the wheel compared to females, they also make up a significant portion of the fatalities as pedestrians involved in collisions. In 2015, 70% of the pedestrians killed in traffic crashes were males (NHTSA, 2017). This equates to a pedestrian fatality rate per 100,000 people of 2.37 for males, more than double for females (NHTSA, 2017). This statistic has remained relatively consistent even since the early 1990s. In 1994, 68% of all U.S. pedestrian fatalities were male (LaScala, Gerber, and Gruenewald, 2000).

Table 3: Summarized odds ratios for injury severity by the model

Independent Variable		Dependent Variable			
		Death From Injury	Disabling Injury	Non-Disabling Injury	Possible Injury
Driver Age (Ref: Under 25)	25-54	0.724	0.773	0.987	0.950
	55-64	0.902	0.643	0.943	0.971
	65-74	0.832	1.046	1.062	1.156
	75+	1.125	1.472	1.738	1.622
Driver Gender	Female	0.589	1.206	1.471	1.508

(Ref: Male)					
Lighting Condition (Ref: Daylight)	Dawn	0.629	1.350	1.185	1.096
	Dusk	2.047	1.832	1.452	1.602
	Dark, street lights on	3.667	2.111	1.339	1.100
	Dark, street lights off	3.190	0.397	0.544	0.452
	Dark, no street lights	10.213	2.472	1.051	0.796
Weather (Ref: Clear)	Overcast	1.235	1.045	1.099	1.265
	Raining	0.940	1.257	1.245	1.565
	Snowing	0.530	1.715	1.144	1.997
	Other	0.890	0.949	0.989	0.316
Day of Week (Ref: Weekday)	Weekend	1.157	0.843	0.846	0.698
Driver Intoxication (Ref: Not Impaired)	Impaired	1.602	1.257	0.865	0.681
Environment Location (Ref: Rural)	Urban	0.325	0.378	0.615	1.026
Road Type (Ref: Interstate)	Arterial	0.351	1.113	1.534	1.732
	Collector	0.348	1.137	2.110	4.155
Vehicle Year (Continuous)	-	0.980	0.988	0.983	0.993

In terms of visual acuity, daylight provides a greater capacity for both driver and pedestrian awareness than compared to a lack of natural lighting during night hours. Fatal injury was found to be the most likely outcome for all non-daylight/dawn scenarios. It is theorized that drivers have a greatly reduced visual acuity and therefore reduced reaction time during low-light settings compared to highly visible settings.

6 DATA LIMITATIONS

Vehicle type could not be analyzed due to accuracy-related issues at the data-collecting-level (i.e. the Washington State HSIS manual did not state vehicle subtypes in their explanatory pages, as the staff believed the codes to be inaccurate. Analogous manuals from other states could not be used as there was no consistency between reported codes for vehicle type). Furthermore, vehicle speed was not available within the data and therefore its impact on injury severity cannot be reported on here. It is hypothesized that greater speed will result in higher injury severity, due to speed's involvement in both momentum and force. However, speed in general likely has an overarching effect on the overall model, causing the effect of other significant variables to appear small in comparison. Other predictors that would ideally be tested in this model are pedestrian characteristics, such as age, gender, and intoxication, as it is hypothesized that physiological aspects of the victim play a contributing role in injury severity. Hour of the day as a temporal parameter may also be included in an ideal model, though was also not available in the data. However, the presented model parameters for light condition act as a moderate proxy toward time of day, as they contain indices of natural lighting (or lack thereof), though there are other conditions as well.

7 CONCLUSIONS

Modelling pedestrian injury severity in vehicle collisions requires consideration of numerous driver characteristics and environmental factors. We estimated Multinomial logistic regression models to analyze pedestrians' injury severity in collisions with automobiles. It was found that an increase in fatal injury was associated with younger and elderly drivers, male drivers to a greater extent than female drivers, dark lighting conditions compared to daylight, overcast weather conditions, specific days of the week, driver intoxication, larger/busier interstate roads compared to smaller arterial roads, rural environments more than urban environments, and older vehicles. The presented model does not address vehicle speed, or pedestrian age, gender, or intoxication. It would be beneficial to include these factors in future models in order to assess their impact.

Future work could also look at the impact of vehicle type, which would help address the nature of the impact itself. Further, injury severity here is presented on a categorical basis overall, but does not address specific injury type, recovery rate and costs, as well as intangible costs due to fatality and severe injury (including mental health injury). The results presented here could be used to formulate public policy and promote awareness about the risks faced by pedestrians. Educating younger drivers about safety and advising pedestrians about being vigilant at times when visibility is poor could help improve safety for pedestrians.

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