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Understanding roundabout safety through the application of advanced econometric techniques

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A B S T R A C T

Intersections present a significant safety concern, as such in an effort to reduce the more serious injuries occurring at or near intersections, many jurisdictions have turned to implementing roundabouts. Despite the advantages that roundabouts provide, crashes still occur, and less severe crashes are on the rise. The study presented in this paper investigates a crash-based analysis to better understand the factors that may influence less severe crashes to those of more severe crashes given various roundabout configurations and crash types. Using Oregon's crash database from 2011 to 2015 a series of log likelihood ratio tests were conducted to validate that four separate random parameters binary probit models by configuration type were warranted. The outcome of each tested configuration (full, three & four leg, four leg, and three leg models) shows a major difference in both the combination and variables included in each model and the magnitude of impact of those variables. These differences illustrate that various roundabout configurations (full, three & four leg, four leg, and three leg models) do in fact have different factors highlighting the need to examined crashes at roundabouts by configuration type. Variables related to driver error, weather, alcohol use, barrier conditions, vehicle movement, location of crash, and restraint use were found as key differences between the various tested configurations.

1. Introduction

Intersections present a significant safety concern, accounting for roughly 2.21 million crashes and 6770 fatal crashes in 2009, while during the period of 2011–2014 there were 48,733 (28%) drivers involved in fatal intersection crashes (AARP and WALC, 2014; Gross et al., 2013; Lombardi et al., 2017; NHTSA, 2009). Almost one in every four fatal crashes occur at or near an intersection (Haleem and Abdel-Aty, 2010). In an effort to reduce the more serious injuries occurring at or near intersections, many jurisdictions have turned to implementing roundabouts, a proven countermeasure (FHWA, 2015; Gross et al., 2013; Nikitin et al., 2017). The construction of roundabouts as an alternative to signalized or stop sign-controlled intersections has increased over the years, with less than 100 in 1997 to as many as 3200 in 2013 and growing (FHWA, 2015; Montella, 2011; Qin et al., 2011). Many intersections have been converted to roundabouts to enhance traffic capacity and

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reduce crashes (Montella, 2011). Compared to other types of intersections, roundabouts have some intrinsic properties favoring traffic safety; for example, they reduce speeds considerably and decrease the number of possible conflict points between road users (Daniels et al., 2011).

The Federal Highway Administration (FHWA) formally defines a conflict as an "*observable situation in which two or more road users approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged*." Traffic at a roundabout is governed by the yield-at-entry rule, and the relatively lower levels of geometric design standards are intentionally applied to force vehicular trajectories at roundabouts into a very narrow space. International studies of intersections that have been converted to roundabouts indicate a steady reduction in injury crashes, particularly for crashes with fatal or severe injuries (Daniels et al., 2010a). These studies indicate that the crash frequencies (average annual crashes per roundabout) in the United State are still high compared to results from Australia, France, and the United Kingdom (Robinson et al., 2000). These same studies also report a considerable decrease in the number of severe crashes (fatalities and crashes involving severe injuries) compared to the reduction of the total number of injury crashes. However, the effects of property-damage-only (no injury) crashes are highly ambiguous (Daniels et al., 2008). Souliman (2016) examines the outcomes of single-lane and double-lane roundabouts in the State of Arizona. The author indicated that single-lane roundabouts decreased the overall rate of accidents by 18%, while double-lane roundabouts increased the accident rate by 62% and Damage rates increased by 2% and 60% for single-lane and double-lane roundabouts. Despite the advantages that roundabouts provide, crashes still occur.

Turning to driver injury severity analyses, various methodological and statistical modeling techniques have been developed and applied to identify various contributing factors to intersection related crashes (Lombardi et al., 2017). Roadway geometric features, driver behavior, demographic information, traffic control elements, traffic compositions, and environmental characteristics are some examples of these factors (Liu et al., 2016; Lombardi et al., 2017; Mannering et al., 2016). To better understand the influences of these factors on roundabout crashes, it is essential to investigate their impacts on crash occurrences in order to develop effective countermeasures to reduce crash risk and severity.

Still, what is not clearly understood is the relationship between roundabout crash-related factors, crash types, injury severity, and roundabout configurations. Therefore, the objective of this study is to conduct a crash-based analysis to better understand the factors that may influence less severe crashes to those of more severe crashes given various configurations and crash types for roundabouts. This will be accomplished through exploring advance econometric techniques applied to roundabout crash data that account for unobserved heterogeneity (unobservable in the data). These advanced econometric techniques have been shown to provide a more accurate understanding of contributing factors to overall safety issues (Mannering et al., 2016; Mannering and Bhat, 2014). Specifically, this work utilizes the random parameters binary probit model. The random parameters binary probit model is used here to gain a better understanding of the complex interactions between factors found to be significant and those unobserved factors that may be influencing estimated outcomes. To accomplish this, Oregon crash data is used. The dataset consists of 1006 crashes in seventeen counties in the State of Oregon for a five-year period (2011–2015). To the best of the authors' knowledge, this is the first attempt at modeling driver-injury severity for crashes occurring at roundabouts using a random parameter binary probit approach on two injury severity outcomes (injury or no injury) in Oregon.

2. Background

Given the sparsity of literature on roundabout injury severity modeling, this section presents studies related to methodological approaches that establish any links between crash characteristics, injury severity, road environments, and other factors related to roundabouts.

According to previous studies in Belgium, no studies for designing and improving road safety policy have ever been carried out in depth. Considering this, De Brabander et al. (2005) studied the impact of roundabouts on the number of crashes and injury severity. Based on a classic negative binomial distribution, the results showed that roundabouts lead to a reduction of 34% in the number of injury crashes. After that study, many studies were completed in Belgium to evaluate the effectiveness of roundabouts. One such study found that the conversion of intersections into roundabouts led to a substantial rise (27%) in the number of injury crashes involving bicyclists on or nearby roundabouts in Flanders, Belgium. This outcome was confirmed by Daniels et al. when attempting to ascertain if roundabouts have an impact on the safety of different types of road users; this was used to develop adequate decision-making criteria for roundabout design (Daniels et al., 2008). Then, in an expanded study in Flanders, Belgium conducted by Daniels et al., the authors looked into which factors might explain the severity of crashes or injuries at roundabouts constructed between 1990 and 2002 (Daniels et al., 2010b). To do this, Daniels et al. investigated the application of the Poisson and gamma modeling techniques to determine which variables might explain a structural part of the variation in crash rates at roundabouts in Flanders, Belgium (Daniels et al., 2010a).

Next, Daniels et al. extended the prediction models for crashes at roundabouts, in which regression models were fitted using available geometric and traffic variables (Daniels et al., 2011). The Poisson and gamma models were equipped with the resulting list of variables. Vulnerable road users (moped riders, motorcyclists, bicyclists, pedestrians) are more often involved in injury crashes at roundabouts. The overall number of crashes is more or less proportional to the number of motorized vehicles (AADT). Three-leg roundabouts tend to perform worse than roundabouts with four or more legs. The larger the central island, the more single-vehicle crashes seem to occur.

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Substantial and highly significant crash reductions were observed by Montella following conversion of signalized and stop-controlled intersections to roundabouts (Montella, 2011). However, roundabout performances can degrade if precautions are not taken during either the design or the operation phase. Thus, the paper aimed to investigate the contributory crash factors at fifteen urban roundabouts located in Italy and to study the interdependencies between these factors. It was found that the most frequent category of contributory crash factors was geometric design. Markings were a contributory factor in more than half of the total crashes. Pavement was identified as a contributory factor in more than one-third of the total crashes, with the most common factor being low friction. Road environment factors were designated as a contributory factor in one-fifth of the crashes.

Furthermore, Kim and Choi investigated the significant factors that contribute to crashes at roundabouts in South Korea by comparing two conventional models (Kim and Choi, 2013). The study found it possible to connect roundabout geometric design elements with real instances of vehicle crashes.

Mamlouk and Souliman (2018) evaluated the effect of using roundabouts on crash rate and severity in Arizona. It was found that single-lane roundabouts reduced the rate of accidents, while double-lane roundabouts increased the rate of accidents. Single- and double-lane roundabout modifications have lowered accident severity rates.

Miranda-Moreno (2013) conducted a crash severity analysis to identify the effects of different contributing factors on injury severity outcomes in Canada by applying an ordered logit model. The result indicated that Factors such as increased number of vehicles involved, accidents at the intersection, vehicle rollovers, bus involvement, accidents in the dark on unlit roads and snow conditions have resulted in increased severity of injury at the roundabouts. In comparison, factors associated with accidents involving only vehicles, animal attacks and snow-covered roads were found to be associated with less serious injuries.

In term of more methodological approach to analyze injury severity outcomes, Tay (2015) utilized random parameter binary probit model to identify the crash contributing factors that differentiated between an urban and a rural intersection crash and determine if urban and rural intersection crashes have different crash characteristics. Haleem et al. (2015) performed separately analysis was for signalized and unsignalized intersections to identify and compare the significant factors affecting pedestrian injury severity. The mixed logit (or random parameters logit) modeling approach was applied, which accounts for the influence of unobserved factors, such as pedestrian physical health and driver behavior.

Furthermore Moore et al. (2011) developed discrete outcome models in order to identify the impacts of numerous factors on the level of injury severity sustained by crash-involved bicyclists at a sample of both intersection and non-intersection locations. Haleem and Abdel-Aty (2010) conducted crash severity analysis by using an ordered probit model to identify the significant factors that contribute to injury severity at unsignalized intersections.

Although roundabouts have gained popularity nationally and in Oregon, it is still not clearly understood what the relationship might be between crash types, injury severity, and roundabout configurations. As such, there is a need for further research to develop advanced crash prediction models that account for unobserved heterogeneity. In addition, from an injury severity analysis and configuration perspective, the lack of literature shows there is much more that can be done to capture the complex interactions of these variables. A reason for this may stem from the lack of available detailed crash-related data. Recent studies have illustrated the use of limited crash data sources to discover relationships between crash-related factors and injury severity through the use of advanced unobserved-heterogeneity-based econometric techniques (Al-Bdairi et al., 2018; Al-Bdairi and Hernandez, 2017; Anderson and Hernandez, 2017; Pahukula et al., 2015; Romo et al., 2014). Hence, the objective of this study is to conduct crash-based analyses to better understand the factors that may influence less severe crashes to those of more severe crashes given various configurations and crash types.

3. Empirical setting

It is generally accepted that there are fewer severe crashes at roundabouts (FHWA, 2015). Therefore, obtaining detailed data that can capture the factors that contribute to crash severity is more complicated regarding the required sample size that accurately represents the population. As such, this research is based on crash data collected and compiled by Oregon's Department of Transportation (ODOT) Crash Analysis and Reporting Unit. The data includes crashes over a five-year period (2011–2015), in which 1006 crashes occurred at roundabouts (shown in Table 1). Fig. 1 illustrates the difference between the normalized crash data vs. the non-normalized crash data to compare the crash patterns during the period 2011–2015. The normalization was performed by calculating the average number of the crashes over five years and their distribution over

Table 1
Crash injury severity at roundabouts in Oregon from 2011 to 2015.

Year	Severe	Minor	No Injury	Sum	% of Total
2011	1	28	125	154	15.31
2012	1	41	179	221	21.97
2013	1	30	165	196	19.48
2014	1	34	160	195	19.38
2015	2	31	207	240	23.86
Total	6	164	836	1006	100

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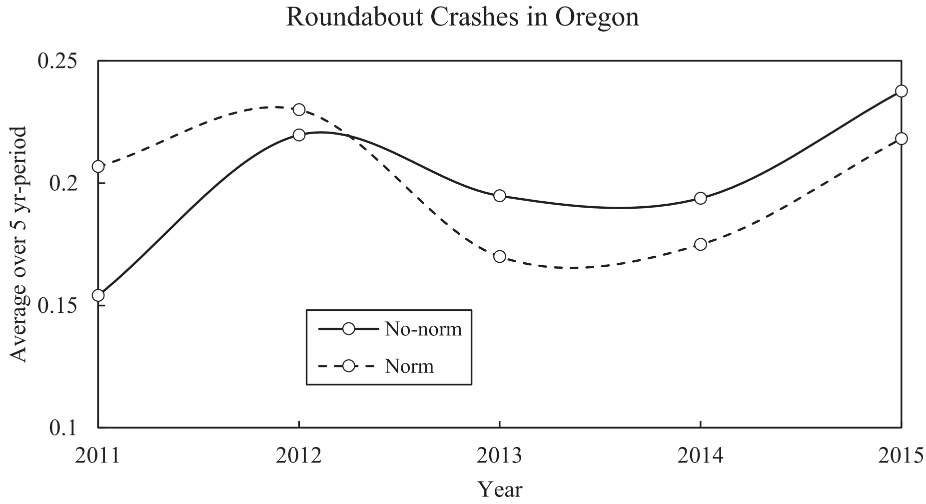

Fig. 1. Normalized vs non-normalized data of roundabout crashes in Oregon from 2011 to 2015.

this time period. These crashes occurred in seventeen counties at different types of roundabouts (unknown, three leg, four leg, and five leg roundabouts), as shown in Fig. 2, with a different geometric design in both rural and urban areas.

As illustrated in Fig. 2, roundabouts with four leg had the highest number of crashes at 704 (70%), followed by roundabouts with three leg at 209 (21%) crashes, unknown roundabout type at 75 (7%), and roundabouts with five leg at 17 crashes. The distribution of the crash injury severity is comprised of six fatal and incapacitating injuries (severe), 164 minor injuries (non-incapacitating and possible injuries – complaint of pain), and 836 no injuries.

Table 2 provides descriptive statistics of variables that were used to model injury severity for all roundabout types (full model), three and four leg roundabouts (three and four leg), four leg roundabouts (four leg), and three leg roundabouts (three leg). These variables consisted of factors related to gender, age of the driver, participant cause, crash level cause, safety equipment use, light condition, population, speed limit, weekdays, movement of the vehicle, weather condition, alcohol use ownership and the type of the vehicle, and barrier type and condition. The dependent variables in each of these models consisted of two specific outcomes: (1) no injury and (2) injury. The sample size characteristics and the frequency for each of these models are illustrate in Table 3.

The vehicle type variable (passenger car, pickup, van, light delivery, and custom van) was found to be significant in all the models, additionally male driver and drivers older than 21 and but less than 36 years old was also found to be significant in all the models. Seatbelt being the safety equipment used by the driver was found to be significant in three models (full, three and four, and four leg models). Participant cause, such as the driver followed too closely and vehicle level action when driver stopped in traffic not waiting to make a left turn were found to be significant in the full and three & four leg models. Crash

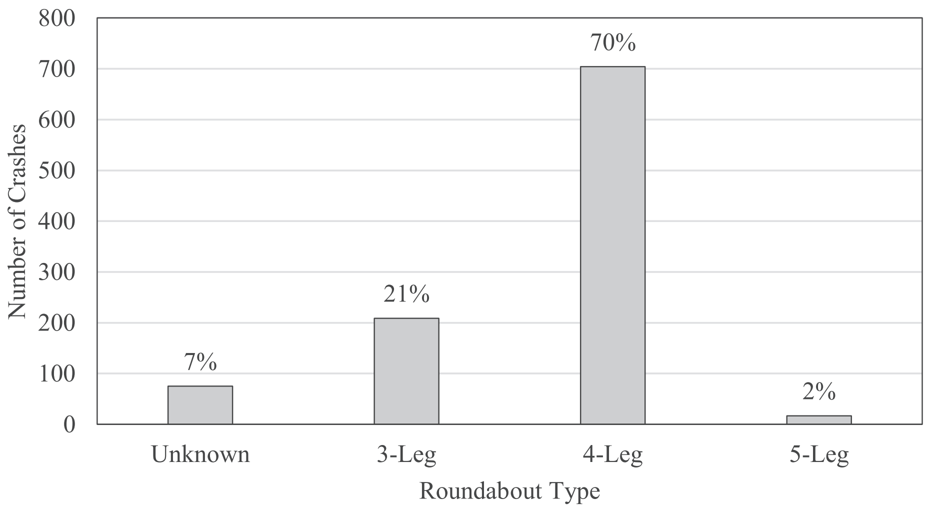

Fig. 2. Number of crashes according to the type of roundabout.

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Table 2
Descriptive statistics of key variables in all models.

Variable	Mean/Standard Deviation			
	Full Model	Three and Four leg Model	Four leg Model	Three leg Model
Vehicle Type (1 the vehicle weight < 10,000 lb., 0 otherwise)	0.95/0.22	0.95/0.22	0.96/0.21	0.92/0.27
Gender (1 if male, 0 otherwise)	0.51/0.50	0.5/0.5	0.49/0.50	0.53/0.50
Age of Driver (1 if 21 < age ≤ 35, 0 otherwise)	0.22/0.42	0.22/0.41	0.21/0.41	0.97/0.17
Participant Safety Equipment Use (1 if seatbelt is used, 0 otherwise)	0.58/0.49	0.58/0.49	0.55/0.5	–
Participant Level Cause (1 if the driver followed too closely, 0 otherwise)	0.13/0.33	0.13/0.34		
Vehicle Level Action (1 if the driver stopped in traffic not waiting to make a left turn, 0 otherwise)	0.16/0.37	0.16/0.36		
Roadside (1 if the crash happened at the right roadside, 0 otherwise)	0.33/0.47	–	0.22/0.41	–
Participant level cause (1 if failed to avoid vehicle ahead, 0 otherwise)	0.04/0.21	–	0.07/0.26	–
Weekdays (1 if the crash happened during the weekdays, 0 otherwise)	–	–	0.79/0.41	0.78/0.41
Crash Level Cause (1 if the crash happened because careless driving, 0 otherwise)	–	–	0.03/0.18	0.04/0.19
Movement of the Vehicle at the Time of the Crash (1 if stopped in traffic, 0 otherwise)	–	–	0.18/0.38	0.15/0.36
Participant Level Cause (1 if the driver followed too closely, 0 otherwise)	–	–	0.14/0.35	–
Barrier Condition (1 if fair condition, 0 otherwise)	–	–	0.003/0.05	–
Posted Speed Limit (1 if the speed limit more than 35, 0 otherwise)	–	–	0.61/0.49	–
Crash Level Cause (1 if the driver disregarded other traffic control device, 0 otherwise)	–	–	–	0.04/0.19
Crash Level Cause (1 if failed to avoid vehicle ahead, 0 otherwise)	–	–	–	0.07/0.25
Barrier Type (1 if concrete type, 0 otherwise)	–	–	–	0.11/0.31
Weather Condition (1 if cloudy, 0 otherwise)	–	–	–	0.08/0.27
Weather Condition (1 if rainy, 0 otherwise)	–	–	–	0.17/0.38
Alcohol Use (1 if that participant had been drinking, 0 otherwise)	–	–	–	0.06/0.23

*Population range is in thousand.

Table 3
Dependent variable frequency and percentage distribution in all the models.

Model number	No injury	Injury
Full Model	836 (83.1%)	210 (16.9%)
Three and Four leg Model	761 (83.35%)	152 (16.65%)
Four leg Model	590 (83.81%)	114 (16.19%)
Three leg Model	171 (81.82%)	38 (18.18%)

occurred at the right side of road and participant failed to avoid vehicle ahead were found to be significant in two models (full and four leg models). The variables related to the crash occurring during the weekdays, crash occurred because careless driving, and speed limit were found to be significant in the three and four leg models.

Driver disregarded other traffic control device, failed to avoid vehicle ahead, concrete barrier, cloudy and rainy weather, alcohol involved were all found to be significant in three leg model.

4. Methodology

Many discrete choice modeling techniques have been used to formulate crash injury severity models. Such frameworks include multinomial logit models, ordered probit models, binary logit models, etc. For this research, fixed and random parameters binary probit models are used to model the probability of two possible crash severity outcomes. These outcomes represent the aggregation of: (1) injury-type crashes and fatal crashes, and (2) no injury crashes. This is done due to the substantial number of no injury crashes in comparison to crashes that result in injuries. Accordingly, the aggregated injury category consists of fatal, major, moderate, and minor injury outcomes, while the no injury category includes only no injury outcomes. The purpose for this aggregation is to increase the number of observations to reduce the variability caused by random effects when statistical methods are implemented (Chang and Mannering, 1999). This is essential since the data that is used in this study has too few observations on incapacitating and fatal injuries to set apart their individual effects. Also, this research aims to discover what is influencing these no injury crashes.

To begin, the binary probit model takes on the form of a binary index response model (Wooldridge, 2010):

$$\mathrm{P}(y = 1|\boldsymbol{X}) = G(\boldsymbol{X\beta}) = p(\boldsymbol{X}) \tag{1}$$

where $\boldsymbol{X}$ is a $1 \times \boldsymbol{K}$, $\boldsymbol{\beta}$ is a $\boldsymbol{K} \times 1$, and the first element of $\boldsymbol{X}$ is taken to be unity. In the case of the probit model, in which $G(\cdot)$ is a cumulative distribution function (CDF), a more general form of the effect of an explanatory variable $\boldsymbol{X}$ on a binary outcome can be expressed as follows (Wooldridge, 2010):

$$y^* = \alpha + \boldsymbol{\beta X} + \varepsilon \tag{2}$$

with:

$$y = 1[y^* > 0] \tag{3}$$

where $y = 1[y^* > 0]$ represents a crash in which an injury occurred ($y = 0$ otherwise). Considering these formulae, the probit model, which specifies the conditional probability, is then a special case of Eq. (1) (Cameron and Trivedi, 2005; Wooldridge, 2010):

$$\Phi\left(\boldsymbol{X}'\boldsymbol{\beta}\right) = \int_{-\infty}^{\boldsymbol{X}'\boldsymbol{\beta}} \phi(z)dz \tag{4}$$

where $\Phi(\cdot)$ is the standard normal CDF, with derivative:

$$\phi(z) = \frac{\exp\left(-z^2/2\right)}{\sqrt{2\pi}} \tag{5}$$

where the probit model above is derived if $\mathscr{E}$ in the latent variable formulation has a standard normal distribution.

Using the presented probit model, the probability of being involved in an injury crash (i.e., y takes on the value 1) is computed. Referring to Eq. (1), $\boldsymbol{\beta}$ is a vector of estimable parameters and $\boldsymbol{X}$ represents a vector of explanatory variables (e.g., gender, age, safety equipment use, participant errors, residency of the participant, vehicle ownership, type of vehicle, intended movement, crash location, road surface condition, speed, pavement condition, and effect of striking vehicle), andε is a disturbance term with a standard normal distribution.

4.1. Unobserved heterogeneity

With the collected data, some of the many factors affecting the likelihood of a crash and the resulting injury severity are likely to be unavailable to the analyst. These unobservable factors, or unobserved heterogeneity, can introduce variation into the model impacting crash likelihood and injury severity (Mannering et al., 2016). For instance, consider gender as an observed human element that affects injury severity outcomes. However, there are clear physiological differences between men and women, as well as many variations across people of the same gender (for instance, differences in height, weight, bone density, etc.). These unobservables can result in unobserved heterogeneity, and if not accounted for, can result is biased parameter estimates. Examples of random parameters methods to account for unobserved heterogeneity can be found in Castro et al. (2013), Venkataraman et al. (2013), and Venkataraman et al. (2014). In an attempt to account for this data heterogeneity, a random parameters technique is applied as shown in Eq. (4) (Greene, 2012):

$$\beta_i = \beta + u_i \tag{6}$$

where u_i is a randomly distributed term. To estimate these random parameters, maximum likelihood estimation is performed through a simulation-based approach to address the computational complexity of computing the outcome probabilities. The chosen simulation approach utilizes Halton draws which have been shown to provide a more efficient distribution of the draws for numerical integration than purely random draws (Bhat, 2003; Halton, 1960; Pahukula et al., 2015). Lastly, marginal effects are computed to show the impact of a one-unit change of explanatory variable X on the injury outcome $i$as shown in Eq. (7) and referred to in Washington et al. (2011).

$$M_{X_{ink}}^{P_n(i)} = \Pr\left[P_n(i) = 1|\overline{\mathrm{X}}_{(X_{ink})}, X_{ink} = 1\right] - \Pr\left[P_n(i) = 1|\overline{\mathrm{X}}_{(X_{ink})}, X_{ink} = 0\right] \tag{7}$$

4.2. Log-likelihood test

Maximum likelihood and simulation-based maximum likelihood methods are used to estimate the parameter vector. During analysis, normal, lognormal, triangular, and uniform distributions were considered for the random parameters' distribution; however, only the normal distribution was found to be statistically significant. In addition, the binary probit model is estimated using two hundred Halton draws, as it is stated in the literature that such number of Halton draws produces accurate estimates of the parameters (Bhat, 2003; Gkritza and Mannering, 2008; Hasan et al., 2011; Milton et al., 2008).

As mentioned before, there are different types of roundabouts (three leg, four leg, and five leg roundabouts). According to ODOT, there were about 1006 roundabout crashes over a five-year period (2011–2015). Of the 1006 crashes, most occurred on four-leg roundabouts (704) and three-leg roundabouts (209). Grouping the data for roundabouts for analysis may lead to erroneous inferences on the significance of particular explanatory variables. Subsequently, a log-likelihood ratio test is proposed to statistically test the overall significance of using a full model (all roundabout crashes regardless of configuration type) over separate models (a model with crashes on three and four leg roundabouts combined, another with crashes on four leg roundabouts only, and a model with crashes on three leg roundabouts). The first log-likelihood ratio test for transferability is as follows:

$$\chi^2 = -2[LL_{Full}\left(\beta^{Full}\right) - \sum LL_{Sep}\left(\beta^{Sep}\right) \tag{8}$$

where $LL_{Full}\left(\beta^{Full}\right)$ is the log-likelihood at the convergence of the full model (−354.73), $LL_{Sep}\left(\beta^{Sep}\right)$ is the log-likelihood at the convergence of a given subgroup (i.e., three and four leg, three leg, and four leg) using the same variables included in the full model, and *Sep* is the total number of subgroups (−610.36). Using Eq. (8) results in a chi-square statistic of −511.26 (statistic (x^2 = −511.26). The critical chi-square (χ^2) value associated with one-tailed probability level and degrees of freedom which equal to the summation of the number of the random estimated parameters in all separate models minus the number of the random estimated parameters in the full model provide a value much greater than 99.99% of confidence limit which the null hypothesis can be rejected. The null hypothesis states that there is no difference between the model parameters in the full model (all roundabout configuration) and the separate models (i.e., the parameters are the same).

For further validation, a more extensive transferability test was conducted to test if modeling crash severity at the roundabouts need to be modeled separately. This log-likelihood ratio test for transferability is as follows (Washington et al., 2011):

$$x^2 = -2LL(\beta_{M1_{M2}}) - \sum LL(\beta_{M1})] \tag{9}$$

where $LL(\beta_{M1_{M2}})$ is the log-likelihood at convergence for model M_1 using the data from model M_2 and is the log-likelihood at convergence for modelM_1. As an illustration, in this equation M_1 refers to the model that utilizes the three and four legs data combination and M_2 refers to the model that can predict this data as shown in Table 4. Then, the variables and parameter estimates from the three leg best model were fixed and run with the three and four legs data combination. The corresponding log likelihood minus the log likelihood at convergence for three and four legs combination model, will show how well the three legs model (both variables and parameter estimates) can describe the three and four legs data combination.

The results of the transferability test indicate with well over 99% confidence that injury severity analyses should be modeled according to the type of roundabout. The only exception being the four leg roundabout data, the chi-square 8.17 with fifteen degrees of freedom is less that the critical chi-square 24.996. This indicate that the estimated parameters from the three and four leg combination model are adequately describing the effects for four-legged roundabouts.

5. Discussion

Fixed and random parameters binary probit models were estimated based on two severity outcomes (no injury and injury) with 20 variables found to be statistically significant, where various variables were found to have estimated random parameters. The following sections illustrate the final estimation results of modeling crash data at roundabouts in Oregon.

5.1. Full model

The estimation results for the original 1006 crashes for fixed and random parameters binary probit models are summarized in Table 5. The marginal effects, which are illustrated in Table 5, provide additional insights on injury severity outcomes, their corresponding probabilities, and the magnitude of change. With regard to the interpretation of the marginal effects for roundabout crashes for example, such as the indicator variable representing drivers who are more than 21 and less than 36 years old, the marginal effects indicate that this age group has a 0.01 higher probability of sustaining an injury compared to other age groups.

Turning to the model, if a crash occurred where the driver was stopped in traffic and not waiting to make a left turn, there is an increase in the outcome probability of sustaining an injury. In addition, the estimated parameter for stopping in traffic and not waiting to make a left turn was found to be random and normally distributed with a mean of 0.92 and standard deviation of 0.56. This suggests that for 5% of crashes where the driver was stopped in traffic and not waiting to make a left turn the estimated parameter mean is less than zero, while 95% of them have an estimated parameter greater than zero. In

Table 4
Chi-square statistics and degrees of freedom for crash severity related to the roundabout type transferability test.

M₁	*M₂*		
	Three and four legs (Model)	Three legs (Model)	Four legs (Model)
Three and Four legs (Data)	0	254.44 (13)	146.32 (18)
Three legs (Data)	26.56 (15)	0	144.48 (18)
Four legs (Data)	**8.17*** (15)	287.25 (13)	0

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Table 5
Fixed and random parameter binary probit models of injury severity for all roundabout type.

Variable	Fixed parameter		Random parameter		
	Coefficient	*t*-statistic	Coefficient	*t*-statistic	Marginal effects
Constant	−1.11	−1.87	−1.5	0.24	
Population (1 if the population is between 50 and 100, 0 otherwise)	−0.45	−3.77	-0.90	−4.67	−0.01
Crash Level Cause (1 if the driver did not yield right-of-way, 0 otherwise)	−0.55	−4.10	−1.25	−5.26	−0.02
Vehicle ownership (1 if private, 0 otherwise)	1.75	2.84	3.86	2.91	0.05
Vehicle Type (1 vehicle weight < 10,000 lb, 0 otherwise)	−1.64	−7.14	−3.51	−9.05	−0.05
Age of Driver (1 if $21 < \text{age} \leq 35$, 0 otherwise)	0.3	2.45	0.65	3.53	0.01
Participant Level Cause (1 if the driver followed too closely, 0 otherwise)	−0.72	−3.19	−1.56	−3.78	−0.02
Participant level cause (1 if failed to avoid vehicle ahead, 0 otherwise)	−1.05	−2.06	−2.19	−2.16	−0.03
Vehicle Level Action (1 if the driver stopped in traffic not waiting to make a left turn, 0 otherwise)	0.51	3.62	0.92	4.40	0.01
Standard Deviation of Parameter, Normally Distributed			0.56	3.54	
Safety Equipment Use (1 if seatbelt is used, 0 otherwise)	0.94	6.97	0.87	4.15	0.01
Standard Deviation of Parameter, Normally Distributed			2.25	11.25	
Gender (1 if male, 0 otherwise)	−0.052	−4.55	−1.32	−6.29	−0.02
Standard Deviation of Parameter, Normally Distributed			1.18	7.53	
Roadside (1 if the crash happened at the right roadside, 0 otherwise)	−0.49	−3.92	−1.32	−5.83	−0.02
Standard Deviation of Parameter, Normally Distributed			1.07	6.19	
Model Statistics					
Log-likelihood function	−361.08	−354.73			
McFadden Pseudo R-squared	0.21	0.22			
Number of Observation	1006	1006			
Log-likelihood function at Zero	−457.001				

other words, 5% of crashes involving drivers who stopped in traffic and not waiting to make a left turn are less likely to result in an injury, yet 95% are more likely to sustain an injury. This could possibly be attributed to unfamiliarity.

Seatbelt use by the driver was found to be significant and the estimated parameter was found to be random and normally distributed with a mean of 0.87 and standard deviation of 2.25. This implies that for roughly 35% (less than zero) of drivers, seatbelt decreased the likelihood of an injury while for 65.1 % of them it increased the likelihood of sustaining an injury. In spite of the benefits of the seatbelt in saving lives, there is a probability of getting injured due to unobserved factors. For example, body physiology differences and proper use of in-vehicle restraints as mentioned in Islam and Hernandez (2013). Anderson and Hernandez (2017) found a similar result on the use of seatbelts and the effects on injury severity. Comparably, other studies have suggested that seatbelt use is over-reported because of the legal implications of not wearing seatbelts (Amoros et al., 2006; Li et al., 1999; Malliaris et al., 1996; Stewart, 1993; Streff and Wangenaar, 1989). Li et al. (1999) showed that Australian police-reported seatbelt use overestimated actual use by 9% in crashes resulting in injuries (Li et al., 1999). Chen et al. illustrated that using seatbelts will significantly reduce the likelihood of drivers being fatally injured in rear-end collisions (Chen et al., 2015). However, Xie et al. concluded that wearing seatbelts could result in possible injuries to the participants, but was still critical for mitigating driver injury severity (Xie et al., 2012).

The indicator for males was also found to be statistically significant and negative. This may indicate that males are less likely to be involved in injury crashes, and this might be due to the physical differences between males and females as previously mentioned with seatbelt use (driver physiology). This indicator was also found to have a random and normally distributed estimated parameter with a mean of −1.32 and standard deviation of 1.18. This suggests that approximately 13.2% of observations have a mean of more than zero. That is to say, 13.2% of males are more likely to get injured in crashes, which follows findings of previous work (Al-Thaifani et al., 2016; Leidman et al., 2016; Ulfarsson and Mannering, 2004). On the other hand, 86.8% of male drivers are less likely to sustain an injury.

Finally, for the roadside variable, results show that crashes which happened on the right roadside of the road have an estimated random parameter that is normally distributed with a mean of −1.32 and a standard deviation of 1.07. This implies that for roughly 11% of crashes that happened on the right side of the road increase the likelihood of sustaining an injury, while 89.1% of such crashes decrease the likelihood of sustaining an injury. This is most likely capturing driver inattentiveness.

5.2. Three and four leg combination model

Table 6 illustrates the results of the three & four leg fixed and random parameter models.

As seen from Table 6, three indicators were found to have random and normally distributed estimated parameters. As with the previous model (Table 5), males, seatbelt use, and being stopped in traffic were all found to have estimated random parameters. No seatbelt use was found to be random and normally distributed with a mean of 0.80 and a standard deviation of 2.02. This implies that for 34.6% of drivers who did not wear their seatbelt were less likely to be involved in an injury crashes and 65.4% were more likely. One possible explanation for this result may stem from the influence of speed at the

Table 6
Fixed and random parameter binary probit models results for three and four leg roundabout combination.

Variable	Fixed parameter		Random parameter		
	Coefficient	*t*-statistic	Coefficient	*t*-statistic	Marginal effects
Constant	−2.13	−2.93	−3.98	−2.61	
Population (1 if the population is between 10 and 25, 0 otherwise)	0.59	2.67	1.10	3.22	0.01
Crash Level Cause (1 if the driver did not yield right-of-way, 0 otherwise)	−0.43	−3.05	−1.001	−4.12	−0.01
Vehicle Movement (1 if turning right, 0 Otherwise)	−0.63	−2.66	−0.9	−2.87	−0.005
Vehicle Ownership (1 if private, 0 otherwise)	1.60	2.26	4.17	2.85	0.02
Vehicle Type (1 vehicle weight < 10,000 lb, 0 otherwise)	−1.67	−6.84	−4.06	−8.55	−0.02
Age of driver (1 if 15 < age ≤ 21, 0 otherwise)	0.52	2.72	2.21	3.24	0.01
Age of driver (1 if 21 < age ≤ 35, 0 otherwise)	0.70	3.47	2.60	3.98	0.01
Age of driver (1 if 35 < age ≤ 50, 0 otherwise)	0.55	3.21	2.56	3.90	0.01
Age of driver (1 if 50 < age ≤ 65, 0 otherwise)	1.06	2.39	1.84	2.82	0.01
Age of driver (1 if 65 < age, 0 otherwise)	1.27	2.02	1.34	1.99	0.01
Participant Level Cause (1 if the driver followed too closely, 0 otherwise)	1.18	0.05	−1.59	−3.63	−0.01
Safety Equipment Use (1 if seatbelt is not used, 0 otherwise)	0.9	4.93	0.8	3.44	0.004
Standard Deviation of Parameter, Normally Distributed			2.02	10.44	
Vehicle Movement (1 if the vehicle stopped in traffic, 0 otherwise)	0.78	3.38	0.8	3.16	0.004
Standard Deviation of Parameter, Normally Distributed			1.8	6.79	
Gender (1 if male, 0 otherwise)	−0.76	−4.55	−1.99	−7.07	−0.01
Standard Deviation of Parameter, Normally Distributed			1.87	8.48	
Model Statistics					
Log-likelihood function	−318.76		−314.30		
McFadden Pseudo R-squared	0.22		0.24		
Number of Observation	913		913		
Log-likelihood function at Zero	−411.09				

time of the crash. Again, roundabouts are a known traffic calming countermeasure where lower speeds are generally observed.

Next, the parameter for vehicles being stopped in traffic was found to be random and normally distributed with a mean of 0.80 and a standard deviation of 1.80. This indicates that for 32.8% of crashes in which the vehicle was stopped in traffic the driver is less likely to sustain an injury and 67.2% of drivers are more likely. This might be due to the operational characteristics of roundabouts; specifically, as traffic approaches an entry point, drivers may have to stop to yield to traffic in the roundabout.

5.3. Four leg model

Table 7 show the results of the four leg fixed and random parameter models.

For the four leg model, seventeen variables were found to be significant of which three of them were found to have estimated random parameters. Turning to the random parameters, the parameter for seatbelt use by the driver was found to be random and normally distributed with a mean of 1.58 and a standard deviation of 2.24. This suggests that for roughly 24.1% of drivers who wore a seatbelt were less likely to sustain an injury and 75.9% of drivers were more likely.

The indicator for drivers aged 35 years to 51 years was found to have a random and normally distributed estimated parameter with a mean of 0.69 and standard deviation of 2.37. This suggests that for 38.6% of drivers in this age group the likelihood of sustaining an injury decreases, while for 61.5% the opposite is true. In general, other studies have found similar results (Al-Thaifani et al., 2016; Amoros et al., 2006; Bédard et al., 2002; Daniels et al., 2011; Ulfarsson and Mannering, 2004). Mannering and Bhat, (2014) found that for drivers in this age group the likelihood of getting injured decreases.

Vehicle type with weight less than 10,000 lb. was found also to be random and normally distribute with a mean of −3.96 and standard deviation of 0.53. This suggests that for roughly a small percent of the drivers who drive these types of vehicle have an increased probability of injury, whereas a larger proportion of them have the opposite effect. A possible explanation for this specific observation could be due to the increased aggressive driving behavior (e.g., entering the roundabout) a finding consistent with research that explored smaller to medium sized vehicle speeds to larger ones (Al-Thaifani et al., 2016).

The indicator variable for male is statistically significant. The associated parameter was also found to be random and normally distributed with a mean of −1.60 and a standard deviation of 1.62. This suggests that for approximately 16.2% of male drivers there is an increase in the likelihood of sustaining an injury, while for 83.8% the opposite is true. Similar results are also found in Ulfarsson and Mannering, (2004), Al-Thaifani et al. (2016), Leidman et al., (2016), and Grivna, Eid and Abuzidan, (2017).

5.4. Three leg model

Finally, for the three leg model, twelve variables were found to be significant and four of them were found to have random and normally distributed estimated parameters as shown in Table 8.

Table 7
Random parameter binary probit model results for four leg roundabout.

Variable	Fixed parameter		Random parameter		
	Coefficient	*t*-statistic	Coefficient	*t*-statistic	Marginal effects
Constant	−0.58	−1.73	−0.70	−1.36	
Posted Speed Limit (1 if the speed limit more than 35, 0 otherwise)	0.30	2.09	0.85	3.34	0.001
Population (1 if the population is between 10 and 25, 0 otherwise)	0.62	2.34	1.32	2.82	0.002
Weekdays (1 if the crash happened during the weekdays, 0 otherwise)	0.34	1.94	0.99	3.18	0.002
Crash Level Cause (1 if the driver did not yield right-of-way, 0 otherwise)	−0.50	−2.90	−1.30	−4.01	−0.002
Participant level cause (1 if failed to avoid vehicle ahead, 0 otherwise)	−0.63	−2.07	−1.39	−2.72	−0.002
Crash Level Cause (1 if the crash happened because careless driving, 0 otherwise)	−0.92	−2.33	−2.46	−3.52	−0.004
Movement of the Vehicle at the Time of the Crash (1 if turning right, 0 otherwise)	−0.81	−2.52	−2.06	−3.43	−0.003
Movement of the Vehicle at the Time of the Crash (1 if stopped in traffic, 0 otherwise)	0.55	3.01	1.54	4.81	0.002
Age of driver (1 if 15 < age ≤ 21, 0 otherwise)	0.67	2.87	1.74	4.03	0.003
Age of driver (1 if 21 < age ≤ 35, 0 otherwise)	0.92	5.23	2.29	6.52	0.003
Participant Level Cause (1 if the driver followed too closely, 0 otherwise)	−1.05	−3.50	−2.68	−4.36	−0.004
Roadside (1 if the crash happened at the right roadside, 0 otherwise)	−0.4	−2.30	−0.95	−3.35	−0.001
Condition of the Barrier (1 if fair condition, 0 otherwise)	2.62	2.27	6.88	3.13	0.01
Safety Equipment Use (1 if seatbelt is used, 0 otherwise)	0.99	5.89	1.58	5.12	0.002
Standard Deviation of Parameter, Normally Distributed			2.24	8.61	
Age of driver (1 if 35 < age < 51, 0 otherwise)	0.57	3.23	0.69	2.07	0.001
Standard Deviation of Parameter, Normally Distributed			2.37	6.57	
Vehicle Type (vehicle weight < 10,000 lb, 0 otherwise)	−1.59	−5.49	−3.96	−6.82	−0.01
Standard Deviation of Parameter, Normally Distributed			0.53	4.28	
Gender (1 if male, 0 otherwise)	−0.49	−3.41	−1.6	−5.20	−0.002
Standard Deviation of Parameter, Normally Distributed			1.62	6.87	
Model Statistics					
Log-likelihood function	−228.66		−224.34		
McFadden Pseudo R-squared	0.27		0.28		
Number of Observation	704		704		
Log-likelihood function at Zero	−311.77				

Table 8
Random parameter binary probit model results for roundabout with three leg.

Variable	Fixed parameter		Random parameter		
	Coefficient	*t*-statistic	Coefficient	*t*-statistic	Marginal effects
Constant	−0.82	−1.14	0.32	0.27	
Weather Condition (1 if cloudy, 0 otherwise)	0.65	1.67	1.16	1.93	−0.01
Weather Condition (1 if rainy, 0 otherwise)	−1.17	−2.32	−3.44	−3.47	−0.007
Weekdays (1 if the crash happened during the weekdays, 0 otherwise)	−0.77	−2.44	−1.88	−3.57	0.007
Crash Level Cause (1 if the driver disregarded other traffic control device, 0 otherwise)	0.95	1.73	1.93	2.05	−0.01
Crash Level Cause (1 if the driver failed to avoid vehicle ahead, 0 otherwise)	−1.22	−1.77	−3.08	−2.16	−0.01
Vehicle ownership (1 if private, 0 otherwise)	1.96	2.34	2.92	1.99	0.01
Gender (1 if male, 0 otherwise)	−0.97	−3.38	−2.51	−4.04	−0.01
Barrier Type (1 if concrete type, 0 otherwise)	0.67	1.73	1.62	2.42	0.01
Vehicle Type (1 vehicle weight < 10,000 lb, 0 otherwise)	−1.50	−3.49	−3.88	−4.50	−0.01
Standard Deviation of Parameter, Normally Distributed			2.01	5.06	
Crash Level Cause (1 if the crash happened because careless driving, 0 otherwise)	1.23	2.38	2.89	3.02	0.01
Standard Deviation of Parameter, Normally Distributed			1.86	1.83	
Alcohol Use (1 if that participant had been drinking, 0 otherwise)	1.06	2.16	1.12	1.03	0.004
Standard Deviation of Parameter, Normally Distributed			4.32	2.80	
Movement of the Vehicle at the Time of the Crash (1 if stopped in traffic, 0 otherwise)	1.15	3.55	2.66	4.03	0.01
Standard Deviation of Parameter, Normally Distributed			1.07	2.30	
Model Statistics					
Log-likelihood function	−72.64		−71.72		
McFadden Pseudo R-squared	0.27		0.28		
Number of observations	209		209		
Log-likelihood function at Zero	−99.1				

With respect to the random parameters, the estimated parameters for vehicle type, careless driving crash-level cause, driver alcohol use, and vehicles stopped in traffic were all found to be random and significant. In regard to vehicle type, the indicator for passenger car, pickup, van, light delivery, and custom van was found to have a random and normally distributed parameter with a mean of −3.88 and a standard deviation of 2.01. This suggests that roughly 3% of the drivers who drive these types of vehicle have an increased probability of sustaining an injury, whereas 97% of them are less likely. Again, as previously stated, a possible explanation for this specific observation could be due to the increased aggressive driving behavior (Al-Thaifani et al., 2016).

The estimated parameter for careless driving was also found to random and normally distributed, with a mean of 2.89 and a standard deviation of 1.83. This suggests that for 6% of crashes where the crash-level cause was reported to be careless driving are less likely to result in an injury, while 94% of such crashes are more likely to result in an injury.

The next random parameter is associated with driver alcohol use. Specifically, the parameter for driver alcohol use was found to random and normally distributed with a mean of 1.12 and a standard deviation of 4.32. This suggests that for 39.8% of drivers who had been drinking alcohol, the probability of an injury decreased. On the other hand, 60.2% of drivers who had been drinking were more likely to sustain an injury. This random parameter may be capturing the varying degree of inebriation on driver performance and safety attitude around three legged roundabouts (Zhao et al., 2014).

The estimated parameter for vehicles that were stopped in traffic at the time of the crash was found to be random and normally distributed. A mean of 2.66 and a standard deviation of 1.07 suggest that for 0.06% crashes that occurred with a vehicle stopped in traffic were less likely to result in an injury, but 99.4% of them were more likely to result in an injury. Although stopping inside the roundabout is prohibited and dangerous, there is the possibility that in situations with dense traffic inside the roundabout or potential hazards, stopping may prevent a more serious crash from occurring.

6. Summary and conclusions

This study involved the estimation of a random parameters binary probit model to capture the significant factors that contribute to specific levels of injury severity sustained by drivers involved in crashes at roundabouts in different locations in Oregon. Four models were estimated using five years (2011–2015) of Oregon crash data. For the current study, two injury severity outcomes were considered: no injury and injury. The four estimated models were based on the geometric design of the roundabout: full model (unknown, three leg, four leg, and five leg), three and four-leg combination model, three leg model, and four leg model.

A number of important factors were found to influence the level of injury severity at roundabouts. In each individual model, a number of variables are homogenous across crash observations (i.e., their estimated parameters are fixed across observations) and various variables are heterogeneous across crash observations (i.e., they have estimated random parameters). For example, vehicles stopped in traffic and not waiting to make a left turn, seatbelt usage, gender, type of vehicle, roadside crash characteristics, vehicle movement, age of the driver, careless driving, and alcohol use were found to have estimated random parameters.

This study provides useful insights and an increased understanding of the factors that contribute to either sustaining injury or not in crashes at roundabouts through a random parameters approach. Although the results of this study are exploratory, they provide evidence that crashes are occurring at roundabouts and several factors lead to crashes that result in an injury. In addition, the modeling approach offers a methodology that can account for unobservable in the crash data.

This study aimed to analyze current and available databases to determine the most significant factors that contribute to injuries in crashes at roundabouts in Oregon. In future work, additional crash-specific variables are recommended to investigate roundabout injury severity, such as the specific location of the crash or additional geometric design details. In doing so, an injury severity picture with a higher resolution can be obtained, which in turn can offer more understanding of the design related factors that lead to severe crashes at roundabouts.

The analysis of injury severity models can help improve safety at roundabouts by considering conditions unique to roundabouts in Oregon. The estimated model within the paper will be used as a basis for future work aimed at expanding the analysis after further collection efforts are completed and building upon more advance models. According to the significant factors it can be noticed that most of them are related to the driver's behavior and the characteristics. For example, there are many injury crashes because of the driver's response at the time of the crash, age of the driver that play main role in the driving experience. As a result, the findings encourage developing education materials for the drivers to improve their understanding on how to navigate the roundabouts and to educate the public on the appropriate use of roundabouts.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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