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Event-Based Modeling of Driver Yielding Behavior to Pedestrians at Two-Lane Roundabout Approaches

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Abstract

Unlike other types of controlled intersections, drivers do not always comply with the “yield to pedestrian” sign at the roundabouts. This paper aims to identify the contributing factors affecting the likelihood of driver yielding to pedestrians at two-lane roundabouts. It further models the likelihood of driver yielding based on these factors using logistic regression. The models have been applied to 1150 controlled pedestrian crossings at entry and exit legs of two-lane approaches of six roundabouts across the country.

The logistic regression models developed support prior research that the likelihood of driver yielding at the entry leg of roundabouts is higher than at the exit. Drivers tend to yield to pedestrians carrying a white cane more often than to sighted pedestrians. Drivers traveling in the far lane, relative to pedestrian location, have a lower probability of yielding to a pedestrian. As the speed increases the probability of driver yielding decreases. At the exit leg of the roundabout, drivers turning right from the adjacent lane have a lower propensity of yielding than drivers coming from other directions. The findings of this paper further suggest that although there has been much debate on pedestrian right-of-way laws and distinction between pedestrian waiting positions (in the street versus at the curb), this factor does not have a significant impact on driver yielding rate.

The logistic regression models also quantify the effect of each of these factors on propensity of driver yielding. The models include variables which are specific to each study location and explain the impact size of each study location on probability of yielding. The models generated in this research will be useful to transportation professionals and researchers interested in understanding the factors that impact driver yielding at modern roundabouts. The results of the research can be used to isolate factors that may increase yielding (such as lower roundabout approach speeds), and can feasibly be incorporated into microsimulation algorithms to model driver yielding at roundabouts.

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Introduction

Safety and operational benefits of roundabouts have increased their use among engineers and planners. Roundabouts are one of the proven safety countermeasures suggested by FHWA (1). In order to take advantage of their operational benefits, two-lane roundabouts are being built across the United States and other countries. However the issue of pedestrian safety and accessibility remains unanswered, especially at multi-lane roundabouts. Several recent studies have shown that roundabouts are not easily accessible by pedestrians, especially those pedestrians with vision impairments, for three reasons: motorists fail to yield to pedestrians where the crossing is not signal controlled, noise from circulating traffic can make auditory detection of gaps difficult (especially at the exit), and gaps large enough to be aurally detected may be infrequent. (2,3)

The rate of driver yielding to pedestrians at (multi-lane) roundabouts varies across locations (4), but in nearly all cases is less than 100%. A range of treatments exist that are intended to increase the rate of driver yielding (4), and yielding behavior has been linked in research to operational characteristics such as vehicle speeds (5), as well as geometric characteristics including the entry versus exit leg at a roundabout (4,6). But to date, these isolated studies of driver yielding behavior at roundabouts have largely been descriptive, with little insight gained towards predicting driver yielding at modern roundabouts.

This research studies the factors that may influence the propensity of driver yielding to pedestrians at two-lane roundabout approaches. The research is based on controlled observations of driver yielding behavior at entry and exit legs of six multi-lane roundabouts across the United States (Maryland, North Carolina, Indiana and Tennessee) and seeks to develop predictive models for yielding. The research rests on the premise that yielding is a critical component of pedestrian accessibility and pedestrian safety, and that an improved understanding of yielding behavior may be of great value to researchers and agencies.

Background and Literature

Several studies explored the concerns over the accessibility of modern roundabouts for pedestrians with vision impairments (2,6,7,8). Due to multiple-threat situations and being exposed to two conflicting lanes of traffic, pedestrian crossings at two-lane approaches are generally more challenging and risky than single-lanes (7,9). The results of NCHRP Report 674 (7) suggest that pedestrians who are visually impaired experience more delay crossing the two-lane approaches of the roundabout since they take longer to utilize crossing opportunities in the form of yields or gaps. Participants also made more risky crossing decisions at two-lane roundabout approaches compared to single-lane roundabouts (7). Research has found that the likelihood of blind pedestrians making a risky crossing decision is 2.5 times higher than sighted pedestrians (6,10). Blind pedestrians required more time (on average 3 to 5 seconds longer) to detect a crossing opportunity (2). The studies also show that drivers tend to yield to blind pedestrians more often than sighted pedestrians (5,6,7)

Findings of pedestrian operations at roundabouts by NCHRP report 572 (4) show that 43% of the drivers at two-lane approaches of the roundabout do not yield to pedestrians. The lack of yielding is only 17% for single-lane roundabouts. Lack of yielding is also higher at exit (54%) compared to 33% not yielding at the entry. Based on these findings, the number of lanes and crosswalk location (entry or exit) are two important design elements that affect pedestrian accessibility at roundabouts.

Schroeder and Roupail (11) formulated a pedestrian delay model at single lane roundabouts as a function of “probability of crossing” and “probability of encountering a yield.” Alternatively, the 2010 Highway Capacity Manual (12) suggests the use of a methodology

for calculating pedestrian delay at the major street of two-way stop-controlled intersections for calculating pedestrian delay at roundabouts. Such crossings do not have control for pedestrians and therefore pedestrian crossing delay is based on availability of gaps or driver yields. The methodology in chapter 19 of HCM2010 (12) defines delay as a function of probability that the i^{th} crossing event is either a driver yield or produces a crossable gap. It further describes the probability of driver yielding as a function of motorist yield rate. The model in (12) is not calibrated from field data and does not take into account behavioral factors. This research explores $P(Y_i)$, the probability that a motorist yields to a pedestrian on a crossing event and attempts to calibrate the model taking into account microscopic traffic parameters related to pedestrian crossing. The methodology in this paper is adopted and modified from similar research approach by Schroeder and Rouphail (13) for midblock crosswalks. The methodology uses an “event-based predictive model” to predict driver yielding behavior from observations of pedestrian and vehicle interactions at crosswalks.

A study at two two-lane roundabouts in Maryland by Geruschat and Hassan (5) shows that the speed of the vehicle at the entry and exit of roundabouts significantly influences the driver yielding rate. The authors found that 65% of the variability of driver yielding rate can be explained by speed. Based on their study, they estimated that the driver yielding rate with speeds lower than 15 miles per hour is about 75% as opposed to 50% with speeds higher than 20 miles per hour. In addition to the speed of the vehicle, they found that drivers yield to pedestrians at the entry 79% of the time as opposed to only 37% of the time at the exit. The authors observed that pedestrian behavior influences the driver yielding rate. Based on their study, the pedestrian behavior affects the driver yielding behavior. For example, if a pedestrian is standing one foot from the curb, at the curb or in the crosswalk, the driver yielding rates are different. The further the pedestrian is standing into the crosswalk the higher the likelihood of driver yielding. Drivers are almost twice as likely to yield to a pedestrian standing one foot in the crosswalk as one foot from the curb. Their study also shows that drivers have significantly higher yielding rates to pedestrians carrying a white cane (2.1 times higher at entry and 4.4 times higher at exit). Although the study has valuable findings, it only observes the interaction of one pedestrian with one vehicle at a certain distance from the crosswalk under the condition of no vehicle platooning or following. This study is *descriptive* of driver yielding behavior but not *predictive*, and does not take into account other traffic factors such as heavy vehicles, multiple pedestrians, platooning, or the lane location of the vehicle with respect to pedestrian. Another study by Schroeder and Rouphail (13) takes a more predictive approach to understanding driver yielding behavior to pedestrians. The authors observed pedestrian-driver interaction at two unsignalized midblock crosswalks, and developed logistic regression models to predict driver yielding (13), as well as pedestrian gap acceptance (21). The data collection methodology involved observing and recording traffic characteristics during the interaction between vehicles and naturally occurring pedestrians crossing the street. Although the research approach takes into account all the factors involved, results are confounded by much variability in (naturally occurring) pedestrian behavior, and is further limited to two midblock crossing sites.

Inspired by the research methodology presented by Schroeder and Rouphail (13) and the roundabout-related findings by Geruschat and Hassan (5) this paper develops logistic regression models to predict the likelihood of driver yielding to pedestrians at the entry and exit legs of six two-lane roundabouts in different states across the United States.

METHODOLOGY

The objective of this research is to develop statistical regression models for predicting driver yielding to pedestrians at two-lane roundabouts and to identify the contributing factors. The methodology is built upon earlier findings of parameters that affect driver yielding behavior,

such as vehicle dynamics, pedestrian behavior and other traffic related factors. Accordingly, a data collection methodology was developed to capture a range of observations in these variables, while controlling for some pedestrian behavioral attributes: 1) Use of a white cane, and 2) waiting position relative to the crosswalk curb.

Various research projects have shown that drivers are more likely to yield to pedestrians with disabilities (1, 5, and 7). Most states further have “White Cane Laws” that emphasize the need to pay attention to pedestrians traveling with a long white cane, and in some cases mandate yielding. This research therefore also seeks to explore the effect of white cane use on driver yielding.

Many state laws are written such that vehicles must yield the right of way to pedestrians within the crosswalk, while many pedestrians choose to wait at the crosswalk. The distinction of whether or not a pedestrian physically has a foot in the roadway therefore has certain legal implications, and furthermore may convey different levels of pedestrian assertiveness. Therefore the authors designed the data collection methodology to include different waiting positions for the pedestrian.

For data collection, special attention is given to the *first vehicle*. The *first vehicle* is the closest vehicle to a pedestrian at the crosswalk (in terms of time and distance), but in a key difference to earlier research (12), that first vehicle may be the lead vehicle of a platoon, and the research accounts for the interaction effects between vehicles on the yield response. An experiment is defined as one of the research team members approaching the crosswalk as a (seeded) pedestrian at random intervals. Pedestrian behavior is controlled as either “blind” or “sighted” (either with or without the white cane) and for waiting position (either standing at the curb or one foot in the crosswalk). Therefore we have a total of four conditions in the study: blind pedestrian standing at the crosswalk, blind pedestrian standing one foot in the crosswalk, sighted pedestrian standing at the crosswalk, and sighted pedestrian standing one foot in the crosswalk. An observer records the events related to the experiment. After the pedestrian arrives at the crossing location, the experiment can have three possible outcomes:

1. The subject detects and identifies a crossable gap, he/she then steps back and the experiment is completed. The observer records the crossing attempt as a crossable gap. A crossable gap is defined as enough time for the pedestrian to finish crossing both lanes of the leg completely before the vehicle arrives at the crosswalk, which was about 8 to 10 seconds for our studied locations.
2. A vehicle or a platoon of vehicles is approaching the crosswalk. The *first vehicle* closest to the pedestrian yields which causes a crossing opportunity (yield event). The pedestrian accepts the yield and crosses (assuming the other lane also has a yield or is free). The observer records all the traffic attributes related to the *first vehicle* and the first vehicle-pedestrian interaction.
3. A vehicle or platoon of vehicles is approaching the crosswalk. The *first vehicle* does not yield to the pedestrian (non-yield event). The pedestrian waits at the crosswalk until a crossing opportunity in a form of a yield or crossable gap is presented. The observer records all the traffic attributes related to the *first vehicle* and the first vehicle-pedestrian interaction. The observer further records the attributes related to the utilized crossing opportunity by pedestrian.

The experiment is repeated 25 times for each of the four pedestrian conditions. This results in 100 controlled pedestrian crossings for each approach, entry and exit, for a total of 200 crossings for each roundabout leg. For the purpose of developing models estimating the likelihood of driver yielding, all the yield and non-yield events related to the first vehicle–pedestrian interaction are taken into account, while gap crossing events are ignored.

Field Data Collection and Parameters

For each experiment a set of variables is collected as shown in Table 1. These variables describe the interaction between the *first vehicle* and the pedestrian. A Bushnell Speedster speed gun was used to measure the speed of the vehicles. The speed gun was wirelessly connected to an LCD Screen that shows the speed of the vehicles (1.5% error in measurement at an angle of 10 degrees off center) (18) and is visible to a video camera (but not to approaching drivers).

A ground level video camera was pointed at the crosswalk and approach to capture the pedestrian, oncoming vehicles and speed screen. The video camera is used as a backup for data collection. The observer (research team member) used a data sheet to record the variables exhibited in Table 1. All the variables, except for speed, are binary variables. Speed is a continuous variable recorded from the speed gun screen. The response variable is yield and is a binary variable (first vehicle yielded=1, first vehicle did not yield=0).

Site Description

The data collection methodology was applied to six multilane roundabouts in four different states; Maryland, North Carolina, Indiana and Tennessee. One two-lane entry and one two-lane exit approach of each of these six roundabouts were studied. All these roundabouts are located in relatively urban areas, and drivers have a general expectation of (some) pedestrian activity. All sites are equipped with pedestrian sidewalks, crosswalks, and have some naturally occurring pedestrian traffic. The list of roundabouts studied is displayed in Table 2.

A review of the state right-of-way laws in the four states (North Carolina, Maryland, Tennessee and Indiana) suggests that traffic laws in these states give the right-of-way to pedestrians crossing within the crosswalk. They also state that drivers should *yield* the right of way to pedestrians carrying a white cane or guide dog (14, 15, 16, 17).

DATA ANALYSIS

Data on 200 simulated crossing attempts were collected from five of the roundabout approaches (Nashville TN, Annapolis MD, Carmel IN, Raleigh NC and Winston-Salem NC). For Towson, MD 150 crossings were recorded, which resulted in a total of 1150 data points for all six roundabouts. For the purpose of developing yielding models, only the data points that described an interaction between the pedestrian and *first vehicle* were considered. The YIELD event is a binary indicator explaining whether the *first vehicle* yielded or not, and serves as the dependent variable. Other factors defined in Table 1 are explanatory variables and are used to develop a model to describe the YIELD response variable.

Descriptive Statistics

Based on previous research (5), three factors were shown to have an effect on driver yielding behavior, speed of the vehicle (SPD), whether the pedestrian is standing at the entry or exit leg of the roundabout (EXT) and whether the pedestrian is carrying a white cane or not (CN). Table 3 shows the yielding rate for each of the study locations based on these three factors (SPD, EXT and CN).

The results of Table 3 show significant variability in driver yielding behavior among the different sites and entry and exit approaches of the roundabout for different pedestrian behavior. Overall, the yielding rates are higher at the entry than exit leg of the roundabouts with a maximum yielding rate of 85% in Annapolis, MD to a pedestrian carrying a white cane while they are waiting “at curb.” On the other extreme, Winston-Salem has 0% yielding rate at the entry (to sighted pedestrian waiting “in road”). At the exit approaches of

roundabouts in Carmel IN, Nashville, TN and Winston-Salem, NC the yielding rate to sighted pedestrians (crossing behavior) similarly was 0%. The study of the exit legs at the six roundabouts shows that drivers overall yield more often to a blind pedestrian than sighted pedestrian. However the effect of pedestrian waiting position on driver yielding behavior changes among sites.

The speed results show generally higher speeds at entry, which is intuitive. Average and maximum speeds are largely consistent in Nashville, TN, Towson, MD, Annapolis, MD and Raleigh, NC. Two locations, Winston-Salem, NC, and Carmel, IN have higher entering speeds. The average exit speeds are consistent across study locations.

The model development section of this paper applies logistic regression models to these factors and other factors explained in Table 1 to determine which factors significantly contribute to driver yielding behavior. Table 4 shows the average and standard deviation for the traffic attribute variables collected at the study locations for entry and exit.

These tables assist in characterizing the sites based on the data collected. For example for Raleigh, NC, on average 75% and 73% of the *first vehicle* events occurred on the far lane at the entry and exit respectively, which are the highest numbers among all sites. Nashville, TN has the highest rate of vehicle platooning both at entry and exit (63% and 43%, respectively). Downstream conflict (DSC), which only applies to the entry leg, was observed for all study locations; however, Nashville, TN has the highest (28%) and Winston-Salem NC (4%) has the lowest rate of DSC among all sites. Right turning vehicle (RT) only applies to the exit leg. Table 4 shows that Towson, MD has the highest (41%) and Winston-Salem, NC has the lowest (0%) rate of right turning vehicles from the upstream adjacent leg. No heavy vehicles (HGV) or multiple pedestrian (MUP) events were observed in Carmel, IN, on either entry or exit legs. There were no multiple pedestrian events (MUP) while studying the entry leg of the roundabout in Annapolis, MD. However, on average, 3% of the data collected at exit had multiple pedestrians involved.

MODEL DEVELOPMENT

Modeling Approach

The driver yielding response is a *nominal* parameter with a binary outcome (1=yield, 0=non-yield) (13,19) Therefore a binary logistic regression model is used to predict the propensity of driver yielding behavior (11). The form of the logistic regression model for yield behavior is (equation 1):

$$\text{Logit} [P = (Y=1)] = \log \left(\frac{P(Y=1)}{1 - P(Y=1)} \right) = \beta_0 + \sum_{i=1}^m \beta_i x_i \quad (\text{Equation 1})$$

Where: β_0 : Intercept β_i : Parameter describing the effects of m explanatory variables x_i on the yield response Therefore the probability estimate of yield response can be calculated using the equation 2.

$$P(Y=1) = \frac{e^{\beta_0 + \sum_{i=1}^m \beta_i x_i}}{1 + e^{\beta_0 + \sum_{i=1}^m \beta_i x_i}} = \frac{1}{1 + e^{-\left(\beta_0 + \sum_{i=1}^m \beta_i x_i\right)}} \quad (\text{Equation 2})$$

Based on equation 2, if the values of all variables except one x_i are kept constant, one unit increase in the value of x_i will increase the odds of response variable Y with a multiplicative effect of e^{β_i} (called the *Odds Ratio*). The R^2 statistic is generally used in regression models

to describe how much variability of the data is explained by the model. For logistic regression models, the variability of the model can be evaluated by max-rescaled R^2 . Higher max-rescaled R^2 is an indication of a better fit of the model to the data and the proportion of the data that can be explained by the model. Further fit statistics, such as -2LogL and Akaike Information Criterion (AIC), are also used to explain the overall fit of the model.

The data from all sites are analyzed using the SAS Logistic regression model to develop the yielding probability models (20). From all the factors described in Table 1, the events where a vehicle was already stopped when the pedestrian approached the crosswalk ($\text{STP}=1$), and the events where the *first vehicle* was a heavy vehicle ($\text{HGV}=1$) were discarded. Stopped vehicles did not contribute to the yielding model since no other traffic characteristics such as speed or platoon, could be associated with them. During the experiments in Raleigh and Winston-Salem in NC, Towson and Annapolis in MD, a few heavy vehicles were observed, which varied from school buses, campus university buses, transit buses or heavy commercial trucks. There was a variability observed in driver yielding behavior of different types of heavy vehicles. School buses and campus university buses yielded to pedestrian all the times while the yielding rate was much lower with transit buses and trucks. Therefore, the authors decided to eliminate the crossing events that were associated with a heavy vehicle as the *first vehicle* event ($\text{HGV}=1$). The authors first used all the variables, DSC, SPD, FAR, RT, MUP, CN, FT and EXT in SAS logit regression model using the forward selection algorithm with a $p=0.05$ threshold. In order to capture the effect of different sites in each model the authors also used five dummy variables to include the six study locations. These dummy variables are shown in Table 2. The effect of the site in Carmel, IN (ST_IND) will be captured in the intercept of the model. The authors chose Carmel, IN to be presented in the base model after carefully investigating and testing other sites. Carmel, IN has moderate yielding rate among other sites.

It is further hypothesized that entry and exit have different effects on the yielding probability model, as will the speed of the approaching vehicle. DSC is a variable that is defined only for entry since it indicates whether queue of vehicles was already present at the entrance of the roundabout when the *first vehicle* approaches the crosswalk. RT is a variable that is defined only for the exit, indicating whether the exiting vehicle was a right-turning vehicle from the adjacent lane or was coming from a different direction. In order to capture the effect of these variables in the yield probability model, the authors separated the entry and exit events and developed separate models for them.

RESULTS

Table 5 demonstrates the results of the SAS logistic regression model development for all sites. Initially, entry and exit are modeled jointly, followed by separate entry and exit models. Table 5a shows the parameter estimate for each explanatory variable, as well as the odds ratio. The parameter significance level is indicated by superscripts. Table 5a does not take into account the effect of sites. This table shows that factors presence of white cane (CN), vehicle lane position (FAR), and vehicle speed (SPD) as well as entry and exit (EXT) are significant to the model with $p\text{-value}<0.001$. Presence of multiple pedestrians (MUP) is significant with $p\text{-value}<0.05$ in the “all” model (combined entry and exit) and entry model, but it is not significant in the exit. Pedestrian waiting position (FT) is only significant in the “all” model with $p\text{-value}<0.1$. The values for Max-rescaled R^2 are 0.35, 0.35 and 0.28 for all, entry and exit models respectively.

Table 5b shows the SAS logistic regression model for all variables in addition to the site variables. As noted before, after careful examination of the effect of each site on the regression model, Carmel, IN (ST_IND) was chosen to be described by the effect of the

intercept. The first observation in Table 5b is that the overall fit has been improved for the models relative to values in Table 5a (Max-rescaled R^2 ; all=0.44,entry=0.47 and exit=0.44). In addition to the significant factors identified in Table 5a, sites Raleigh (ST_RAL), Winston-Salem (ST_SLM), Annapolis (ST_ANN) and Towson (ST_TSN) showed significance in three models as well as right turning vehicle (RT) for exit model.

The final iteration of the analysis uses SAS forward selection (SAS proc logistic; selection=forward; slstay=0.05) with a $p=0.05$ threshold on all variables, including site dummy variables and is illustrated in Table 6. Similar to previous findings, CN, FAR, SPD, EXT (for only the combined “All” model) and RT (for only “Exit” model) have a significant effect on the likelihood of driver yielding to pedestrians ($p<0.001$). In addition to these factors, each studied site has a different effect on probability of yielding. As noted before, the authors tried different sets of dummy variables to ensure the same results about the site variables (dummies) that are significant. Therefore site-specific differences exist that impact yielding beyond the effects of traffic attributes (such as CN, SPD, FAR). Nashville, TN does not show up as significant in all three models which suggests that its yielding model is similar to Carmel, IN. In the “Entry” model Towson, MD and in the “Exit” model Winston-Salem, NC sites are not significant at 95% confidence level, which suggests similar yielding models as Nashville, TN and Carmel, IN.

Among all factors, entry and exit (EXT) has the largest impact on the models with estimate of -2.27 and odds ratio of 0.1 . The odds ratio suggests that for each study location, if all the other variables (CN, FAR, SPD) are kept at the same value, moving from entry to exit reduces the probability of yielding by a multiplication of 0.1 . Overall; the roundabout located in Annapolis MD had the highest yielding rate among all other studied locations. The model estimate for Annapolis is 1.22 and the odds ratio is 3.07 . The odds ratio indicates that with the same conditions of speed, pedestrian, lane location, and roundabout approach, the probability of a driver yielding in Annapolis, MD is 3 times higher than a driver in Carmel, IN.

DISCUSSION

The statistical tests for the three models (likelihood ratio, Wald and Score tests) are significant at $p=0.0001$ for all three models. The Max-rescaled R^2 varies from 0.43 to 0.46 which is fairly good for the fit of the models and better than yielding models for midblock crossings developed in prior research (13). The Akaike Information Criterion AIC for the “Entry” (AIC= 399.95) and for “Exit” (AIC = 289.64) both have lower values than the AIC for the “All” model (AIC= 734.10), which shows less information was lost during modeling entry and exit and these two models are better fits for the data than the “All” model.

The logistics regression modeling of driver yielding behavior to pedestrians at two-lane roundabouts shows there are few factors that have significant effect in the likelihood of yielding. Drivers that exit the roundabout have lower likelihood of yielding to a pedestrian than drivers entering the roundabout. At the exit leg of the roundabout, drivers who are turning right from the adjacent leg to the approach the pedestrian is standing, have lower propensity of yielding to pedestrians than drivers who are exiting from other directions. Drivers tend to yield more often to a pedestrian who is carrying a white cane compared to a sighted pedestrian. Drivers located in the far lane relative to the pedestrian location have lower likelihood of yielding to a pedestrian standing at the curb than driver located in near lane. As the speed of the vehicle entering or exiting the roundabout increases, the likelihood of driver yielding decreases.

Other factors such as vehicle platooning, multiple pedestrians and downstream conflict (for entry approaches) did not significantly influence yielding rate at 95% confidence level in the final model (Table 6). However, multiple pedestrian factors were significant at 90% confidence level (Table 5b).

Previous research on midblock crossings by Schroeder and Rouphail (13) found a significantly reduced probability of yielding for vehicles traveling in a platoon; this is seemingly related to the perceived risk of rear-end collisions. Presumably, there is a greater expectation of pedestrians and reductions in speeds at roundabouts, which may explain why drivers are possibly less sensitive to being part of a platoon in deciding whether or not to yield.

Pedestrian waiting position (FT: in crosswalk versus at curb) also did not have a significant impact on yielding at 95% confidence level. This is important to note, given the fact that there is a debate about pedestrian right-of-way laws and the distinction between “in” versus “at” the crosswalk. State laws imply that drivers yield the right of way to pedestrians “in” the crosswalk (14,15,16,17).

Figure 1 shows the effect of varying speed on probability of yielding with different conditions (CN=1, 0 and FAR=1,0). For the exit approach, it was assumed that the vehicle is not a right turning vehicle. The diagrams are plotted for the base model (Carmel, IN) with all the other site variables at zero level. Comparing the plots in Figure 1 shows that probability of yielding is more sensitive to variability in speed at entry than exit. At 25 mph speed at the exit the likelihood of driver yielding is near to zero (for Carmel, IN) for different conditions (CN and FAR). However, for speed of 25 mph at entry the likelihood of driver yielding is still greater than zero.

For both entry and exit, the probability graphs are highest for an encounter with a blind pedestrian with vehicle in near lane (CN=1, FAR=0). The probability graph for sighted pedestrians and vehicle in the near lane (CN=0, FAR=0) are very close to the probability graph for blind pedestrian and vehicle in far lane (CN=1, FAR=1) for both entry and exit. The effect of blind pedestrians and a vehicle in far lane (CN=1, FAR=1) generates a slightly higher likelihood of yielding at entry. However, the impacts of these two variables for exit are very similar such that both graphs overwrite each other. The encounter of a sighted pedestrian with a vehicle in the far lane (CN=0, FAR=1) is predicted to have the lowest yielding rates for both entry and exit. For a speed of 15 mph at the entry, the probability of yielding changes from 65% (CN=1, FAR=0) , 35% (CN=1, FAR=1) to 27% (CN=0, FAR=0) and to only 10% (CN=0, FAR=1)

Figure 2 plots the likelihood of predicted yielding rates by comparing all sites for a certain condition; no cane (CN=0) and vehicles located in near lane (FAR=0). The graphs in figure 2 illustrate how the yielding rate varies among sites. For the entry approach, Annapolis, MD has the highest and Winston-Salem, NC has the lowest yielding rate among all sites (Figure 2a). The curvature of the graphs in figure 2a suggests that the probability of yielding in sites with overall lower yielding (Raleigh and Winston-Salem, NC) drops less rapidly as the entry speed increases.

Figure 2b shows that Towson, MD has the highest yielding rate at exit among all sites. The base model for Carmel, IN, which is also the suggested model for Nashville, TN and Winston-Salem, NC, illustrates the lowest yielding rate among all sites. The graph in figure 2b emphasizes the effect of study locations. Further analysis is needed to understand what the site-specific variables are and how they can be incorporated into the model. Some factors such as cultural driver behavior, the severity of right-of-way enforcement by police officers in each area, driver courtesy or driver urgency may not be quantified into the regression

models as variables but can always be described as a general site variable. The modeling approach showed the importance of calibration for each study location and how driver behavior varies from one area to another.

The models can be implemented in stochastic micro-simulation systems. The models are microscopic in nature and therefore capable of incorporating a discrete decision outcome of yielding for drivers and crossing for pedestrians. These models are based on probability functions and therefore the outcome of the model would vary by randomizing the input variables to the model. The models contain speed which describes the vehicle dynamics in car following algorithms. It also includes vehicle lane position and movement (RT for exit model) which are related to vehicle attributes in simulation, modeling. It also includes variables related to pedestrian attributes (CN). In the simulation environment variables such as pedestrian attribute and site are global attributes that will have a certain value throughout the simulation. Variable speed (SPD) will vary by time in simulation since the nature of simulation software is such that variables are dynamically updated at every simulation time step (0.1 second for most software). Therefore the logistic yielding models can be incorporated as core algorithms in simulation software to predict driver decision of yielding at roundabouts. The site dummy variables in the model further help to calibrate the model for each region.

Conclusion and Future Work

This paper aimed to identify the contributing factors affecting the likelihood of driver yielding to pedestrians at two-lane roundabouts. It further tried to model the likelihood of driver yielding based on these factors by using logistic regression modeling. The results show that the likelihood of driver yielding at the entry leg of roundabouts is higher than exit. Drivers tend to yield to pedestrians with white canes more often than sighted pedestrians. Drivers traveling in the far lane, relative to pedestrian location, have lower probability of yielding to a pedestrian than drivers in the near lane. As the speed increases the probability of driver yielding decreases. At the exit leg of the roundabout, drivers turning right from the adjacent lane have lower propensity of yielding than drivers coming from other directions.

The results further show that factors such as vehicle platooning, downstream conflict (for only entry leg of the roundabout) and pedestrian waiting position, “at curb” versus “in crosswalk” do not have a significant impact (with 95% confidence level) on the probability of a driver yielding to a pedestrian. It is important to note that all the right-of-way laws to pedestrians have been reviewed for these six study locations. The laws imply that drivers yield the right of way to a pedestrian crossing “in” the crosswalk. However none of the models show the effect of pedestrian waiting position as significant.

The modeling approach also explored the effect of model calibration for different study locations. For the six studied roundabouts, three sites showed significant intercept terms (or dummy variables) that suggest a significantly different yielding performance. In other words, even when controlling for vehicular speed, pedestrian behavior, vehicle platooning, and other factors, this research showed that other site-specific variables and/or driver culture explain a significant portion of yield differences.

Future work includes expanding the data set to other two-lane roundabouts across the country and identifying the site-specific factors that contribute to different yielding rates in different regions (while keeping all the other variables with the same value). With further expansion of these models to other sites, the methodology and analysis approach presented here can provide valuable insights into geometric and cultural differences in driver yielding.

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Figure 1.
Model Probability Plots for Base Case with No Dummy Variable a) Entry and b) Exit

Figure 2.
Model Probability Plots for Across All Sites for a) Entry and b) Exit

Table 1

Traffic Characteristics Collected for Yielding Study

Factor		Description	Value
Condition	EXT	Exit or entry approach of Roundabout	Exit =1, Entry=0
	CN	If the pedestrian was acting to be blind and carried a white cane	Cane=1, No Cane=0
	FT	Waiting Position; whether the pedestrian was standing at the curb (at curb, or passive) or one foot in the crosswalk (in-road or aggressive)	FT=1(at curb, Passive), FT=0 (in-road, Aggressive)
First-Vehicle-Parameters	SPD	The speed of the first vehicle (mph),at the start of the experiment	MPH
	FAR	Lane that first vehicle was driving (near-lane or far-lane with respect to pedestrian),	Far =1, Near=0
	STP	Whether the first vehicle had already stopped at the time that pedestrian arrived	Stopped=1, Moving=0
	YIELD	Whether the first vehicle yielded (Response Variable)	Yield Yes=1, Yield No=0
	PLT	If the first vehicle was in a platoon	Platoon=1 None-Platoon=0
	MUP	If there were other pedestrians present near the crosswalk; if any pedestrian is at either sides of the street or the splitter island and intends to cross	Multiple Pedestrian =1 One pedestrian=0
	HGV	First vehicle type: passenger car or heavy vehicle	Heavy Vehicle= 1 Passenger car=0
	RT	If first vehicle was turning right from adjacent leg of roundabout (only applicable to exit leg)	Right=1, Through=0
	DSC	If there were any downstream conflicts present (only applicable to the entry leg of roundabouts); downstream conflict happens when there is queuing at the entry to enter the roundabout or the circulating traffic is congested	DS Conflict=1 No Conflict=0

Table 2

List of the Roundabouts Studied for Driver Yielding Behavior

Site ID	City, State	Intersection	Approach	Approach Speed Limit (mph)	Area type	X-Walk Dist.
ST_NASH	Nashville, TN	Music Square/ Division St./ 16th Ave./ Demonbreun St.	Eastbound Exit and Westbound Entry at Demonbreun St.	25	Suburban	20 ft.
ST_TSN	Towson, MD	MD 45/Dulaney Valley Rd./Joppa Rd./Allegheny Ave.	Northbound Entry and Southbound Exit at Dulaney Valley Rd.	25	Urban	40 ft.
ST_ANN	Annapolis, MD	MD 450 (West St.)/Taylor Ave./Spa Rd.	Eastbound Exit and Westbound Entry at Taylor Ave.	25	Urban	20 ft.
ST_IND	Carmel, IN	Old Meridian St./ Guilford Ave.	Eastbound Entry and Westbound Exit at Old Meridian St.	25	Suburban	40 ft.
ST_RAL	Raleigh, NC	Hillsborough St./ Pullen Rd.	Northbound Entry and Southbound Exit at Pullen Rd.	25	Suburban	20 ft.
ST_SLM	Winston-Salem, NC	Old Salem Rd./ S. Main St./ Salem Ave.	Southbound Entry and Southbound Exit at Old Salem Rd.	25	Suburban	25 ft.

Table 3

Yielding Rates and Speed Measurements for Each Site

Site, (n=25 for each condition)		Entry (EXT=0)				Exit (EXT=1)			
		Sighted (CN=0)		Blind (CN=1)		Sighted (CN=0)		Blind (CN=1)	
		Passive	Aggressive	Passive	Aggressive	Passive	Aggressive	Passive	Aggressive
Carmel, IN	Yield Rate	16%	18%	80%	70%	0%	0%	6%	13%
	Overall	46%				5%			
	Speed	Average = 30 mph, Max= 44 mph				Average = 19 mph, Max= 31 mph			
Nashville, TN	Yield Rate	39%	23%	75%	82%	0%	0%	0%	20%
	Overall	55%				5%			
	Speed	Average = 19 mph, Max= 31 mph				Average = 17 mph, Max= 25 mph			
Raleigh, NC	Yield Rate	17%	20%	21%	50%	16%	5%	17%	16%
	Overall	27%				13%			
	Speed	Average = 19 mph, Max= 31 mph				Average = 17 mph, Max= 26 mph			
Winston-Salem, NC	Yield Rate	0%	10%	19%	20%	0%	0%	12%	26%
	Overall	12%				10%			
	Speed	Average = 27 mph, Max= 44 mph				Average = 17 mph, Max= 24 mph			
Towson, MD	Yield Rate	30%	59%	57%	79%	48%	N/A	N/A	64%
	Overall	56%				56%			
	Speed	Average = 20 mph, Max= 31 mph				Average = 15 mph, Max= 21 mph			
Annapolis, MD	Yield Rate	40%	78%	94%	85%	29%	13%	41%	40%
	Overall	74%				31%			
	Speed	Average = 22 mph, Max= 31 mph				Average = 15 mph, Max= 26 mph			

Table 4

Descriptive Statistics for Each Site- a) Entry, b) Exit

Entry	Carmel, IN		Nashville, TN		Raleigh, NC		Winston-Salem, NC		Towson, MD		Annapolis, MD	
	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev
sample size	71		54		68		83		79		58	
a)												
<i>Response Variable</i>												
YIELD	0.451	0.501	0.519	0.504	0.265	0.444	0.120	0.328	0.557	0.500	0.776	0.421
<i>Binary Factors</i>												
FAR	0.366	0.485	0.630	0.487	0.750	0.436	0.723	0.450	0.468	0.502	0.276	0.451
RT	-	-	-	-	-	-	-	-	-	-	-	-
PLT	0.324	0.471	0.630	0.487	0.103	0.306	0.133	0.341	0.405	0.494	0.328	0.473
DSC	0.085	0.280	0.278	0.452	0.118	0.325	0.048	0.215	0.241	0.430	0.224	0.421
HGV	0.000	0.000	0.000	0.000	0.015	0.121	0.048	0.215	0.051	0.221	0.034	0.184
MUP	0.000	0.000	0.093	0.293	0.088	0.286	0.012	0.110	0.076	0.267	0.000	0.000
<i>Continuous Factor</i>												
SPD (mph)	29.746	7.653	18.593	6.227	18.765	4.960	27.133	7.638	19.696	4.797	21.707	6.170
b)												
Exit	Carmel, IN		Nashville, TN		Raleigh, NC		Winston-Salem, NC		Towson, MD		Annapolis, MD	
	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev
sample size	64		79		81		75		50		91	
b)												
<i>Response Variable</i>												
YIELD	0.047	0.213	0.051	0.221	0.136	0.345	0.107	0.311	0.560	0.501	0.308	0.464
<i>Binary Factors</i>												
FAR	0.500	0.535	0.481	0.503	0.728	0.448	0.480	0.503	0.340	0.479	0.385	0.489
RT	0.141	0.350	0.152	0.361	0.247	0.434	0.000	0.000	0.400	0.495	0.176	0.383
PLT	0.297	0.460	0.430	0.498	0.062	0.242	0.027	0.162	0.340	0.479	0.198	0.401
DSC	-	-	-	-	-	-	-	-	-	-	-	-
HGV	0.000	0.000	0.051	0.221	0.037	0.190	0.027	0.162	0.020	0.141	0.022	0.147
MUP	0.000	0.000	0.165	0.373	0.099	0.300	0.013	0.115	0.060	0.240	0.033	0.180

b)

Exit	Carmel, IN		Nashville, TN		Raleigh, NC		Winston-Salem, NC		Towson, MD		Annapolis, MD	
	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev	Ave.	StdDev
<i>Continuous Factor</i>												
SPD (mph)	18.703	4.108	16.582	3.112	17.074	3.308	17.480	3.351	14.780	2.444	15.495	2.639

Table 5

Results of Logistic Regression for All Sites: a) Without Site Dummy Variables, b) With Site Dummy Variables

a)						
	<u>P(Yield)-All</u>		<u>P(Yield)-Entry</u>		<u>P(Yield)- Exit</u>	
	Estimate	Odds Ratio	Estimate	Odds Ratio	Estimate	Odds Ratio
Intercept	2.06	-	1.62	-	3.45	-
DSC	0.29	1.33	0.43	1.54	-	-
SPD	- 0.11 ^a	0.90	- 0.09 ^a	0.92	- 0.33 ^a	0.72
FAR	- 1.46 ^a	0.23	- 1.65 ^a	0.19	- 1.16 ^a	0.31
RT	-0.09	0.91	-	-	-0.44	0.64
PLT	0.13	1.13	0.13	1.14	0.02	1.02
MUP	-0.79	0.45	-1.07	0.34	-0.52	0.59
CN	1.28 ^a	3.59	1.41 ^a	4.09	1.10 ^a	3.01
FT	0.36 ^b	1.44	0.31	1.37	0.45	1.57
EXT	- 2.14 ^a	0.12	-	-	-	-
AIC	796.782		442.652		408.410	
-2logL	776.782		426.652		327.158	
R ²	0.2501		0.2622		0.169	
Max-rescaled R ²	0.354		0.352		0.276	

b)						
	<u>P(Yield)-All</u>		<u>P(Yield)-Entry</u>		<u>P(Yield)- Exit</u>	
	Estimate	Odds Ratio	Estimate	Odds Ratio	Estimate	Odds Ratio
Intercept	2.07	-	2.52	-	2.18	-
DSC	0.22	1.25	0.29	1.33	-	-
SPD	- 0.11 ^a	0.90	- 0.11 ^a	0.90	- 0.32 ^a	0.73
FAR	- 1.21 ^a	0.30	- 1.25 ^a	0.29	- 1.26 ^a	0.29
RT	-0.34	0.71	-	-	- 1.28 ^a	0.28
PLT	-0.15	0.86	-0.36	0.70	0.17	1.19
MUP	-0.79	0.46	-1.06	0.35	0.03	1.03
CN	1.40 ^a	4.05	1.61 ^a	5.03	1.31 ^a	3.70
FT	0.33	1.40	0.41	1.51	-0.34	0.71
ST_RAL	- 0.89 ^b	0.41	- 1.79 ^a	0.17	1.28 ^c	3.62
ST_NASH	-0.34	0.72	-0.27	0.77	-0.47	0.63
ST_SLM	- 1.37 ^a	0.25	- 2.36 ^a	0.10	0.34	1.40
ST_ANN	0.89 ^a	2.44	0.82 ^c	2.28	1.95 ^a	7.01
ST_TSN	0.74 ^b	2.09	-0.41	0.67	3.38 ^a	29.29
EXT	- 2.26 ^a	0.10	-	-	-	-

b)			
	<u>P(Yield)-All</u>	<u>P(Yield)-Entry</u>	<u>P(Yield)- Exit</u>
	<u>Estimate Odds Ratio</u>	<u>Estimate Odds Ratio</u>	<u>Estimate Odds Ratio</u>
AIC	738.015	399.424	297.674
-2logL	708.015	373.424	271.674
R ²	0.3098	0.3537	0.2701
Max-rescaled R ²	0.439	0.475	0.441

^a
p<0.001

^b
p<0.05

Table 6

Results of Forward Selection Logistic Regression Model (Final Models)

	<u>P(Yield)-All</u>		<u>P(Yield)-Entry</u>		<u>P(Yield)- Exit</u>	
	Estimate	Odds Ratio	Estimate	Odds Ratio	Estimate	Odds Ratio
Intercept	1.74	-	2.00	-	2.18	-
DSC	-	-	-	-	-	-
SPD	-0.10 ^a	0.91	-0.10 ^a	0.91	-0.32 ^a	0.73
FAR	-1.22 ^a	0.30	-1.31 ^a	0.27	-1.31 ^a	0.27
RT	-	-	-	-	-1.33 ^a	0.26
PLT	-	-	-	-	-	-
MUP	-	-	-	-	-	-
CN	1.41 ^a	4.09	1.62 ^a	5.06	1.32 ^a	3.74
FT	-	-	-	-	-	-
ST_RAL	-0.66 ^b	0.52	-1.35 ^a	0.26	1.31 ^c	3.70
ST_NASH	-	-	-	-	-	-
ST_SLM	-1.10 ^a	0.34	-1.93 ^a	0.15	-	-
ST_ANN	1.22 ^a	3.07	1.14 ^a	3.13	1.94 ^a	6.94
ST_TSN	0.94 ^a	2.57	-	-	3.23 ^a	25.27
EXT	-2.27 ^a	0.10	-	-	-	-
AIC	734.606		395.837		289.639	
-2logL	716.606		381.837		273.639	
R ²	0.3026		0.34		0.2667	
Max-rescaled R ²	0.429		0.457		0.435	

^a $p < 0.001$ ^b $p < 0.05$