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Mixed-Priority Pedestrian Delay Models at Single-Lane Roundabouts

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Abstract

This paper presents an approach for developing mixed-priority pedestrian delay models at single-lane roundabouts using behavioral crossing data. Mixed-priority refers to crosswalk operations where drivers sometimes yield to create crossing opportunities, but where pedestrians sometimes have to rely on their judgment of gaps in traffic to cross the street. The models use probabilistic behavioral parameters measured in controlled pedestrian crossings by blind pedestrians as part of NCHRP project 3-78a. While blind pedestrians clearly represent a special population of pedestrians, the developed delay model is structured to be applicable to any pedestrian population. Delay is predicted as a function of the probability of encountering a crossing opportunity in the form of a yield or crossable gap, and the probability of utilizing that opportunity, which are combined to produce an overall probability of crossing. The paper presents the theoretical approach to estimating the probability parameters and uses a multi-linear log-transformed regression approach to predict the average pedestrian delay. The final delay model explains 64% of the variability in the observed data and therefore represents a reasonable model for predicting pedestrian delay at single-lane roundabouts. The paper concludes with a discussion of how agencies can estimate the underlying probability parameters for existing or proposed roundabouts using empirical and theoretical approaches, and how pedestrian crossing treatments can be used in the context of the model to reduce average pedestrian delay. The research is important in light of the ongoing debate of the accessibility of modern roundabouts to pedestrians who are blind.

INTRODUCTION

Modern roundabouts are a popular new form of intersection control in the US with over 1,500 existing and many more proposed (1). In contrast to older traffic circles, modern roundabouts are compact, unsignalized, have low design speeds, and use a yield prioritization at the entering approach with circulating traffic having the right-of-way. The strongest selling points for modern roundabouts are a significant reduction in collisions compared to signalized intersections (2), aesthetic appeal, and the ability to process varying traffic patterns without the need to adjust signal parameters.

Many modern roundabouts are constructed in areas with pedestrian activity, including downtown areas or suburban residential areas. Roundabout crosswalks are typically marked

with a zebra pattern or another form of marking (3) and feature a two-stage crossing with a splitter island between entry and exit legs for pedestrian refuge. State motor vehicle codes commonly give pedestrians the right of way within the crosswalk (4). This suggests that roundabouts should be accessible to pedestrians. But yielding laws can be misinterpreted and the actual yielding behavior varies over a range of observed values at different sites and geometries (2). Consequently, pedestrians are expected to experience some delay when attempting to cross at these locations.

The 2000 US Highway Capacity Manual (HCM) (5), the guide book for traffic operational analysis methodologies in the US and many other countries, currently offers no delay methodology for a mixed-priority crossing situation, where drivers sometimes yield to create crossing opportunities, but where pedestrians sometimes have to rely on their judgment of gaps in traffic to cross the street. The HCM gap acceptance-based methods are limited to cases where pedestrians have full priority (100% of traffic yields) or where drivers have priority (no yields) and pedestrians are limited to crossings in gaps only. An updated pedestrian delay model that allows for a reduction of pedestrian delay due to drivers that yield is currently being considered for the 2010 release of the HCM. However, the proposed theoretical model is not calibrated from field data and does not distinguish between different sub-populations of pedestrians.

In the context of building modern roundabouts, much national attention has been given to pedestrians who are blind. Without the ability to see, blind travelers have to rely on auditory cues to identify crossing opportunities. Research has shown that roundabouts can cause significant challenges to this group of travelers, evident by long delays, missed crossing opportunities, and risky situations (6,7,8). In the absence of a signal equipped with an accessible pedestrian signal (APS), a pedestrian who is blind has a difficult time discerning between exiting and circulating traffic and interpreting curved vehicle trajectories causing a confusing auditory environment.

This paper presents an approach for estimating pedestrian delay at single-lane roundabouts on the basis of observable behavioral parameters by pedestrians and drivers. The analysis uses field-observed probabilities of yielding, gap occurrence, and the rate of utilization of yield and gaps to develop statistical pedestrian delay models. The models are developed from observations of blind pedestrian crossings at three single-lane roundabouts, but can be expanded to other pedestrian populations and roundabout geometries using information available in the literature, as well as widely known traffic flow theory concepts. The underlying performance assessment framework for (blind) pedestrian crossings at roundabouts was previously published by the authors in (10) and (11).

BACKGROUND

The issue of pedestrian delay at modern roundabouts, and more specifically the accessibility of modern roundabouts to pedestrians who are blind is being investigated in two related research projects: National Cooperative Highway Research Program (NCHRP) Project 3-78a (12) and a National Eye Institute Bioengineering Research Partnership investigating *Blind Pedestrian Access to Complex Intersections* (13). The data used in this paper were collected in conjunction with those two projects.

Research on pedestrian behavior is typically of an observational nature, as researchers observe and quantify behavior by pedestrians and drivers. This approach has been adopted in a NCHRP-funded national survey of pedestrian crossing treatments (2) and research on the operational performance of modern roundabouts (14). The latter project involved observations for a total of 769 pedestrian crossing events at seven different roundabouts, but

the dataset was deemed insufficient to develop pedestrian delay models for roundabouts and no special pedestrian populations were included in the study.

Other countries have developed methodologies for estimating the impact of pedestrians on vehicular traffic, assuming pedestrian priority (15). Those approaches are conceptually similar to the US HCM methods (5) that quantify pedestrian delay at a vehicle-priority crossing or driver delay at pedestrian-priority crosswalk. A mixed-priority pedestrian delay model will enable engineers to make predictions about the current or future operational performance of a roundabout for this important travel mode. It can further aid in comparing pedestrian performance of a roundabout to a signalized intersection alternative. Finally, without the ability to predict crossing performance for blind travelers, engineers cannot adequately address requirements for the accessibility of modern roundabouts to pedestrians who are blind.

The American with Disabilities Act (ADA) of 1990 mandates equal access to public facilities to all users of that facility, including those with mobility or vision impairments (16). The US Access Board is tasked with interpreting the ADA legislation and issuing guidance to engineers and planners to assure that the public right of way is *accessible to and usable by* pedestrians with disabilities. The US Access Board has recognized the crossing challenges at roundabouts and has proposed language that supports the installation of APS-equipped pedestrians signals at multi-lane roundabouts (17).

Through the aforementioned two research projects (12,13), crossing behavior was studied through controlled experiments. In the studies, pedestrians would cross repeatedly at the same crosswalk under supervision of an orientation and mobility (O&M) specialist, resulting in extensive pedestrian-specific behavioral data sets than would be difficult to obtain from uncontrolled observational studies.

In prior work, the authors had developed a framework for describing the accessibility of modern roundabouts for blind pedestrians (11,18). The accessibility framework is intended to provide measures to quantify the crossing performance at these locations. In particular, the crosswalk usability measures quantify the *availability* of crossing opportunities in the form of yields and crossable gaps, the *rate of utilization* of those opportunities, and the *delay* and *risk* experienced by pedestrians during the crossing. This paper expands on that prior work and relates the performance outcome, delay, to the observed behavioral probability parameters.

METHODOLOGY

The data used for the delay model development were collected in controlled crossing experiments with blind volunteers as part of two research projects (12,13) investigating the accessibility concerns of modern roundabouts to pedestrians with vision impairments. While blind pedestrians represent a special pedestrian population, the approach allows the analyst to distinguish between driver and traffic behavior and incorporates pedestrian characteristics. It can thus be hypothesized what the delay would have been in a different behavioral context. For example sighted pedestrians would have a higher rate of yield utilization (presumably 100%). However, the blind pedestrian data set had the advantage that the full range of crossing performance was observed (e.g. yield utilization ranging from 0% to 100%). The distribution of explanatory variables across a range of values is indeed a critical prerequisite for model development as discussed below.

In the experiments, a total of 40 blind participants crossed independently at three different roundabouts, with each site having a sample of 10-18 pedestrians. The pedestrians were always accompanied by an O&M specialist and were familiarized with the roundabout and

the study design before crossing. Each pedestrian crossed the roundabout multiple times, where each trial consisted of four lane crossings (for example entry-exit-exit-entry). Depending on the site, each pedestrian completed four to six trials at the roundabout, resulting in 16 to 24 lane crossings with half of the crossings at the entry and exit leg, respectively. The dataset used for the delay model development uses the average crossing performance for a single pedestrian at a given leg (entry or exit), resulting in a total of 80 observations. Using the average of all trials for each participant yields a more robust dataset. It assures a sufficient representation of accepted and rejected opportunities for each pedestrian needed to calculate opportunity usability statistics. Overall, a total of approximately 800 observations were used to generate the 80 data points.

Observational Variables

The following intermediate variables are calculated for each of the 80 data points.

- **P(Yield):** The probability of a vehicle yielding to the pedestrian, defined as the number of yields divided by the number of yields plus the number of non-yielding vehicles that cross the plane of the crosswalk while a pedestrian is waiting to cross. This parameter describes driver behavior and does not include gap events.
- **P(Y_ENC):** The probability of encountering a yield event, defined as the number of yields divided by the total number of events encountered by the pedestrian until he/she completes the crossing. An event is defined as the interaction of a pedestrian with a single vehicle. This measure is used to develop the pedestrian delay models.
- **P(GO|Yield):** The probability of yield utilization, defined by the number of crossings in a yield divided by total number of yields encountered by the pedestrian.
- **P(CG):** The probability of a gap being crossable, defined as the number of crossable gaps (CGs) divided by the number of all crossable plus non-crossable gaps. This parameter describes gap occurrence and does not include any yields events. In this study, the CG was calculated from the time required to cross at a walking speed of 3.5 ft/s (1.07) plus 2 seconds to account for start-up and clearance time. This is consistent with the pedestrian critical gap definition in the HCM, given below in equation 3.
- **P(CG_ENC):** The probability of encountering a CG event, defined as the number of crossable gaps divided by the total of all events (vehicles) encountered by the pedestrian. **P(GO|CG):** The probability of crossable gap utilization, defined by the number of crossings in a CG divided by total number of CGs encountered by the pedestrian.
- **Observed Delay per Leg (sec.):** The average pedestrian delay in seconds, defined as the time difference between when the trial started and when the pedestrian initiated the crossing at the leg. Note that a full crossing at the roundabout includes two legs and this delay is given per leg!
- **Minimum Delay (sec.):** The minimum delay or waiting time until the first opportunity, defined as the time difference between start of the trial and the first yield or crossable gap encountered by the pedestrian. Presumably, this delay corresponds to the experience of sighted pedestrians who tend to utilize the first available crossing opportunity whether in the form of a yield or a crossable gap (at the defined CG time).

The above variables are largely identical to measures used to define pedestrian accessibility that were presented in (11). That paper used P(Yield), P(GO|Yield), P(CG), P(GO|CG), but

stopped short of relating those to pedestrian delay in a predictive model. For the purpose of developing predictive delay models, it was necessary to define two additional variables that describe the probability of encountering a yield and crossable gap. The measures $P(Y_ENC)$ and $P(CG_ENC)$ use the same denominator: The total number of pedestrian-vehicle interaction events, where one event is always defined as the interaction of one vehicle and one pedestrian. With the same denominator, the two terms become additive and their sum by definition is limited by 1.0. Figure 1 illustrates the definition of observational variables using a hypothetical example of a pedestrian encountering 10 different vehicles (10 events). Figure 1 shows a timeline of a pedestrian encountering 10 hypothetical vehicle events. The timeline proceeds from left to right, from the start of the experimental trial until the last vehicle that interacts with the pedestrians crossed the plane of the crosswalk. Of the ten vehicles, vehicles 2, 4, 7, and 8 yielded to the pedestrian, but none of these yields were utilized. Vehicles 1, 3, 5, 6, 8, and 9 didn't yield even though a pedestrian was waiting at the crosswalk. No yield information is available for vehicle 10, since the pedestrian had already crossed by the time it crossed the plane of the crosswalk. Consequently, the variable $P(Yield)$ is calculated from four yields divided by a total of nine drivers that could have yielded and is therefore =44.4%. By contrast, the variable $P(Y_ENC)=40\%$ is calculated by dividing four yields by a total of 10 vehicles encountered in the trial.

The temporal separation between vehicles 2-3, 5-6, and 9-10 constituted three crossable gaps, the last of which was utilized by the pedestrians. The gap from the start of the trial to vehicle 1, and the gaps between vehicles 4-5 and 8-9 were below the crossable gap threshold. The measure $P(CG)=50.0\%$ is calculated by dividing three crossable gaps by six total gaps encountered. $P(CG_ENC)=30.0\%$ is calculated by dividing three crossable gaps by a total of ten events.

The rates of yield and crossable gap utilization are calculated at $P(GO|Yield)=0.0\%$ and $P(GO|CG)=33.3\%$, respectively. The reasons for not utilizing one of these crossing opportunities may include uncertainty about driver intent or high levels of ambient noise. Delay is defined as the temporal duration from the time the trial starts until the pedestrian initiates the crossing. The Minimum Delay is less, calculated as the time spent waiting until the first crossing opportunity, which in this case is the yielding event by vehicle 2.

Site Description

All three studied roundabouts have one circulating lane and single-lane entries and exits. The major approaches at the roundabouts are arterial streets with a mix of commuter and local traffic. All three roundabouts have bus stops in close proximity and thus exhibit at least some heavy vehicle activity. Site DAV-CLT is located at the intersection of 9th Street and Davidson Street in Charlotte, NC in a downtown residential area and has an inscribed diameter of 100-120 feet (30.5-36.6m). The major approach at DAV-CLT has an approximate Average Annual Daily Traffic (AADT) of 9,900 vehicles. Site PS-RAL is located at the intersection of Pullen Road (AADT 15,000) and Stinson Drive in Raleigh, NC near a major university with an inscribed diameter of 88 feet (26.8m). Site ULY-GOL is located at the intersection of Golden Road (AADT 15,000) and Ulysses Drive in Golden, CO in a suburban business district and has an inscribed diameter of 100 feet (30.5m). Figure 2 shows aerial views of all three sites. The studied crosswalks are highlighted.

Descriptive Statistics

Table 1 shows a summary of the described measures at the three roundabouts. The results indicate that they exhibit considerable differences in the performance measures. Site ULY-GOL shows higher $P(Yield)$ rates than the other two sites, with DAV-CLT having the lowest yielding rates. The likelihood of encountering a yield, $P(Y_ENC)$, follows a similar trend.

The rates of yield utilization are comparable for PS-RAL and ULY-GOL, with a slightly lower rate observed for DAV-CLT.

The rates of gap availability show the reverse trend from the yielding data with DAV-CLT showing the highest availability of crossable gaps, followed by PS-RAL and ULY-GOL. The rate of gap utilization is highest at ULY-GOL, followed by DAV-CLT and PS-RAL.

The overall delay is comparable for PS-RAL and ULY-GOL, but highest at DAV-CLT, a trend mirrored by the Delay>Min statistics. Interestingly, the highest delay is evident at the site with the lowest availability of yields and a lower rate of yield utilization. At similar crossable gap and gap utilization rate across the three sites, this may suggest that the lack of yielding at the site contributes to delay difference. This point is explored further on the delay model development for individual participants.

The results in Table 1 point to a high level of inter-subject variability as evident in high observed standard deviations. With high standard deviations, the interpretation of the accessibility of a single site is challenging. But for the purpose of model development, the observed variability is considered an asset. For example, if no variability in yielding was observed, it would be impossible to use that variable to predict pedestrian delay. The critical point in this context is that the observed variability (in yielding) is correlated with pedestrian delay. Consequently, if the model development process shows that an increasing likelihood of yielding results in reduced pedestrian delay, the yield probability becomes an important explanatory variable in the delay prediction model.

MODEL DEVELOPMENT

For the purpose of model development, some additional performance measures are defined in this section that were considered as potential independent variables in model development, in addition to the ones already defined above. The following three variables are obtained by summation and multiplication of the intermediate behavioral probability parameters.

- **P(Yield_and_GO):** The probability of crossing in a yield, defined as the probability of utilizing a yield multiplied by the probability of encountering a yield:

$$P(Y_and_GO) = P(Y_ENC)*P(GO|Y).$$

- **P(CG_and_GO):** The probability of crossing in a crossable gap, defined as the probability of utilizing a CG multiplied by the probability of encountering a CG:

$$P(CG_and_GO) = P(CG_ENC)*P(GO|CG).$$

- **P(Crossing):** The probability of crossing, defined as the sum of the probabilities of crossing in a yield and crossing in a crossable gap.

$$P(Crossing) = P(Y_and_GO) + P(CG_and_GO)$$

Additional independent variables considered in the analysis are:

- **Site_Gol:** Dummy variable that identifies the site as GOL-PRE if Site_Gol=1.
- **Site_RAL:** Dummy variable that identifies the site as PS-RAL if Site_RAL=1. By definition, if Site_Gol=Site_Ral=0 then the data refers to an observation at DAV-CLT.
- **ENTRY:** Dummy variable denoting that the observation represents the average of events at the roundabout entry if ENTRY=1.

A total of 40 subjects were included in the analysis from three different sites. Each observation represents the average of four or more lane crossings at a particular site. With the distinction of entry versus exit crossings, the dataset contains 80 observations. However, four observations had to be excluded because these subjects either didn't encounter any crossable gaps or because no drivers yielded to them. As a result, the final data set contained 76 observations. Descriptive statistics for the data set in Table 2 suggest that a range of values was observed for most probability terms, suggesting a good basis for model development.

The model development uses a multi-linear regression approach to predict delay, as a function of various independent variables. All variables are expressed on a per leg basis at the roundabout and as a result the total delay at the crossing is the sum of predicted entry and exit delays. A histogram of the distribution of the delay variable showed significant skew to the left, suggesting a log-normal distribution. Consequently, all predictive probability variables were transformed by applying the natural logarithm of the variable. All regression is performed in SAS statistical analysis software.

RESULTS

The analysis includes a range of potential model forms to explain the dependent variable as a function of the behavioral probability terms. Table 3 shows seven candidate models for the Delay dependent variable.

The delay models in Table 3 suggest a good overall fit, with most variables having a significant explanatory effect on the response. The variable ENTRY is not significant in any model, including others that are not shown. This is because differences in behavior at entry and exit leg are already captured in the probability terms. Model A and several other models suggests a significant effect of the site dummy variables with variables SITE_RAL and SITE_GOL shifting the overall delay curve upward relative to site DAV_CLT. This finding is significant, because the descriptive statistics in Table 1 suggested that this site had the highest overall delay. The model results suggest that the high observed delays at DAV_CLT are explained by the relative lack of crossing opportunities and that the delays at PS_RAL and ULY_GOL would have been much higher with more traffic (fewer crossable gaps) and less courteous driver behavior (fewer yields).

The goal of this analysis is the development of a universal pedestrian delay model for single-lane roundabouts. Therefore, additional models were tested without the site effects. The guiding principles for the final model were significant parameter estimates, a high adjusted R-Square value, and a relatively simple and practical model form. When removing the site variables from Model A, the four probability terms in Model B lose statistical validity. Consequently, the remaining models use the pooled probability terms. Model E and G both represent viable alternatives, predicting delay as a function of P(Yield_and_Go) and P(CG_and_GO) and the overall probability P(Cross), respectively. Both models have comparable adjusted R-Square values and significant parameter estimate. Ultimately, model G was selected, because it provides a better fit with the data at low probability values. In turn Model E was overly optimistic at low probabilities. Both models converge in the higher probability ranges (See Figure 3).

The recommended model G predicts pedestrian delay as a function of P(Cross), which is calculated from the four individual probability parameters. The overall model and the P(Cross) parameter are significant $p < 0.0001$. The adjusted R-Square value suggests that 63.6% of the variability in the data is explained by the model, which is very high given that

inter-subject variability of crossing performance was very high. Equation 1 shows the recommended pedestrian delay model.

Equation 1: Recommended Pedestrian Delay Model (Model G)

$$d_p = -0.78 - 14.99 * LN(P_{CROSS})$$

where,

d_p = average pedestrian delay (s)

P_{CROSS} = Probability of Crossing

$$= P(Y_ENC) * P(GO|Yield) + P(CG_ENC) * P(GO|CG)$$

Figure 3 plots the predicted pedestrian delay as a function of $P(Cross)$, which is the sum of the $P_{Y\&GO}$ and $P_{CG\&GO}$ model parameters. The different data points were obtained by strategically varying $P(Y_ENC)$ and $P(CG_ENC)$ for a fixed utilization of $P(GO|YIELD)=P(GO|CG)=0.5$. The figure shows that the general trends of the model delay curves fall within the cloud of observed data (blue crosses). The figure shows that in a comparison of Models E (green triangle) and G (blue squares) with field-observed delays, the latter fits the data better in the lower $P(Y_ENC)$ and $P(CG_ENC)$ region.

Figure 3 further plots the curve for suggested model G corresponding to perfect opportunity utilization of $P(GO|YIELD)=P(GO|CG)=1.0$ (solid red circles). This curve may approximate the behavior of a sighted pedestrian, assuming that this group of pedestrians has identical thresholds for crossable gaps. Given that the definition used for crossable gap is consistent with the HCM, the resulting delay should be an appropriate, albeit conservative estimate. The perfect utilization curve generally fits well with the observed minimum delay times (red hollow circles), which were calculated by subtracting the Delay_OverMin from the observed delay for each subject.

Figure 4 plots the field-observed and predicted delay and minimum delay for all 76 data points. The delay corresponds to the actual crossing experience of the blind study participants. The minimum delay approximates the corresponding crossing experience of sighted pedestrians encountering the same number of yields and crossable gaps, but having perfect opportunity utilization.

Figure 5 shows a sensitivity analysis of the four base probability parameters ($P(Y_ENC)$, $P(GO|Yield)$, $P(CG_ENC)$, and $P(GO|CG)$) against the field-observed range of those data. In each of the sub-figures, one of the probability parameters was varied from 0.0 to 1.0 (shown on the x-axis), while keeping the other three fixed at two varying levels. The first level uses the field average for that parameter for all subjects as shown in Table 2. The second level again assumes perfect utilization, approximating the delay for a sighted pedestrian.

The plots in figure 5 show how the delay model responds to changes in one of the four probability terms. The greatest sensitivity is evident for rates of yield and gap encounters, $P(Y_ENC)$ and $P(CG_ENC)$, suggesting that changes in these parameters have the largest impact on the predicted delay. The sensitivity curves for the utilization curves are flatter, suggesting that improvements to the ability (or willingness) of pedestrians to utilize crossing opportunities has less of an effect than changing the overall occurrence of these opportunities. All plots generally show a good fit with observed field data. The worst fit is evident for the $P(CG_ENC)$ plot, where the majority of field observations are clustered

towards a low gap occurrence rate. With increasing probability levels, the predicted pedestrian delay decreases. The delay estimate for perfect utilization is expectedly below the field averages.

DISCUSSION

The delay model presented in equation 1 above can be used to predict the delay at single-lane roundabouts by estimating the four probability parameters $P(Y_ENC)$, $P(GO|YIELD)$, $P(CG_ENC)$, and $P(GO|CG)$ that ultimately feed into the model parameters. In order to apply the model to predict delay at single-lane roundabouts, these parameters therefore need to be field-measured or derived from literature, previous studies, and traffic theory.

The rate of driver yielding and the availability of crossable gaps can easily be measured in the field using manual tally and stop watch methods described in the ITE Manual of Transportation Studies (19) or other sources. In the absence of field data, a recent NCHRP Report (14) has collected data on driver yielding behavior at US roundabouts that can be used for guidance. The availability of crossable gaps can be estimated using traffic flow theory concepts based on traffic volume and an assumed headway distribution. Using a simple negative exponential distribution, the probability of observing a headway greater than t_c seconds is given by (20):

Equation 2: Estimating $P(CG_ENC)$ from Traffic Flow Theory (20)

$$P(headway \geq t_c) = e^{-\frac{t_c}{t_{avg}}}$$

where,

t_c = critical headway for crossable gap (sec.)

t_{avg} = average headway, defined as $t_{avg} = (3,600 \text{ sec/hour}) / (V \text{ vehicles/hour})$

In the absence of pedestrian platoons, the critical gap for pedestrians can be calculated by equation 3 following the HCM (5) methodology:

Equation 3: Pedestrian Critical Gap after HCM2000 Equation 18-17 (5)

$$t_c = \frac{L}{S_p} + t_s$$

where,

L = crosswalk length (ft)

S_p = average pedestrian walking speed (ft/s), and

t_s = pedestrian start-up and clearance time (s)

Using the above relationship, the probability of observing a crossable gap in a stream of 400 vehicles per hour at a 14 foot-lane crossing at a roundabout and a corresponding critical headway of $t_c = 14/3.5 + 2 = 6$ seconds is:

$$P(\text{headway} \geq 6 \text{ sec.}) = e^{-\frac{t_c}{t_{avg.}}} = e^{-\frac{6}{9}} = 51.3\%$$

The estimation of yield and gap utilization rates is more difficult for blind pedestrians, since it requires controlled field experiments. In the absence of field data, the results from the three roundabouts used in this analysis that were presented in Table 1 can be used as a starting point. For sighted pedestrians utilization rates of or near 100% can be assumed. For other special pedestrian populations, including children and the elderly analyst judgment will be required. A basic sensitivity analysis can assure that a range of values are considered.

The sensitivity of the model to the different probability parameters that was presented in Figure 5 can inform the debate on how to reduce pedestrian delay through the use of pedestrian crossing treatments. An extensive national survey of different pedestrian crossing treatments and their impact on driver yielding behavior is found in NCHRP Report 562 (14). For example, a treatment that enhances driver yielding from 10% to 30% while keeping the availability of crossable gaps fixed at 20% would presumably decrease the pedestrian delay for sighted pedestrians (perfect utilization) from 13.0 to 4.6 seconds, and the delay for a blind pedestrian (assumed 50% utilization) from 23.3 to 15.0 seconds.

Pedestrian crossing treatments tested in (14) included some with red signal indication, some with yellow flashing beacons, and other static signs that are all intended to increase driver yielding. The results suggested a large variability of the effectiveness of different treatments depending on site-specific parameters. In other research (7) driver yielding behavior was found to increase with decreasing vehicle speeds. Consequently, low roundabout design speeds and traffic calming treatments may be the most effective treatment to assure pedestrian accessibility. This hypothesis is supported by the model response to increases in $P(Y_ENC)$ shown in Figure 5.

The forthcoming report of NCHRP Project NCHRP 3-78 (12) will include field-observed data on the effect of special blind pedestrian treatments in enhancing both the availability and utilization of crossing opportunities. Following the delay framework, any treatment that improves one or more of the underlying probability parameters will reduce overall pedestrian delay.

CONCLUSION

This paper demonstrated the application of a framework based on pedestrian and driver behavioral parameters to develop a mixed-priority delay models for pedestrian crossings at single-lane roundabouts. Mixed-priority refers to crosswalk operations where drivers sometimes yield to create crossing opportunities, but where pedestrians sometimes have to rely on their judgment of gaps in traffic to cross the street. The underlying data set was obtained from controlled experiments including 40 blind pedestrians at three different single-lane roundabouts. It can however be readily adopted to sighted pedestrians or other special populations by varying the appropriate probability parameters. The use of data from blind pedestrians proved to be extremely valuable, since it allowed the distinction between available crossing opportunities and the actual utilization of these opportunities. A dataset containing only sighted pedestrians expectedly would not have captured the utilization effect, since sighted pedestrians would likely utilize the first opportunity that is presented to them. The delay to sighted pedestrians can be predicted with the developed model by assuming perfect utilization. However, the model further allows the analyst to consider pedestrian populations with less-than perfect rates of opportunity utilization. In addition to fully blind participants, the approach is therefore adoptable to people with low vision or

children, who have been shown to have difficulty judging the speed and distance of oncoming traffic (9).

The resulting mixed-priority delay model is statistically significant and produces good estimates of pedestrian delay that match observed field data. It is applicable to situation where pedestrian delay is governed by a mix of pedestrian gap acceptance and driver yielding behavior. The underlying probability terms can be estimated from field observations for other sites, or can be estimated from literature or traffic flow theory concepts. In future research, the authors hope to expand the data collection and analysis to other unsignalized crossing locations, including multi-lane roundabouts, which pose more severe crossing difficulties for both blind and sighted pedestrians.

The authors recognize that the material presented here has potential implications for the ongoing national debate in the US on the accessibility of modern roundabouts to pedestrians who are blind. The focus of this paper is not to propose policies, but rather to contribute and inform the ongoing debate on roundabout accessibility. Roundabout treatments including signalization schemes are discussed extensively in the roundabout engineering and accessibility communities and are far beyond the scope of this paper. The authors are hopeful that the developed delay models can assist with that discussion by offering potential users a methodology for quantifying and predicting (blind) pedestrian delay at roundabouts. However, it is emphasized that the approach presented here excludes any implications on pedestrian safety, which also need to be considered in any comprehensive evaluation of treatments. The readers are encouraged to consult the final report for NCHRP project 3-78a (11) for a more complete discussion of these accessibility issues.

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Variable	Definition	Unit	Source
Age	Age in years	Years	Survey
Gender	Male or Female	Categorical	Survey
Income	Annual household income	Dollars	Survey
Education	Years of schooling completed	Years	Survey
Health	Self-reported health status	Categorical	Survey
Marital Status	Married, Divorced, Single, Widowed	Categorical	Survey
Employment	Employed or Unemployed	Categorical	Survey
Travel Time	Time taken to travel to work	Minutes	Survey
Mode of Transport	Car, Bus, Train, Bicycle, Walking	Categorical	Survey
Accident History	Number of traffic accidents in the last 5 years	Count	Police Records
Insurance Status	Has health insurance or not	Boolean	Insurance Companies
Property Value	Estimated value of the property	Dollars	Real Estate Agents
Crime Rate	Rate of crime in the neighborhood	Percentage	Police Department
Population Density	Number of people per square mile	People per square mile	Census Bureau
Weather Data	Temperature, Humidity, Wind Speed	Degrees, Percent, Miles per hour	Weather Service
Local Events	Events occurring in the area	Categorical	Local Government
Public Services	Availability of public services	Categorical	Local Government
Quality of Life	Overall quality of life index	Index	Survey

Figure 1.
Graphical Illustration of Variable Definitions

Figure 2.
Aerial views of Comparison roundabouts (Source: www.bing.com)

Figure 3.
Graphical Comparison of Model 5 against Field Data

Figure 4.
Field Observed versus Predicted Delay and Min. Delay

Figure 5.
Model 5 Sensitivity versus Field Data

Table 1

Summary Comparison of Three Single-Lane Roundabouts

	Site ID					
	DAV-CLT		PS-RAL		ULY-GOL	
	ENTRY	EXIT	ENTRY	EXIT	ENTRY	EXIT
P(Yield)						
Mean	10.8%	11.8%	41.5%	18.2%	65.6%	20.2%
Std.Dev	8.9%	7.9%	32.8%	17.9%	36.1%	17.2%
P(Y_ENC)						
Mean	5.8%	6.7%	37.9%	28.1%	51.1%	29.6%
Std.Dev	4.8%	5.0%	17.8%	14.4%	18.4%	13.7%
P(GO Yield)						
Mean	64.1%	70.4%	83.0%	87.8%	82.8%	76.0%
Std.Dev	41.2%	44.1%	20.4%	14.1%	20.1%	26.1%
P(CG)						
Mean	62.1%	60.9%	53.5%	50.2%	53.7%	29.8%
Std.Dev	14.2%	12.9%	28.1%	23.5%	21.6%	12.2%
P(CG_ENC)						
Mean	29.8%	27.8%	17.7%	20.5%	26.3%	20.6%
Std.Dev	6.9%	6.7%	8.9%	9.7%	12.4%	8.4%
P(GO CG)						
Mean	66.3%	60.3%	52.0%	63.6%	83.2%	86.8%
Std.Dev	20.6%	17.9%	41.3%	26.6%	23.7%	23.4%
Delay (sec.)						
Mean	26.6	24.0	10.5	11.6	10.9	13.0
Std.Dev	17.0	9.7	8.9	6.8	7.3	7.9
Delay >Mfin (sec.)						
Mean	18.8	17.2	5.6	6.1	2.8	2.7
Std.Dev	15.5	9.6	7.2	5.8	2.1	2.3

Table 2

Descriptive Statistics for Delay Model Data Set

Variable	Site	N	Mean	Std Dev	Min	Max
P(Y_ENC)	All	76	27.7%	18.8%	1.7%	66.7%
P(GO Yield)	All	76	61.4%	37.0%	0.0%	100.0%
P(CG_ENC)	All	76	24.7%	8.3%	4.8%	44.4%
P(GO CG)	All	76	71.5%	28.0%	0.0%	133.3%*
P(Yield_and_GO)	All	76	21.7%	18.5%	0.0%	58.3%
P(CG_and_GO)	All	76	17.5%	8.6%	0.0%	44.4%
P(Crossing)	All	76	39.2%	21.1%	12.1%	88.9%
Entry	All	76	48.7%	50.3%	0.0%	100.0%
Delay	All	76	15.5	10.6	3.5	58.3
Delay_overMin	All	76	7.8	9.1	0.1	46.0

* A value of $P(GO|CG) > 1.0$ can occur when a pedestrian utilizes a "non-crossable" gap that is below the selected CG threshold.

Table 3

Regression Results for Dependent Variable Delay

	Model A Estimate	Model B Estimate	Model C Estimate	Model D Estimate	Model E Estimate	Model F Estimate	Model G ⁺ Estimate
Intercept	-15.40***	0.90	-11.21**	9.31**	4.45*	-1.54	-0.78
Ln[P(Y_ENC)]	-4.65**	-2.35*					
Ln[P(GO Yield)]	-5.78***	-3.54***					
Ln[P(CG_ENC)]	-3.48**	-2.62					
Ln[P(GO CG)]	-9.32***	-8.66***	F	F	F	F	F
Ln[P(Yield_and_GO)]			-6.11***		-3.33***		
Ln[P(Gap_and_GO)]	F	F	F	-9.20***	-6.03***	F	F
Ln[P(Crossing)]	F	F	F	F	F	-15.75***	-14.99***
Entry	1.29	F	F	F	F	F	F
Site_gol	13.21***	F	14.97***	-12.43***	F	1.97	F
Site_ral	8.30**	F	13.71***	-17.34***	F	-3.29	F
Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
DF	7	4	3	3	2	3	1
R-Square*	0.779	0.679	0.634	0.460	0.640	0.683	0.641
Adj. R-Square*	0.755	0.659	0.619	0.436	0.630	0.670	0.636

⁺ Represents Recommended Model

* Significant at p < 0.1

** Significant at p < 0.05

*** Significant at p < 0.01