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Working Concept of Accessibility:

Performance Measures for Usability of Crosswalks by Pedestrians with Vision

Impairments

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Abstract

This research presents an analysis framework and associated performance measures for quantifying the accessibility of pedestrian crossings at modern roundabouts for pedestrians who are blind. The measures, developed under two ongoing national research projects, NCHRP Project 3-78A and a bioengineering research grant from the National Institutes of Health–National Eye Institute, attempt to isolate the components of the crossing task for a blind pedestrian into computable and replicable quantities that allow the comparison of accessibility across individuals or sites. The framework differentiates between crossing opportunities in the form of yields and crossable gaps and the utilization of these opportunities by the pedestrian. It further accounts for the amount of delay and risk involved in the crossing. The analysis framework and measures are demonstrated for two single-lane roundabouts in North Carolina evaluated under the aforementioned research projects. The application shows that the accessibility of a pedestrian crossing to a blind pedestrian is characterized by a combination of different measures and further depends on crossing geometry, traffic volume, driver behavior, and the travel skills and risk-taking behavior of the individual. With successful demonstration at roundabout crosswalks, the analysis framework is hypothesized to have broader application to unsignalized pedestrian crossings, including midblock locations.

In recent years, extensive research has been conducted on the accessibility of roundabouts and other complex intersections to pedestrians who are blind. Among those, two multiyear research projects, NCHRP Project 3-78A (1) and a bioengineering research grant from the National Institutes of Health–National Eye Institute, have carried out numerous studies evaluating the crossing performance of blind travelers at roundabouts and intersections with channelized right-turn lanes. Although roundabouts in the United States are still not as common as they are in other countries, more than 1,400 were known to be in operation at the time of this research (2). With national research documenting their proven safety and operational benefits for vehicular traffic (3,4), it is expected that many more will be built in the near future.

One of the primary challenges in conducting research on the accessibility of roundabout pedestrian crossings (and similarly for the evaluation of pedestrian facilities in general) is

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assessing the crossing performance in quantifiable and reproducible terms. This research presents a framework of performance measures that can be used to describe the crossing performance of (blind) pedestrians and presents supporting data from two single-lane roundabouts evaluated under the aforementioned projects to illustrate the concepts.

BACKGROUND

Recent research on the crossing performance of people who are blind at complex intersections demonstrated that there are unique challenges for this population (5,6). In particular, the crossing task can be categorized into four distinct components:

1. Locating the crosswalk,
2. Aligning to cross,
3. Deciding when it is safe to cross,
4. Maintaining alignment during crossing.

A pedestrian traveling along a sidewalk needs to identify the location of the crosswalk, which can be facilitated by the use of audible pedestrian signals (7) or other wayfinding aids such as landscaping. Once at the crosswalk, the traveler needs to align to the crossing in a way that the crossing path is aimed at the far end of the crosswalk. Alignment treatments such as detectable warning surfaces or sloped curb cuts can help with this task (8).

The focus of this research is on measures describing the third component, the task of identifying crossing opportunities in a conflicting traffic stream. At unsignalized crossings, these crossing opportunities generally take the form of crossable gaps in moving traffic or of drivers yielding to pedestrians at or near the crosswalk. At signalized crossings, the pedestrian “Walk” phase presents a planned crossing opportunity that is a function of signal phasing. Finally, the pedestrian still needs to maintain alignment during the crossing, which is greatly facilitated by straight crosswalk geometry and may be supplemented by other treatments such as a far-side locator beacon.

Complex intersections, including roundabouts, present some unique challenges for pedestrians with vision impairments. The traffic control strategy at a roundabout entry leg is typically a yield sign, and many drivers are able to enter the circle without the requirement to come to a full stop. Similarly, traffic exiting the roundabout is free-flowing, resulting in largely uninterrupted traffic flow at the exit portion of the crosswalk. Roundabout crosswalks are typically not signalized (3) and the task of identifying crossing opportunities is thus unassisted. Depending on the geometric design of the roundabout and the location of the crosswalk, vehicle speeds may be relatively high and the auditory interpretation is complicated because vehicles are moving on a circular path (5). At signalized intersections, the two traffic streams typically move perpendicular to each other, making it easier for somebody who is blind to interpret directional traffic movements. Finally, the continuous flow of traffic circulating the roundabout can create a difficult auditory environment and the listening task is complicated by elevated levels of ambient noise.

WHAT MAKES A SITE ACCESSIBLE?

The question of accessibility is as complex as the crossing task just described. A variety of factors contribute to the ability of a blind pedestrian to safely cross at a particular facility. The United States Access Board is tasked with developing standards by which the accessibility that is required by law and implementing regulations governing new construction can be measured. The recently published revised draft public rights-of-way accessibility guidelines (PROWAG) (9) outline geometric requirements for making a site

compliant with the 1990 Americans with Disabilities Act (ADA). The document is fundamentally based on Title II of the ADA, which specifies that a new public facility should be “readily accessible to and usable by individuals with disabilities” (Americans with Disabilities Act of 1990, Title 42, Chapter 125, U.S. Code; <http://www.ada.gov>), including those with vision loss, mobility impairments, or other disabilities.

Although there is no accessibility standard for roundabouts yet, the document outlines geometric features that if adopted make a site ADA-compliant. Specifically, a pedestrian signal with accessible pedestrian signal (APS) technology provides a “safe harbor” for pedestrians at multilane roundabout approaches, making the site usable by those who are blind.

The language in the PROWAG document has been relaxed in relation to single-lane roundabouts, but it remains unclear how different roundabout geometries compare in terms of crosswalk usability and accessibility.

Even after the geometric components of crosswalk usability are accounted for, the crossing task for a blind traveler at an unsignalized roundabout crossing is affected significantly by the level of conflicting traffic volume, driver behavior, background noise, and ultimately by his or her personal travel skills and risk-taking behavior.

Given the multitude of factors contributing to the usability question, it is important to propose metrics that can be used to compare the crossing ability across sites before and after a crossing treatment is installed or even from one pedestrian to another.

FRAMEWORK FOR EVALUATING UNSIGNALIZED PEDESTRIAN CROSSINGS

In an initial effort to quantify pedestrian crossing performance, Schroeder and Rouphail (10) suggested that pedestrian–vehicle interaction at unsignalized crosswalks can be conceptualized as the function of four probability parameters:

$P(G)$ = likelihood of a crossable gap in the traffic stream to allow for a safe crossing,

$P(GD)$ = likelihood that the crossable gap is detected by the pedestrian,

$P(Y)$ = likelihood that a driver will yield, and

$P(YD)$ = likelihood that the yield is detected by the pedestrian.

In those probability parameters, a gap is defined as the time between two successive vehicle arrivals at the crosswalk and is measured in seconds. A yield is defined as a voluntary deceleration by an approaching driver with the intent to give way to the pedestrian.

The authors developed this analysis framework with the intent of representing pedestrian–vehicle interaction in a microsimulation environment. They argued that different pedestrian populations and the impact of crossing treatments could be represented through changes in one or more of these probabilities. Using hypothesized distributions of those probabilities, it was demonstrated that a simulation model could be made responsive to changes in parameters resulting in increased or decreased vehicle and pedestrian delay and conflicts.

In ongoing research on the accessibility of complex intersections to people who are blind (1), it has become evident that the terminology of yield and gap detection is misleading because pedestrians may well be able to identify a yielding vehicle but may still choose not to seize the opportunity because they are uncomfortable crossing in front of a stopped car. Consequently, the following discussion will generally refer to yield and gap utilization,

because the terms directly describe observed crossing behavior. No further interpretation is given about the rationale for utilizing a crossing opportunity. That facet of this research is described elsewhere (11).

In this discussion, the authors expand on these concepts by customizing the measures to the particular situation of blind travelers to include additional measures to quantify pedestrian delay and risk. The measures are then applied to field data collected at two single-lane roundabouts in North Carolina.

ACCESSIBILITY CRITERIA

The crossing task at an unsignalized pedestrian crosswalk is assessed in terms of four accessibility criteria:

1. Crossing opportunity: Are there sufficient crossing opportunities in the form of yields or crossable gaps?
2. Opportunity utilization: Are the crossing opportunities utilized by the pedestrian?
3. Delay: Is a crossing opportunity taken within a reasonable time?
4. Safety: Does the crossing interaction occur without a significant degree of risk?

At a pedestrian signal, the first criterion would be equivalent to the relative frequency of the “Walk” indication. At an unsignalized crossing, it describes whether the traffic characteristics and driver behavior result in crossing opportunities. For lower conflicting flows, pedestrians will encounter gaps that are long enough for a safe crossing. Conceptually, the decision whether a gap is crossable is a function of the crossing width, pedestrian walking speed, and a safety buffer on completion of the crossing. Schroeder et al. (12) defined the minimum time for a safe crossing as 75% of the average crossing time, reasoning that pedestrians are safe even before completing the entire crossing. This notion is consistent with software interpretations of pedestrian crosswalks, in which the effective crosswalk width is less than the actual distance between curbs (13). Alternatively, different approaches to describing pedestrian gap acceptance account for an additional safety buffer to distinguish crossable from too-short gaps. In particular, Yang et al. (14) and Rouphail et al. (15) calculated the crossable gap by dividing the crossing distance by an assumed walking speed and adding a 1- to 2-s safety buffer.

Crossing opportunities may also take the form of yields. Although legislation in most U.S. states requires drivers to yield to pedestrians already in the crosswalk, the law is often ambiguous about the requirement to yield to a pedestrian waiting at the curb. Consequently, a wide range of driver yielding rates has been observed at U.S. unsignalized pedestrian midblock crossings (16). Yielding behavior at roundabouts was studied by Geruschat and Hassan (17), who found an increased likelihood of yielding at the roundabout entry lane and that yielding is sensitive to vehicle speed, pedestrian behavior, and in some cases the presence of a long cane.

The second criterion quantifies the level of pedestrian utilization of the available crossing opportunities. The utilization of crossable gaps is a function of the gap acceptance characteristics of the pedestrian. It may further be influenced by background noise at the site. At a roundabout in particular, the noise from circulating traffic may mask the auditory information at the crosswalk, affecting the ability of a blind pedestrian to identify a crossable gap or yield (15). Previous research has shown that pedestrians with vision impairments often do not cross in front of yielding vehicles because they either cannot hear the car or they are not confident that the crossing is safe despite the yield condition (5,18).

Multiple-threat situations (19) at multilane approaches, in which a vehicle in the near lane visually or auditorily masks the events in the far lane, further complicate yield utilization.

On the basis of the first two criteria, most pedestrians will eventually utilize a crossing opportunity, raising the question of what amount of delay is acceptable before this happens. The *Highway Capacity Manual* (HCM) (20) uses delay to define levels of service for pedestrian crossings. From an engineering perspective, it is thus intuitive that an inordinate amount of delay would make a crossing inaccessible. In the HCM, a (sighted) pedestrian delay over 45 s at an unsignalized intersection corresponds to level-of-service (LOS) F, which is the worst category on the scale of A through F. The manual further emphasizes that the likelihood of risk-taking behavior (by sighted pedestrians) is very high at this level of delay.

Finally, the fourth criterion attempts to quantify the safety of a crosswalk. Even if pedestrians utilize crossing opportunities within an acceptable amount of time, it can be argued that the site remains inaccessible if these crossings occur in dangerous situations. Schroeder et al. (12) found that blind pedestrians make significantly more risky decisions than sighted pedestrians at unsignalized crosswalks at channelized right-turn lanes. In a study of blind pedestrians crossing at a two-lane roundabout, Ashmead et al. (5) found that the experimenter sometimes had to physically restrain the study participant from crossing to avoid a potential collision. The overall observed intervention rate of 6% was a clear indication of the risky nature of the studied two-lane roundabout crossing.

PERFORMANCE MEASURES

The accessibility criteria just stated create a framework for evaluating crossing performance at pedestrian crossings. Performance measures in line with these criteria that can be measured from field observations are defined from the time the pedestrian arrives at the crosswalk until he or she initiates crossing:

- $P(\text{Yield})$ = probability of yielding, defined as the ratio of the number of conflicting vehicles that have yielded to all vehicles encountered during the observation period while a pedestrian is waiting to cross. In some cases it may be necessary to exclude vehicles that were unable to come to a stop because they were too close to the crosswalk at the time the pedestrian arrived (11).
- $P(\text{GO}|\text{Yield})$ = probability of “Go” given a yield, defined as the ratio of yields that resulted in a pedestrian crossing, or “Go” decision, to all yields encountered during the observation period. Conceptually, this measure represents the rate of yield utilization.
- $P(\text{Crossable Gap})$ = probability of a crossable gap, defined as the ratio of the number of time-based vehicle gaps that exceeded the crossable-gap time to all gaps encountered during the trials. The crossable-gap size is calculated by dividing the crossing distance by an assumed crossing speed of 3.5 ft/s and adding a 2-s safety buffer. This definition of crossable gap is conservative and can be further calibrated.
- $P(\text{GO}|\text{Crossable Gap})$ = probability of “Go” given a crossable gap, defined as the ratio of crossable gaps that resulted in a “Go” decision to all crossable gaps encountered during the observation period. This measure represents the rate of crossable-gap utilization.
- Observed delay = time elapsed from the pedestrian arrival at the crosswalk until the crossing is initiated, in seconds.

- Delay>Min = delay beyond first opportunity, defined as the difference between the observed delay and the delay assuming the pedestrian had crossed at the first crossing opportunity (i.e., the first encountered yield or first crossable gap after arrival).
- $P(\text{Risky Crossing})$ = proportion of actual crossings that are considered risky. A risky situation may be defined in terms of pedestrian–vehicle conflicts, where a collision may have occurred barring a pedestrian or driver intervention. In field observations, a conflict may be evident by a forced yield (rapid driver deceleration), a pedestrian running across the road, or the pedestrian pulling back from an initiated crossing. In controlled field research with pedestrians who are blind, the rate of experimenter interventions is correlated with the relative safety of the crossing decision.

A TALE OF TWO ROUNDABOUTS

To illustrate the implementation of the analysis framework, the performance measures were calculated for two single-lane roundabouts studied under the NCHRP Project 3-78A (1) and the National Institutes of Health–National Eye Institute research project.

The first single-lane roundabout, at the intersection of 9th Street and Davidson Avenue in Charlotte, North Carolina (Site DAV-CLT), was studied as part of NCHRP Project 3-78A. The second single-lane roundabout, at the intersection of Pullen Road and Stinson Drive in Raleigh, North Carolina (Site PS-RAL), was evaluated during the National Institutes of Health project to test the feasibility of a system that automatically detects and reports the presence of yielding vehicles at the crosswalk. In this study, only the crossing data when the yield detection system at the PS-RAL site was deactivated were used.

Data at both roundabouts were gathered by the same observers and by applying an identical data collection protocol. In both cases, blind study participants were asked to cross the road independently while accompanied by an orientation and mobility (O&M) specialist. Participants would cross the road when they felt comfortable that it was safe. The O&M specialist would intervene if necessary to avoid potential collisions. Trials in both projects were videotaped and were reviewed and extracted by the same analysts.

SITE COMPARISON

The DAV-CLT roundabout has an inscribed diameter of approximately 140 ft (42.7 m) and an approach speed limit of 25 mph (40 km/h). It is located in a mostly residential neighborhood just northeast of uptown Charlotte. The crossing distance for each lane is 16 ft (4.9 m), corresponding to a crossing time of 4.6 s at a walking speed of 3.5 ft/s (1.1 m/s).

The PS-RAL site has a smaller inscribed diameter of 88 ft (26.8 m) and a similar approach speed limit of 25 mph (40 km/h). The roundabout is located close to the main campus of North Carolina State University and thus experiences frequent pedestrian activity from students walking to and from class. The crossing distance is 13 ft (4.0 m), indicating a theoretical crossing time of 3.7 s.

Figure 1 shows aerial views of both sites. The tested crosswalks are highlighted with a white oval. The major approaches at the two roundabouts are north–south arterial streets with a mix of commuter and local traffic. Both roundabouts further have university or city bus stops in close proximity and thus exhibit at least some heavy-vehicle activity. Although both roundabouts have sidewalks and marked pedestrian crossings, it needs to be recognized that the proximity of PS-RAL to a major university likely raises driver expectation of ongoing pedestrian activity.

In terms of traffic volumes, the major approaches to the roundabouts, namely, Davidson Avenue and Pullen Road, have an approximate average annual daily traffic (AADT) of 9,900 and 15,000 vehicles per day, respectively. Both sites have much lower volumes on the side streets. Table 1 shows the peak-hour entering volumes for both sites.

The peak-hour volumes suggest that the a.m. and p.m. peak hours at the PS-RAL site have about 50% and 90% more traffic than the DAV-CLT site, respectively. More important, the lunch peak hour at PS-RAL has 240% more traffic, mostly as a result of the generally low daytime volumes at the DAV-CLT site. A similar trend was observed during the experimental trials. Although the DAV-CLT site showed medium traffic volumes in the a.m. and p.m. peak hours, traffic during the actual experimental trials was relatively low.

The research team also took sample speed observations at both sites. The approach speeds on the entry approach lanes to the north and south crosswalks at the DAV-CLT site were 27.6 and 26.0 mph (44.4 and 41.8 km/h), respectively. Upon entry, the average vehicle speed drops to approximately 17.6 mph (28.3 km/h) because of the roundabout geometry. The average approach speed at the southern crosswalk of the PS-RAL roundabout is lower than that at DAVCLT—22.8 mph (36.7 km/h). The average entering speed to the PS-RAL roundabout is 15.6 mph (25.1 km/h). The average exiting speeds at DAV-CLT and PS-RAL are approximately 17.3 and 15.3 mph (27.8 and 24.6 km/h), respectively. The lower speeds at PS-RAL are likely attributable to the smaller inscribed diameter and associated lower design speed of the roundabout.

The data analysis at DAV-CLT included a total of 10 blind study participants. The data set for PS-RAL resulted in usable data from 12 blind participants. At both sites, a trial consisted of four lane crossings (e.g., entry-exit-exit-entry) with the starting order of lanes randomized for each subject. At DAV-CLT each subject completed three trials at the northern and three trials at the southern crosswalk, resulting in a total of 12 entry- and 12 exit-lane crossings. At the PS-RAL site each subject completed eight full trials at one crosswalk, resulting in 16 entry- and 16 exit-lane crossings.

ANALYSIS

From an assessment of vehicle operations, PS-RAL can be described as the smaller-diameter, higher-volume, and lower-speed site relative to DAV-CLT. The smaller inscribed diameter and correspondingly lower speeds at PS-RAL might suggest that the site is more accessible. Lower speeds have been linked to higher yielding rates (17) and lower injury rates in the event of a collision (19,21). However, the much lower traffic volumes at DAV-CLT suggest more frequent gap crossing opportunities and a reduced likelihood of encountering a vehicle in the crossing. Ultimately, it is difficult to rate the accessibility of either site without investigating the behavioral components of pedestrians and drivers. The proposed usability measures allow for this type of assessment.

Table 2 compares the yield probabilities for the two sites. It shows generally higher yielding rates at the PS-RAL roundabout, which may be related to the proximity to a major college campus. The PS-RAL site further suggests lower yielding at the roundabout exit leg, which is not evident at DAV-CLT. Both sites further exhibit a range of yielding percentages. For participants at PS-RAL, the yielding rate varied from 9.4% to 70% (mean 37.2%) with a smaller range evident at DAV-CLT (0% to 33.3%, mean 11.3%).

Table 2 also shows the yield utilization rates at the two sites. A lower overall yield utilization rate is evident at DAV-CLT (67.4%) than at PS-RAL (85.4%). Both sites suggest a slightly higher yield utilization rate at the exit leg. By combining yielding and yield utilization rates, it can be stated that the PS-RAL site exhibits a higher likelihood of crossing

in a yield than DAV-CLT. The range of observed yield utilization points to a difference in crossing abilities among participants, with some utilizing 100% of yields, whereas others do not utilize any.

The observed yield probabilities and yield utilization rates can be multiplied to obtain the probability that a pedestrian crosses in a yield. For DAV-CLT this average likelihood of a yield crossing is 7.6% of all observed events. For PS-RAL the corresponding probability is 31.8%, indicating that a crossing in a yield is significantly more likely at this site.

Table 3 shows the availability of crossable gaps at the two sites. Following the previous definition, the minimum crossable gaps for DAV-CLT and PS-RAL are approximately 7.0 and 6.0 s, respectively. To allow for a direct comparison across sites, the results for PS-RAL are shown for minimum gap thresholds of 6.0 as well as 7.0 s. Table 3 shows that DAV-CLT (61.5%) has a slightly higher overall rate of gaps greater than the crossable gap than PS-RAL does (51.8% for the 6-s gap). The difference in gap availability is of course greater if the threshold for “crossable” is increased to 7.0 s at PS-RAL. For both sites, the gap occurrence is comparable for entry and exit legs.

Table 3 also shows gap utilization rates for DAV-CLT of approximately 60%. At PS-RAL the gap utilization rate is higher for the exit leg than the entry leg with 63.6% and 52% utilization, respectively. When the crossable-gap definition is increased to 7.0 s, the utilization rate increases, as expected. Overall, the gap utilization rates across the two sites are comparable. Combining gap occurrence and utilization, there is a somewhat higher likelihood of crossing in a gap at DAV-CLT. The range of gap utilization again varies between 0% and 100%, emphasizing the need for a sufficient sample size given the variability of crossing behavior. In this context it is also important to point out that no utilized gaps below the defined crossable-gap threshold were observed at either site. However, for some sighted pedestrians who were included in the PS-RAL research (data not shown), gap utilization of shorter gaps was common.

Consistent with the foregoing discussion, the probability of a crossable gap’s occurring and the rate of gap utilization can be multiplied to obtain the overall likelihood of crossing in a gap. For the DAV-CLT roundabout this likelihood of a gap crossing is 38.9%. For PS-RAL, the corresponding probability is 29.9% or 27.2%, depending on whether a crossable gap is defined as 6 or 7 s. The difference between the two sites in the probability of a gap crossing is thus less than that for yield crossings.

Table 4 compares the observed delay experienced by the blind pedestrians at both sites and reveals significantly lower delays at PS-RAL. Interpreting this difference in light of the results in Tables 2 through 5, the lower delay is likely attributable to greater $P(\text{Yield})$ and greater $P(\text{GO}|\text{Yield})$ at this site. The delay at DAV-CLT correspondingly is higher because pedestrians wait for crossable gaps in the absence of yields. The delay is comparable for the entry and exit legs at both sites. The average total delay to get across both entry and exit lanes represents the sum of the two estimates.

Table 4 also shows the delay beyond the first crossing opportunity for both sites. The findings are similar to those for observed delay with pedestrians at PS-RAL experiencing less “unnecessary delay” compared with DAV-CLT. Again, the reason for the differences is likely related to $P(\text{Yield})$ and $P(\text{GO}|\text{Yield})$. When the crossable-gap threshold at PS-RAL is raised to 7.0 s, the delay over the minimum reduces slightly, because some pedestrians encountered a crossable gap earlier. The difference in delay suggests that a crossing opportunity is utilized more quickly at PS-RAL. If these sites were analyzed by using LOS definitions in the HCM, the average delay times at PS-RAL and DAV-CLT (approximately

11 and 25 s) would correspond to LOS C and D, respectively. To recall, the HCM defines levels of service on a scale from A (best) to F (worst) in terms of average delay per person.

Again, it needs to be emphasized that the delay estimates varied greatly among subjects as indicated by the ranges shown in Table 4. Also, the values in Table 4 represent the range of average delay per subject, with even greater variability in individual crossings per subject. For example, the highest observed delays for one lane crossing at PS-RAL and DAV-CLT were 127 and 180 s, respectively. Also, all delay figures are reported per lane crossed, because participants paused on the splitter island at the roundabout crossings. Consequently, the average total delay per crossing for PS-RAL and DAVCLT was 22 and 50 s, resulting in HCM LOS equivalents D and F, respectively.

Table 5 shows the rate of experimenter interventions. The intervention rates at PS-RAL are clearly higher than those at DAV-CLT, especially the exit-lane crossing, which is risky at an intervention rate of 5.8%. However, with repeated crossings, even the 1.0% intervention rate at DAV-CLT could result in a high likelihood of a risky decision over time. Ashmead et al. (5) proposed that the probability of a dangerous crossing decision is given by $1 - (1 - p_{\text{per crossing}})^n$, where $p_{\text{per crossing}}$ is the observed intervention rate and n is the number of crossing attempts. Consequently, for a pedestrian who crosses this roundabout twice a day, the probability of a dangerous decision after one month (10 crossings per week over 4 weeks) is 33.1%. At the 3.9% intervention rate for PS-RAL, this likelihood increases to 79.6%.

From a safety perspective, these estimates suggest that the PS-RAL site is riskier to cross and thus less accessible from that perspective.

DISCUSSION OF RESULTS

It was hypothesized that both site geometry and conflicting traffic volumes contribute to the accessibility of a site but that ultimately driver and pedestrian behavior may play the most crucial role in rendering a site accessible to and usable by pedestrians who are blind. With more frequent occurrence of yields and similar crossable-gap frequency, the PS-RAL site appears to be more accessible than DAV-CLT. Especially in light of similar yield and gap utilization statistics, it appears as if a crossing is more likely at PS-RAL. In fact, the delay measures suggest that travelers at PS-RAL find a crossing opportunity more quickly. The site is thus more usable from a delay perspective, although the delay times are still high when the HCM thresholds for unsignalized crossings are used.

But the question of usability is not only a function of delay; the relative risk of the crossing needs to be considered also. The rate of experimenter interventions was higher at PS-RAL, indicating lower usability from a safety perspective. It is unclear what factors contribute to the higher rate of interventions, but it is likely a combination of background noise, auditory confusion, travel skills, and ultimately higher traffic volumes. Clearly, more research is necessary to isolate any of these effects.

The analysis demonstrated that the usability framework and associated performance measures are transferable across sites. More important, the framework enables the analyst to distinguish between different performance measures and thus isolate the specific effects that contribute to the usability of a crosswalk for pedestrians who are blind.

In light of these findings, it becomes evident that the question of roundabout accessibility is complex and cannot be reduced to a simple relationship to traffic volumes. Although a low-volume site may have the appearance of being usable, a higher-volume site may result in lower delay if combined with a greater rate of yielding. The greater usability of the PS-RAL

site from a delay perspective is attributable to higher $P(\text{Yield})$ and $P(\text{GO}|\text{Yield})$ probabilities. These two factors seemed to have a significant overall impact on reduced pedestrian delay despite the fact that the site had higher volumes and consequently a lower availability of a crossable gap, $P(\text{Crossable Gap})$. Given a high propensity to yield, the greater volumes at PS-RAL thus result in more frequent crossing opportunities per unit of time. However, higher volumes also lead to more noise and an increased likelihood of a vehicle's approaching as the pedestrian steps into the crosswalk. This factor may explain the higher rate of interventions at the site. It also raises the question of what the intervention rate at DAV-CLT would have been at higher traffic volumes.

CONCLUSION

This research presented a framework for quantifying the usability of crosswalks at modern roundabouts for pedestrians who are blind. Although the tasks of locating the crosswalk, wayfinding, and crossing alignment also contribute to the overall usability of a crosswalk, the ability to make the decision to cross remains the vital task. It was argued that the crossing task at an unsignalized roundabout crosswalk can be described by four components: the availability of crossing opportunities, the utilization of these opportunities, the delay until an opportunity is utilized, and the overall risk involved in the task.

The discussion further identified several simple performance measures that are associated with these usability components. The approach implementation was illustrated at two single-lane roundabouts. The two sites differed in geometric configuration and traffic volume levels and correspondingly performed very differently. Although the higher-volume site may have seemed less usable at first glance, it became evident that the frequent utilization of yield crossing opportunities actually resulted in a low average delay to the blind study participants. However, the site also exhibited a significant amount of risky decisions, thereby reducing the overall usability. Although seemingly safer, a lower-volume site actually resulted in significant delay to the participants related to a low yielding rate and utilization of crossing opportunities. At $P(\text{Yield})$ in the range of 10% to 12% there appears to be much room for improvement, and it can be hypothesized that the accessibility of the site could be increased by increasing the likelihood that drivers will yield. It can also be hypothesized that an increase in traffic volumes likely would have decreased the overall usability because of (a) fewer gap crossing opportunities, (b) higher background noise, and (c) a potentially increased likelihood of risky decisions. An interesting follow-on study would assess the crossing ability of the same study participant across different sites, which is planned as part of NCHRP Project 3-78A in the comparison of a single-lane and a multilane roundabout.

The analysis showed that one site is more usable from a delay perspective, whereas the other is more usable because of safety. It can be argued that personal safety outweighs delay, especially if actual crossings are infrequent. At the same time, there is some limit to how much delay is acceptable even if a crossing is attempted only rarely. At some risk and delay thresholds, it is likely that a traveler will avoid using a site altogether, at which point it must be considered unusable and thus in violation of the ADA legislation.

From these limited findings, a crisp definition of accessibility for single-lane roundabouts remains elusive, and more data at varying geometries and volume levels are needed before final conclusions can be drawn. Nevertheless, the analysis showed that it is possible to quantify and contrast operational differences of various sites by using the proposed framework and measures. In future research, it will thus be beneficial to apply these measures at additional sites and fill in the blanks on the question of roundabout accessibility and the effectiveness of crossing treatments. It is hypothesized that with this successful

demonstration at two roundabout sites, the analysis framework has broader application to unsignalized pedestrian crossings, including those at midblock locations.

Although the analysis framework represents a tool to quantify crossing performance, it is recognized here that it will not be usable directly by the U.S. Access Board or engineering agencies, since it does not tie crosswalk usability to specific geometric configurations or traffic conditions. In other words, crosswalk usability is not defined in terms of metrics that are available to agencies faced with making decisions about roundabout construction or about pedestrian treatments to be installed at roundabouts. In future research, it is necessary to link crossing performance of blind travelers to actual roundabout geometries and physical treatments that can be installed by agencies to make a site more usable by this group of pedestrians. The authors see their contribution as developing a set of performance measures that can be used to quantify the effect of geometric differences and pedestrian treatments beyond anecdotal evidence. Using the developed analysis framework along with expert judgment about thresholds for the different measures, future research will be able to quantify the net effect of a treatment on crosswalk usability.

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FIGURE 1.
Aerial views of comparison roundabouts: (a) DAV-CLT, Charlotte, North Carolina, and (b) PS-RAL, Raleigh, North Carolina. (Source: www.google.com.)

TABLE 1

Peak-Hour Entering Volumes for Study Sites

	Total Peak-Hour Entering Volumes				
	North	East	South	West	Total
PS-RAL ^a					
Morning peak (7:30–8:30 a.m.)	779	3	461	36	1,279
Lunch peak (12:15–1:15 p.m.)	583	38	560	113	1,294
Afternoon peak (5:00–6:00 p.m.)	454	20	887	123	1,484
DAV-CLT ^b					
Morning peak (7:30–8:30 a.m.)	157	79	506	92	834
Lunch peak (1:00–2:00 p.m.)	198	26	272	39	535
Afternoon peak (5:00–6:00 p.m.)	364	70	277	76	787

^aSeptember 2007.^bNovember 2007.

TABLE 2
Comparison of Yield Availability and Utilization

	Avg. (%)	Min. (%)	Max. (%)	SD (%)
<i>P</i> (Yield)				
DAV-CLT				
Entry	10.8	0.0	21.3	8.9
Exit	11.8	0.0	33.3	7.9
Overall	11.3	0.0	33.3	8.3
PS-RAL				
Entry	41.5	13.9	66.7	18.2
Exit	32.8	9.4	70.0	17.9
Overall	37.2	9.4	70.0	18.2
<i>P</i> (GO Yield)				
DAV-CLT				
Entry	64.1	0.0	100.0	41.2
Exit	70.4	0.0	100.0	44.1
Overall	67.4	0.0	100.0	42.3
PS-RAL				
Entry	83.0	50.0	100.0	20.4
Exit	87.8	60.0	100.0	14.1
Overall	85.4	50.0	100.0	17.3

TABLE 3
Comparison of Gap Availability and Utilization

	Avg. (%)	Min. (%)	Max. (%)	SD (%)
<i>P</i> (Crossable Gap)				
DAV-CLT				
Entry	62.1	38.5	85.7	14.2
Exit	60.9	28.6	83.3	12.9
Overall	61.5	28.6	85.7	13.4
PS-RAL (min = 6 s)				
Entry	53.5	16.7	100.0	28.1
Exit	50.2	17.0	100.0	23.5
Overall	51.8	16.7	100.0	25.4
PS-RAL (min = 7 s)				
Entry	40.9	0.0	100.0	29.0
Exit	40.8	0.0	100.0	26.5
Overall	40.8	0.0	100.0	27.2
<i>P</i> (GO Crossable Gap)				
DAV-CLT				
Entry	66.3	25.0	100.0	20.6
Exit	60.3	33.3	100.0	17.9
Overall	63.3	25.0	100.0	19.3
PS-RAL (min = 6 s)				
Entry	52.0	0.0	100.0	41.3
Exit	63.6	18.8	100.0	26.6
Overall	57.8	0.0	100.0	34.4
PS-RAL (min = 7 s)				
Entry	60.3	0.0	100.0	37.6
Exit	72.4	25.0	100.0	28.5
Overall	66.6	0.0	100.0	26.1

TABLE 4
Comparison of Observed Delay

	Avg. (%)	Min. (%)	Max. (%)	SD (%)
Observed Delay per Leg (s)				
DAV-CLT				
Entry	26.6	11.2	74.0	17.0
Exit	24.0	11.4	41.8	9.7
Overall	25.3	11.2	74.0	13.8
PS-RAL				
Entry	10.5	4.1	34.2	8.9
Exit	11.6	5.2	26.7	6.8
Overall	11.1	4.1	34.2	7.8
Delay > Min (s)				
DAV-CLT				
Entry	18.8	4.8	59.4	15.5
Exit	17.2	5.2	35.1	9.6
Overall	18.0	4.8	59.4	12.8
PS-RAL (min = 6 s)				
Entry	5.6	0.8	24.7	7.2
Exit	6.1	0.8	19.4	5.8
Overall	5.8	0.8	24.7	6.4
PS-RAL (min = 7 s)				
Entry	5.2	0.8	23.0	6.7
Exit	5.7	0.8	19.1	5.7
Overall	5.5	0.8	23.0	6.1

TABLE 5
Experimenter Interventions: $P(\text{Risky Crossing})$

Roundabout Site	Avg. (%)
DAV-CLT	
Entry	1.0
Exit	1.0
Overall	1.0
PS-RAL	
Entry	2.1
Exit	5.8
Overall	3.9