DRAFT FINAL REPORT

Pedestrian Safety Enhancements on Hillsborough Street Roundabout Corridor

A study sponsored by the Southeastern Transportation Center

by

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August 18, 2008
Raleigh, NC
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Abstract

This research explores pedestrian behavior and the interaction between motorized and non-motorized modes along an urban arterial corridor separating a major university campus from an urban business district. The analysis focuses on behavior at signalized crossings along the corridor and investigates mid-block jaywalking trends. The study goal is to provide guidance on an improved representation of pedestrian behavior in a microsimulation environment for the observed context and similar applications.

The research was funded by the Southeastern Transportation Center (STC) through a matching grant for an existing project. In that original scope, the authors were working with Kimley-Horn and Associates to develop a microscopic simulation model of a proposed urban corridor re-design project next to the campus of North Carolina State University. The "Hillsborough Street Project" features a narrowed roadway cross-section, extensive modifications to the streetscape, and the creation of two modern roundabouts with expected construction start in the fall of 2008. The project utilized microsimulation to model traffic operations along the corridor before and after construction. This research supplements the original project scope with a detailed study of pedestrian crossing behavior to and from the university. Conceptually, this research represents a "before" study of pedestrian behavior and the authors hope to perform a follow-up study once the project is completed.

The analysis shows evidence of frequent pedestrian non-compliance, both in terms of utilization of the crosswalks and the WALK phase at signalized crossings. In particular, 16% of pedestrians were observed to cross informally at midblock segments in-between traffic signals. Non-compliance at both signals and midblock locations were further related to signal phase indications and expected wait times of pedestrians. The analysis showed that only 30% of pedestrians, who cross at a signalized intersection wait for the WALK indication, with the remainder crossing in gaps in traffic. The arrival distribution of pedestrians were found to be concentrated during lunchtime and class changes with correspondingly lower volumes while class is in session.

The results are significant in light of operational analyses of these types of urban corridors, especially with respect to modern microsimulation analysis tools that require assumptions about pedestrian behavior and its relation to traffic control and vehicle interaction. The analysis suggests that behavioral models for pedestrians need to account for jay-walking behavior and non-compliance and that both path choices and arrival distributions need to be linked to local conditions. It is expected that the reduced crossing width after completion of the corridor re-design project will lead to a further increase of non-compliance.

A summary of the results from this study has been submitted for consideration for presentation and publication at the 88th Annual Meeting of the Transportation Research Board.
Introduction

University campuses are noted for a high level of pedestrian activity. In many cases, universities in urban settings have a strong impact on the local economy as faculty, students and staff seek out local coffee places, restaurants, and office supply stores. Given the magnitude of pedestrian activity, the interaction with motorized traffic is distinctive, as vehicular predominance on the abutting roadway system is challenged. While pedestrian activity in many suburban environments is scarce, roadways in proximity to universities see frequent pedestrian crossings at both signals and mid-block locations. In the analysis of vehicle operations it is important to understand the nature of pedestrian activity and link pedestrian volumes to path choices and behavioral patterns. This is especially important in light of new analysis options made possible by modern microsimulation models where pedestrian behavioral patterns should be accurately reflected.

Microsimulation offers a modern approach for operational analysis of unique geometric configurations and assessment of system-wide impacts of traffic. These tools have been enhanced significantly over the past decade, moving from simple car-following algorithms to sophisticated models that incorporate multiple facility and vehicle types in a multimodal context. With respect to the analysis of pedestrian-vehicle interaction, these tools conceptually allow the analyst to account for different behavioral patterns of pedestrians and drivers. The challenge for this type of detailed analysis is calibrating the behavioral algorithms to reflect actual behavioral conditions observed in the field.

The interaction of pedestrians and vehicles can be governed through the use of traffic signals or can occur at unsignalized locations, based on driver yielding and pedestrian gap acceptance processes. In the evaluation of an urban corridor, it is further expected that a significant number of pedestrians will chose to cross informally at midblock locations if the conflicting traffic stream allows for gap crossings. Especially in a university environment, the expected frequency of these jay-walking events is high, as is the expected rate of pedestrian non-compliance at signalized crossings. All these features play into a microscopic evaluation of a pedestrian-oriented urban corridor, as path choices and behavioral patterns dictate where and when pedestrians interact with vehicular traffic.

This research was funded by the Southeastern Transportation Center (STC) with the objective of supplementing an existing microsimulation effort for the proposed Hillsborough Street roundabout corridor in Raleigh, NC. The project team collaborated with Kimley-Horn and Associates to develop calibrated microsimulation models of a proposed urban roundabout corridor project. While the initial project focused on the vehicle element along the corridor, the emphasis of this research was to collect supplementary pedestrian safety data that can be used to improve the pedestrian element in a microsimulation representation of this and similar corridors.

In particular, this research explores pedestrian behavior and the interaction of motorized and non-motorized modes along an urban arterial corridor separating a major university campus from an urban business district. The objective is to capture information on signal compliance and jay-walking behavior
(also known as "informal crossing") as a function of signal phases and the pedestrians' activity schedule. The latter is expected to increase during class changes, and it is hypothesized that the rate of non-compliance will rise accordingly. This research is especially important in the context of simulating the operations along this and similar corridors. The findings are also important in a policy context, when deciding on the placement of pedestrian crossing locations and identifying other pedestrian-related traffic control strategies.

**Study Context**

Before presenting the findings of this research, it is necessary to establish a local context, as it pertains directly to the research hypothesis and motivation. North Carolina State University in Raleigh, NC has a total student population in excess of 31,000, in addition to approximately 8,000 faculty and staff (NCSU, 2008). The university main campus is separated from an urban business district by Hillsborough Street, an urban arterial corridor with a 2005 average annual daily traffic (AADT) of 22,000. The Hillsborough Street corridor is significant in this context, because a series of pedestrian collisions in the 1990s have resulted in a public outcry for improved pedestrian safety and spawned a series of stakeholder workshops. These charettes ultimately resulted in an urban re-design plan termed the *Hillsborough Street Project*, featuring a modified streetscape and a road diet reconfiguration of vehicle traffic into an urban roundabout corridor. Since that time the project has gone through a series of revisions and eventually passed city council approval in the Fall of 2006. With construction scheduled to start in late 2008, this research represents an in-depth look at the “before” condition, capturing pedestrian behavior and compliance to traffic signals and mid-block jay-walking. While the authors eventually plan to perform a similar “after” study of the corridor, the findings of this initial research serve to illustrate important behavioral characteristics of the pedestrian population that have implications for other urban corridors as well.

Figure 1-a shows an aerial view of the Hillsborough Street corridor with overlaid street view. The NCSU campus is just south of the street and a variety of businesses are on the northern side. Figure 1-b shows a schematic drawing of the existing Hillsborough Street corridor and the project scope for the re-design project. The proposed road diet and intersection reconfiguration is shown in Figure 1-c, adopted from design drawings posted on the project website (www.hillsboroughstreet.org). The main features of the project include a lane reduction from four to two lanes, the creation of a landscaped median, the conversion of two intersections to roundabouts, and simplified two and three-phase signals along the rest of the corridor. The figure shows a total of 11 signalized pedestrian crosswalks in the existing condition, one of which will be converted to unsignalized control. Other planned aesthetic enhancements including wider sidewalks, underground utility lines and street furniture are not reflected in the drawings.
a) Aerial and Road View of Corridor (Source: www.google.com)

b) Schematic of "BEFORE" or Current Condition

c) Schematic of Planned "AFTER" Condition

Figure 1: Overview of Project Scope
Literature Review

It is generally understood in the study of pedestrian behavior that not everyone complies with traffic laws. While drivers are directly accountable for following the rules of the road, the enforcement of pedestrian non-compliance with traffic rules is rarely emphasized. Yagli (2000) found pedestrian compliance to be dependent on several internal influences, including the perception of their own safety, which was found to be higher in males than females. The author further found that arriving pedestrians were more likely to check for traffic as part of a smaller group, and were more likely to wait if encountering a group of pedestrians already waiting at the crosswalk.

In a meta-analysis of previous research on pedestrian compliance, Ishaque and Noland (2007) found a number of factors influencing the crossing behavior of pedestrians, including the crossing speed, gap acceptance and signal compliance with relation to age and gender. In 2001, Tarawneh found that pedestrian walking speed in Jordan varies by age, gender, distance and group size and further increases with wait time. The author concluded a suggested walking speed of 1.11 m/s (3.6 ft/s) with males walking faster than women, groups of three or more walking slower than smaller groups and the age group of 21-30 being the fastest walkers of them all. In the conclusion of a recent US study, Fitzpatrick et al. (2007) recommend a walking speed of 3.5 ft/s (1.07 m/s) for signal timing applications, to replace the current standard of 4 ft/s (1.22 m/s) in the Federal Highway Administration (FHWA) Manual on Uniform Traffic Control Devices (MUTCD, FHWA 2003).

Similar to their impact on walking speed, factors such as age, gender, and wait time were shown to have an impact on the compliance of pedestrians, as well as, the willingness of pedestrians to accept risk. Tiwari et al. (2006) studied pedestrian risk exposure at signalized intersections in India and found that when pedestrians experience delay exceeding thirty seconds, they are more likely to cross and accept risk by crossing against the signal. This is consistent with language in the US Highway Capacity Manual (HCM, TRB 2000) acknowledging an increased likelihood of pedestrian risk taking at worse levels of service. In these circumstances, the pedestrian decision is a result of gap acceptance thresholds, where pedestrians screen gaps in vehicular traffic, much like they would at an unsignalized intersection or roundabout crossing.

In the context of microsimulation, this varying behavior is significant, because three different algorithms are required to fully capture pedestrian behavior: signal timing, signal compliance, and gap acceptance. Regarding the latter, Yang et al. (2006) derived a pedestrian gap acceptance formulation for the critical gap (CG) of pedestrians from observations in China, \( CG = L/S + F \), where \( L \) is the length of the crossing, \( S \) is the walking speed and \( F \) is a factor of safety based on the pedestrian’s confidence. Similar assumptions for pedestrian gap acceptance were used by Rouphail et al. (2005) and Schroeder et al. (2006) in the analysis of unsignalized pedestrian crossings at roundabouts and channelized right turn lanes, respectively. To better describe the process of pedestrian gap acceptance, Schroeder (2008)
developed logistic regression-based gap acceptance models for unsignalized crossings incorporating vehicle dynamics, pedestrian characteristics and concurrent events at the crosswalk. The author further developed event-based describing the likelihood of drivers yielding to pedestrians at unsignalized crossings.

Sisiopiku and Akin (2003) also studied factors that contribute to pedestrian compliance. The authors found that the most important factor for utilizing a crossing was if it was positioned between the point of their origin and their destination. This makes evident that path choices and the strategic location of pedestrian crossings is a key factor in promoting compliance, which is recognized by guidebooks in the pedestrian safety field (Harkey and Zegeer, 2004).

The issue of signal compliance is not reflected in the pedestrian delay estimation procedures found in the Highway Capacity Manual (HCM, TRB 2000). Pedestrian delay at a signalized intersection is a function of signal timing parameters only, implicitly assuming perfect pedestrian compliance with the signal phase. For unsignalized crossings, the manual offers a methodology for estimating delay based on gap acceptance characteristics that could feasibly be applied to non-compliant pedestrians at signals. Guo et al. (2004) created a delay model for non-compliant pedestrians at signalized crossings taking into account the effect of traffic platooning resulting from upstream signals. The authors found an increase in delay for pedestrians who would otherwise cross against the light, while having little effect on compliant pedestrians.

One challenge for the evaluation of pedestrian facilities is a lack of understanding of what constitutes lawful behavior. Hatfield et al. (2006) studied pedestrian and driver understanding of right of way rules in Australia. In an experiment involving surveys of pedestrians and drivers downstream of a crossing, it was found that in many cases both groups felt that they had the right-of-way. In the US, there is documented ambiguity about the yielding laws for drivers at a pedestrian crossing (Herbert Martinez and Porter, 2004); on the pedestrian side, it is recognized that there is often no clear understanding of the legal meaning of the ‘Flashing Don’t Walk’ phase.

The described characteristics of pedestrians and their interaction with vehicular traffic have implications for implementation in microsimulation. These models represent vehicles (and in many cases now pedestrians) as individual entities that travel through a road network following certain rules. These behavioral algorithms are used among others to represent car-following, lane-changing, or gap acceptance behavior and need to be calibrated to accurately reflect real conditions in the field. The need to improve the representation of pedestrians in microsimulation is recognized by the FHWA "Next Generation Microsimulation" effort (NGSIM) and ranks 7th in the top 10 list of model stakeholder needs (FHWA, 2004-1). NGSIM further identifies a range of simulation models that model pedestrian-vehicle interaction at varying levels of detail: SimTraffic, VISSIM, MUTSIM, PARAMICS, and AIMSUN (FHWA, 2004-2). An ongoing National Cooperative Highway Research Program effort, NCHRP 3-78a (TRB, 2008) has selected VISSIM (PTV, 2008) from the aforementioned list of models because of its flexibility in modeling different geometries, multiple vehicle and pedestrian types, and its integration of signalized
and unsignalized control. The authors previously published on the use of VISSIM to represent unsignalized (Schroeder and Roupail, 2007) and signalized pedestrian crossings (Schroeder et al., 2008) and have thus selected to use VISSIM in this project.

Methodology

The objective of this research is to understand and document pedestrian behavior in the "before" condition, i.e. prior to the onset of construction on the Hillsborough Street Project. In particular, this research reviews 2006 pedestrian counts performed by the project consultant, Kimley-Horn and Associates, and distinguishes between signal and midblock crossings. The pedestrian counts are supplemented by in-depth analysis at a typical signalized crossing and a typical mid-block section along the corridor (both highlighted in Figure 1-b). The signalized crossing analysis was performed at the western crosswalk at the intersection of Hillsborough Street and Horne Street (crossing #4); the midblock analysis focused on the section between the midblock signal west of Chamberlain Street and the intersection of Hillsborough Street and Logan Court (Segment D). Both study segments are associated with heavy pedestrian traffic between the university and the business district directly across the street.

For the signalized intersection analysis, video recordings were collected during typical weekdays in the Spring of 2008 while school was in session. The 90-minute video sessions were timed to include at least one class change to capture the associated surges in pedestrian activity. The video observations were conducted with a synchronized two-camera set-up, where one camera was zoomed into the vehicle signal phase indication. The two videos were later converted to a picture-in-picture view on one DVD. The analysis included a total of eight 90-minute sessions, one of which had to be excluded because of video malfunction. The midblock section videos were recorded in a similar fashion and all eight observation periods were used in the analysis. For both segments, the video sessions were recorded on different days of the week and included morning and afternoon observations. Figure 2 shows screenshots of the picture-in-picture views for the signalized intersection analysis.
The four pictures in Figure 2 show a group of pedestrians arriving during the vehicular green phase, who decide to cross in a gap in traffic before the WALK phase commences. The light then changes to yellow before while the pedestrians are in the street, indicating that the crossing occurred at the end of vehicular green. The time stamp at the bottom can be used for temporal analysis. While the signal indication for the pedestrian phase is not visible in the picture, the onsets of WALK, Flashing Don't Walk, and Don't Walk indications can be calculated using fixed phase lengths in the timing plan.

The resulting video DVDs were analyzed with a MSExcel/VisualBasic time stamp macro to capture important events (signal changes, pedestrian and vehicle arrivals, and point of origin). All pedestrian events were ultimately compiled in a master spreadsheet for analysis using the SAS statistical analysis software (SAS Institute, 1999).
Study Hypothesis

It is hypothesized that many (if not most) pedestrians do not cross at the intended signalized pedestrian crossings, but rather cross at more 'direct' routes across mid-block sections. It is expected that pedestrian travel is highly sensitive to origins and destinations (i.e. from class to lunch) and that this contributes to jay-walking behavior. It is further hypothesized that even pedestrians who decide to cross at the signals will frequently do so against the signal WALK indication, provided adequate crossing gaps exist in vehicular traffic. Finally, it is expected that some waiting pedestrians cross during additional perceived crossing opportunities created by times in the signal cycle where main-line traffic is stopped (yellow, all-red, side-street phase). In general, it is expected that any non-compliant behavior will increase as a function of pedestrian delay, urgency (class change, lunch), the anticipated wait time to the next WALK phase (i.e. for pedestrians arriving as the light turns green for vehicles), and the availability of crossable gaps on the conflicting vehicle approach.

Analysis of Results

The analysis of pedestrian behavior has three main components: First, a six-hour pedestrian volume count conducted by Kimley-Horn and Associates is evaluated to get a general feel for the distribution of pedestrian flows along the corridor and over time. Second, a detailed look at a typical midblock section aims to quantify jay-walking behavior in-between signalized intersection crosswalks. In the third component, an analysis of a representative signalized crossing investigates pedestrian compliance to signal phases. Finally, the discussion will present some prior research findings by the authors in relation to a single-lane roundabout crossings in close vicinity to the studied corridor.

Midblock Crossing Behavior

The first analysis component focused on pedestrian crossing behavior along mid-block segments between the signalized pedestrian crossings along the corridor. The midblock data has two components: A general pedestrian volume count conducted by the project consultant, and an in-depth evaluation of crossing patterns on one typical midblock segment (segment D).

Figure 3 plots hourly pedestrian volumes along Hillsborough Street between Gardner Street and Fendell Lane collected from 7:30am until 1:30pm in September 2006. The graph is labeled 1 through 10 for the signalized crosswalks, and A through G for the mid-block sections. Figure 3-a shows pedestrian flows in the northbound direction, leaving campus and walking towards the business district along Hillsborough Street. Temporally, pedestrian flows are expectedly highest around lunchtime (11:30am). Spatially, the two crossings at the intersection with Horne Street and at the midblock signal east of Chamberlain Street, where the bulk of lunch options are available, exhibited the highest flows. Figure 3-b shows that these pedestrians return to campus in the next hour, presumably after having finished their lunch.
Figure 3: Pedestrian Count Distribution in Six-Hour Period
In addition to the volume distribution, it is significant to note that the majority of pedestrians indeed cross at the intended signalized crosswalks, with lower volumes along the lettered midblock sections. Overall, 7859 pedestrians were observed to cross within the studied facility over the six-hour period, with 1100 of those crossing at mid-block locations in-between signals (16.3%). The highest midblock flow is evident in segment B, between the intersections of Pogue Street and Horne Street. This may be explained by the length of this segment compared to other ones (see Figure 1-a). With increased segment length, the origins and destinations of pedestrians are more likely to be located in the middle of the segment, thus resulting in longer detours if a signalized crossing were to be used. The high usage of the signalized crossing east of Chamberlain Street underlines the strategic location of this midblock signal, creating an additional safe crossing opportunity midway along the long segment between Horne Street and Logan Court.

Despite the fact that most pedestrians cross at the signals, the volume survey makes it evident that a significant percentage of pedestrians (one out of six) still crosses between signals. This study took a closer look at segment D, between Chamberlain Street and Logan Court. The analysis included a total of eight 90-minute video recording sessions, which were timed to include at least one major class change at the university. Overall, 944 jaywalking events were observed along the segment over 733 minutes of analysis. This corresponds to an average rate of 1.29 jaywalking events per minute. It is hypothesized that the rate of jaywalking is higher during phases of higher pedestrian activity given by class breaks. Figure 4 shows the distribution of one-minute flows of midblock jay-walking events for the eight day and time periods and the total for all pedestrians.

![Jaywalking Rates in Segment D by Period of Occurrence](chart.png)

* 1 = During Class Break, 0 = While Classes are in Session

*Figure 4: Midblock Jaywalking One-Minute Flow Rates*
It is evident from Figure 4 that the jay-walking flow rates are consistently higher during class breaks and that the non-break flow rate is fairly constant at about one event per minute. During class changes, the jaywalking rate increases to almost five events per minute, depending on the observation period. The highest jay-walking events are evident during short 15-minute breaks in Discs 2 and 4, which represent lunchtime flows on Tuesday and Thursday.

From an operational (and simulation) perspective, the midblock jaywalking events can be viewed as accepted gaps by pedestrians in vehicular traffic. Pedestrians arriving at the curbside were observed to screen the conflicting traffic for crossing opportunities. Some pedestrians would actually walk along the sidewalk (towards a signal) and would cross whenever a gap presented itself. In the observational analysis, it was difficult to distinguish these pedestrians from those who were deliberately walking to the signal and those that were merely walking along the sidewalk. The analysis only evaluated accepted gaps when the pedestrian stepped off the curb, because gap rejections could not be identified unambiguously. While a typical critical gap analysis (ITE, 1994) is not possible without monitoring both accepted and rejected gaps, the distribution of gaps still gives some insight onto the relative risk associated with these jaywalking events. Figure 5 shows the distribution of accepted gaps for all events.

The figure distinguishes between near-side gaps (first vehicle arrival was in the two-lane closest to the pedestrian) and far-side gap (first vehicle in the two far lanes relative to the pedestrian). At a theoretical crossing speed of 3.5 feet per second (1.07 m/s), the time to cross the 48-foot (14.6 meters) road is...
estimated at 13.7 seconds. Relative to this theoretical crossing time, Figure 4 confirms that most pedestrians crossed in fairly large gaps. In fact, many of the gaps in excess of 40-50 seconds may have been at times where vehicles were stopped at one of the adjacent signals, thus creating safe (yet illegal) crossing opportunities at the midblock.

Figure 6 evaluates the midblock crossings in terms of the signal phase at the adjacent signal at Chamberlain Street. The phasing terminology in the figure uses vehicular green, yellow, and all-red phases (AR1), followed by pedestrian WALK and Flashing Don’t Walk (FDW) phases. The time between the end of FDW and the next vehicular green is termed AR2. From Figure 6 it is evident that some pedestrian cross in gaps during the vehicle green phase while traffic is free-flowing. However, a significant percentage cross during the WALK phase or when traffic is stopped. The analysis of the pedestrian signal at Chamberlain Street indicated that approximately 34.2 percent of pedestrian phases were skipped due to a lack of signal actuation. Theoretically, the pedestrian phase and associated clearance phases take up 25% of the 100-second cycle. Taking into account skipped pedestrian phases, the vehicle green time was present 83.5% of the time ((100 seconds * 34% + 75 seconds * 66%)/100 seconds) and yet only about 35% of crossings occurred then. This confirms that the midblock jay-walk behavior is impacted by adjacent signalized intersections as pedestrians seize crossing opportunities while vehicle traffic at nearby signals is stopped.
Segment D Crossings from North (445 Events)

Break = 1
Break = 0

Segment D Crossings from South (499 Events)

Break = 1
Break = 0

Figure 6: Midblock Jay-Walking Events by Signal Indication at Nearest Signalized Crossing
Behavior at Signalized Crossings

The second component of the behavioral analysis focused on one typical signalized pedestrian crossing. The discussion above indicated that the crosswalks at the intersection at Horne Street exhibited the highest pedestrian volumes. The western crosswalk (#4 in Figure 1) was selected for the analysis. Similar to the midblock analysis, data were extracted from video observations of the crossing. Special emphasis was given to the specific signal phase present at the time the pedestrians arrived at the crosswalk and the phase in which they crossed. The same phasing terminology is introduced as was used for the midblock analysis, with a typical cycle including 1) main street green, 2) main street yellow, 3) an all-red phase (AR1), 4) pedestrian WALK, 5) pedestrian flashing don’t walk (FDW), and finally 6) a red phase until the start of the next vehicular green (AR2). The daytime non-peak cycle length at the signal is 95 seconds, with phases yellow, AR1, Walk, and FDW fixed at 4.0, 2.0, 5.0 and 13.0 seconds, respectively. In the actuated-coordinated signal system, phase times for vehicle green and AR2 vary as a function of traffic demand, but field measurements indicated average times of 64.0 and 7.0 seconds, respectively. Table 1 shows the distribution of 1267 pedestrian crossing events by arrival and crossing phase.

<table>
<thead>
<tr>
<th>Arrival Phase</th>
<th>1_Green</th>
<th>2_Yellow</th>
<th>3_AR1</th>
<th>4_Walk</th>
<th>5_FDW</th>
<th>6_AR2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_Green</td>
<td>315</td>
<td>128</td>
<td>86</td>
<td>229</td>
<td>21</td>
<td>7</td>
<td>786</td>
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<td></td>
<td>24.9%</td>
<td>10.1%</td>
<td>6.8%</td>
<td>18.1%</td>
<td>1.7%</td>
<td>0.6%</td>
<td>62.0%</td>
</tr>
<tr>
<td>2_Yellow</td>
<td>0</td>
<td>29</td>
<td>19</td>
<td>20</td>
<td>1</td>
<td>0</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>0.0%</td>
<td>2.3%</td>
<td>1.5%</td>
<td>1.6%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>5.4%</td>
</tr>
<tr>
<td>3_AR1</td>
<td>0</td>
<td>4</td>
<td>18</td>
<td>14</td>
<td>5</td>
<td>0</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>0.0%</td>
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<td>0.4%</td>
<td>0.0%</td>
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</tr>
<tr>
<td>4_Walk</td>
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<td>0</td>
<td>0</td>
<td>106</td>
<td>31</td>
<td>1</td>
<td>138</td>
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<td>10.9%</td>
</tr>
<tr>
<td>5_FDW</td>
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<td>1</td>
<td>1</td>
<td>3</td>
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<td>6</td>
<td>173</td>
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</tr>
<tr>
<td>6_AR2</td>
<td>11</td>
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<td>60</td>
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<tr>
<td></td>
<td>0.9%</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.7%</td>
<td>0.0%</td>
<td>2.8%</td>
<td>4.7%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>329</td>
<td>166</td>
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<td></td>
<td>26.0%</td>
<td>13.1%</td>
<td>9.8%</td>
<td>30.1%</td>
<td>17.1%</td>
<td>3.9%</td>
<td>100.0%</td>
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</table>

The table indicates that most pedestrians (786, 62.0%) arrive during the vehicle green phase, the longest phase in the cycle \((g/C = 0.67)\), and that arrival volumes decrease proportionally to the relative phase duration in the remaining phases. The distributions of events by crossing phase suggest that only about 30% of crossings occur during the intended WALK phase, and that most pedestrian crossings are illegal. Figure 7 plots the crossing phase separately for each arrival phase.
Figure 7: Pedestrian Crossing Phase Frequency by Arrival Phase

For arrivals in main street green, yellow and all-red, a consistent 30% of pedestrians appear to wait for the WALK phase, with the remaining pedestrians crossing earlier. Figure 7-d expectedly shows that all pedestrians who arrive in the WALK phase cross immediately, although some are registered as crossing in the FDW if they arrived at the very end of the WALK phase. More importantly, Figure 6-e shows that 92% of pedestrians who arrive in the FDW phase cross immediately, presumably because vehicle traffic remains stopped and because they additionally can expect long delays, where they must wait for the next WALK phase. Finally, for pedestrians arriving in the AR2, about 56.7% cross immediately. Only 16.7% wait for the next WALK phase, with the remaining 26.6% crossing in vehicle green and yellow,
when an opportunity presents itself. Overall, Figure 6 demonstrates that the mode for each distribution is the arrival phase, indicating that pedestrians are most likely to cross in the same phase they arrive in.

The patterns of noncompliance in the different signal phases are intuitively a result of long anticipated wait times to the next legal crossing opportunity. Figures 8-a and 8-b show the average wait time by pedestrian arrival and crossing phase, respectively.

![Graphs showing pedestrian waiting time and arrival frequency by arrival and crossing phases.](image-url)
The figures show superimposed estimates of wait time (blue bars) and observation frequency (red bars), with error bars at one standard error for the mean delay estimates. The average delay for all 1267 pedestrians is 19.5 seconds. However, the delay for arrivals in the vehicle green phase is higher. Delay times are highest for arrivals in green and AR2, with the latter exhibiting large variability, as some pedestrians cross immediately while others wait for the next WALK phase.

By examining the delay distribution by crossing phase, it is evident that pedestrians crossing in the vehicular yellow and AR1 experienced the greatest delay, which is probably the reason why they decide to cross rather than waiting a few extra seconds for the WALK phase. While the relative frequency of these crossings is low, they are also hazardous because they occur in phases where there is a strong likelihood of vehicles still passing through the crosswalk. An impatient pedestrian crossing in yellow or AR1 may be less observant of traffic conditions, causing potential conflicts with late yellow and red-light running vehicles.

These data suggest that the rate of pedestrian compliance with the signal indication is a function of the pedestrian arrival phase. Figure 9 offers a graphical representation of the rate of compliant pedestrians using three different definitions of compliance: 1) the lawful definition restricted only to the WALK phase, 2) the WALK and FDW phase, recognizing that pedestrians probably still have sufficient time to cross, and 3) the additional inclusion of AR1, assuming that vehicles are already stopped. Again, this third definition is controversial as it also represents the phase where red-light running is most likely to occur.
The graph confirms the above hypotheses, as compliance is generally greatest for those pedestrians that expect to cross within a reasonable amount of time. For arrivals in vehicle green and especially in AR2, the compliance rate is reduced significantly.

Similar to the midblock section method, the signal analysis paid special attention to pedestrian behavior during class breaks. Figure 10 shows the average one-minute pedestrian flow rates categorized by whether or not class was in session.

![Figure 10: Intersection Pedestrian Flow and Compliance by Class Break Status](image)

The figure further reports compliant and non-compliant crossings separately, using the legal definition of compliance that only includes the WALK phase. The figure shows that the pedestrian flow rate is significantly higher during class breaks (about 2.7 pedestrians per minute) than while class is in session (1.7 peds/minute). Interestingly, the average share of compliant behavior stays constant at approximately 30% in both.

For those pedestrians crossing outside of the WALK indication, the crossing decision is presumably based on the arrival time of the next vehicle. Crossings in the vehicle yellow, AR1, FDW, and AR2 phases occur during times when mainline traffic is stopped, thus creating relatively safe crossing opportunities. A pedestrian crossing in vehicle green is a gap acceptance task. Figure 11 shows the distribution of near and far gaps, consistent with the terminology introduced in the midblock discussion.
Distribution of Accepted Gaps at Signalized Crossing

Theoretical Crossing Time is 13.7 seconds at walking speed of 3.5 ft/s (1.07 m/s)

Figure 11: Pedestrian Gap Acceptance Distribution at Signals during Vehicle Green Phase

For near gaps, the crossing distance for the first two lanes is 24’ (7.3m) and gaps in excess of 6.9 seconds can therefore be considered safe. Again a significant portion of gaps are in excess of 60 seconds, suggesting that these vehicles had to stop at a red light before actually proceeding through the crosswalk. The distribution of far gaps tells a similar story with the majority of crossings occurring during times where pedestrians had sufficient time to the next vehicle arrival.

Behavior at Roundabout Crossings
This section is based on prior research by the authors, but is presented here because it is addresses pedestrian-vehicle interaction at unsignalized roundabout crossings and thus pertains to the proposed re-design of the corridor. The studied single-lane roundabout site is located at the intersection of Pullen Road and Stinson Drive, which is just south of the proposed two-lane roundabout. Conceptually, the re-design project will create a three-roundabout corridor along the north-south minor arterial street, Pullen Road. For more detail, the reader is referred to the author’s doctoral dissertation (Schroeder, 2008) available through North Carolina State University.

Previous research at an existing single-lane roundabout in the vicinity of this project has provided insight in the pedestrian operations at an unsignalized roundabout crossing. While there are expected differences in the operations of single and multi-lane roundabouts, this analysis points to some of the
concerns in representing the interaction microscopically. More specifically, Schroeder (2008) found that only about 40.0% of drivers yield to pedestrians, which is generally within the wide range of yielding rates observed at unsignalized crossings nationally (Fitzpatrick et al., 2006-2 and Rodegerdts et al., 2007). In a logistic regression approach, the author found that drivers are less likely to yield at the roundabout exit lane and at higher speeds. In a coupled analysis of pedestrian gap acceptance, the author found a critical gap of about 3.6 seconds for the single-lane crossing between curb and splitter island. Through the logit approach, the likelihood of a pedestrian crossing was described as a function of the gap time between vehicles, the pedestrian waiting time, whether vehicles were traveling in platoons and whether or not pedestrians exhibited assertive behavior (brisk walking speed) during their approach to the crosswalk.

The roundabout results emphasize the importance of modeling both driver yielding and pedestrian gap acceptance in a microsimulation representation of roundabout crosswalks. As yielding behavior increases, the associated delay to drivers is expected to increase while pedestrian delay is decreased. This relationship was previously demonstrated by Schroeder and Rouphail (2006). Similarly, a decrease in the pedestrian critical gap will decrease pedestrian delay, and presumably driver delay as well (because a pedestrian is less likely to require a yield to cross).

**Implications for Microsimulation**

The findings of above analysis have important implications for the microscopic representation of the Hillsborough Street Corridor project. In the authors’ original involvement in the project, the proposed re-design was modeled in the microsimulation tool VISSIM (PTV, 2008), because of the unique combination of a signalized arterial and two roundabouts. Figure 12 shows screenshots of the simulation file.
The screenshots in figure 12 show the VISSIM network of the Hillsborough Street corridor as currently proposed. The top figure shows the corridor looking west with the two new roundabouts in the front of the view. The bottom left figure shows the re-designed segment adjacent to the university including the crossings studied in this research. The figure on the bottom right shows a close-up of the studied crosswalk at the intersection of Hillsborough Street and Horne Street.

While traditional analysis methodologies in the Highway Capacity Manual (HCM, TRB 2000) can evaluate the different intersections in isolation, the HCM options are limited in application to corridors or combinations of intersection types. Modern Simulation tools model vehicles moving through the network and therefore account for the interaction of different nodes.
Additionally, microsimulation models bring the flexibility of simulating the effects of different modes operating on the corridor, including transit vehicles and pedestrians. While the first is modeled as a bus with scheduled stops and dwell times, simulating pedestrian movements is more challenging. Theoretically, pedestrians cross at signalized crossings and comply with the signal phases. But findings from this research and previous literature clearly indicate that this is not always the case, as signal non-compliance, midblock jay-walking, and varying yielding rates at unsignalized zebra-striped crossings complicate the matter.

However, these behavioral patterns have real impacts on vehicular operations. In particular, this research observed the following behaviors that have implication for modeling:

- Observed pedestrian volumes at signals are lower than the actual demand, because some pedestrians cross at uncontrolled mid-block locations. This study showed an average rate of 16.3% of pedestrians crossing in-between signals.
- Pedestrian crossings during the pedestrian WALK phase are lower than the observed volumes at signals because of pedestrian non-compliance. This study observed that only about 30% of pedestrians, who decide to cross at the signal wait for the WALK indication.
- The actuation frequency at pedestrian-only signalized crossings is sensitive to pedestrian volumes and push-button actuation. At one crossing observed in this study, 34% of cycles were skipped although despite heavy pedestrian volumes.
- Pedestrian arrival volumes in a university environment are not randomly distributed, but are concentrated during lunch time and class breaks. The pedestrian effect on vehicle operations is thus elevated during those periods and is consequently lower while classes are in session.
- Behavioral models of pedestrians at signals need to account for non-compliance with the signal phase. Pedestrians crossing during the vehicular green phase need to be modeled using a separate gap-acceptance algorithm.
- At unsignalized crossings, vehicle operations are impacted by voluntary and forced yields at some overall yielding rate less than 100%.
- Behavioral models of pedestrian-vehicle interaction at unsignalized crossings need to account for pedestrian gap acceptance and driver yielding behavior.

Overall, the predicted vehicle operations along the signalized corridor and at roundabouts is impacted by pedestrians and is sensitive to the volume of pedestrians. The simulation analysis therefore needs to account for the presence of pedestrians, but also needs to consider the specific path choices and behavioral patterns present in the study area.
Conclusions

The observational analysis presented in this research has implications for the operational evaluation of the subject and similar corridors in a microsimulation environment. The analysis suggests that a good number of pedestrians will cross outside the intended crosswalks, requiring a gap acceptance model to describe this behavior. The data suggest that the frequency of jaywalking behavior is higher at longer midblock segments and further increases during class breaks as phases of elevated pedestrian activity. With some percentage of pedestrians crossing at midblock, the impact of pedestrians on the operations at traffic signal is reduced, as was made evident by skipped WALK phases. The concentration of pedestrian flows during class breaks further impacts the assumed arrival distributions of pedestrians, which can no longer be considered a random event.

Furthermore, the observed behavior at signalized pedestrian crossings implies the need for implementing multiple algorithms to fully describe the behavior. One algorithm would describe the operations of the traffic signal, another the likelihood of compliance to the signal indication as a function of arrival phase, and a third one the gap acceptance process as a function of conflicting vehicle traffic. While an average 30% of pedestrians cross in the intended WALK phase, compliance is shown to vary as a function of the phase present upon pedestrian arrival. While more research is necessary to derive and calibrate these algorithms, this research already shows that the analyst needs to pay special attention to the assumptions underlying a model involving pedestrian activity. The issues of path choice and time sensitivity seem to be major contributing factors, where jaywalking behavior is increased along long midblock segments, high (anticipated) wait times, and during class changes.

For this particular corridor, it will be interesting to observe how pedestrian behavior is impacted by the proposed re-design of Hillsborough Street and the authors are hopeful about conducting a follow-up study upon project completion. From the “before” observations, the authors hypothesize that the frequency of midblock jaywalk events will further increase, as the gap acceptance task for pedestrians is greatly facilitated by a reduced number of lanes and the creation of a median refuge. The same applies for behavior at signalized crossings, where non-compliant pedestrians will be able to cross the road more quickly. While the signal timing scheme for the corridor has not been finalized, it is likely that the geometric changes will allow for shorter cycle lengths and thus reduced average wait times for pedestrians. This research confirms earlier findings suggesting that shorter anticipated wait times are correlated with increased compliance. It remains to be seen how these tradeoffs will ultimately be reflected in pedestrian behavior once the project is on the ground.
Recommendations for Future Research

In addition to the aforementioned "after" study of pedestrian behavior, it would be of central interest to the simulation effort to calibrate the vehicle operations along the corridor with field observations of delays and travel times. The corridor re-development and the roundabouts are expected to increase travel times along the subject corridor (through reduced cross-sections and speed limits) and thereby cause some traffic diversion to alternate corridors. By comparing corridor travel times on the subject and these alternative routes, the system-wide effect of this type of project could further be assessed.

In this type of analysis, special consideration should be given to the environmental impacts of these types of projects. The creation of a more pedestrian-oriented environment may cause a reduction in vehicular trips during lunchtime to alternate locations and thereby reduce emissions. At the same time, roundabouts and signal coordination projects have both been cited for their potential in reducing tailpipe emissions by reducing the number of stops (most emissions occur while re-accelerating from a stop). It could therefore be argued that the Hillsborough Street Project may reduce emissions along the studied corridor. Through the additional evaluation of parallel corridors it remains to be seen if the overall environmental impact is in fact reduced, or if traffic diversions offset the potential benefit.

Acknowledgement

This research was supported by the Southeastern Transportation Center matching grant "Pedestrian Safety Enhancements on Hillsborough Street Roundabout Corridor Project". The first portion of this project was completed in collaboration with Kimley-Horn and Associates and focused on modeling the expected vehicle operations along the Hillsborough Street corridor after the re-design of the street. The authors acknowledge the financial support of STC and appreciate the opportunity to share the project results with the TRB community through a paper that was submitted for possible presentation and publication to the 88th Annual Meeting of the Transportation Research Board. The authors would also like to thank the City of Raleigh and Kimley-Horn and Associates for sharing pedestrian counts conducted as part of the Hillsborough Street Project.
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