Assessing the Impact of Pedestrian-Activated Crossing Systems

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Pedestrian-Activated Crossing (PAC) systems have been shown to have a generally positive impact on driver yield rates. However, there has been insufficient research on the effect PAC treatments have on pedestrian crash rates, and there is little guidance as to when and where each treatment should be used. This study estimates the effects of PACs on pedestrian crash rates using Monte Carlo simulation and examines the relationships between driver yield rates and a variety of treatments and site designs by conducting an observational study using video data from 34 locations. The simulation outcomes suggests that while the percentage of yielding drivers might be a useful indicator of pedestrian level of service, it is less helpful as safety surrogate. This could be because a driver's yielding to a pedestrian, as observed in field studies, might not be the same behavior as a driver attempting to stop during a vehicle/pedestrian conflict. The observational study shows that the number of lanes to cross at a crossing is positively correlated with the rate at which pedestrians activate the system, but it is not correlated with the delay. Additionally, the study showed that the effect of PAC systems is most pronounced at sites with a higher number of movements conflicting with the crossing or poor visibility from upstream without signs warning drivers of an upcoming crosswalk.

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FINAL REPORT

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EXECUTIVE SUMMARY

Pedestrian-Activated Crossing (PAC) systems such as the High intensity Activated crossWalK beacon (HAWK), the Rectangular Rapid Flashing Beacon (RRFB), and flashing LED crosswalk signs have been shown to have an aggregate positive effect on driver yielding rates. However, their relative effects on pedestrian safety are less clear; richer insight as to their selection and placement is needed to justify their cost, which led to the development of this project. This study estimates the effects of PACs on pedestrian crash rates using Monte Carlo simulation and examines the relationships between driver yield rates and a variety of treatments and site designs by conducting an observational study using video data from 31 crossings. While this study represents an extensive data collection effort, the scope of the study could not satisfy both this data collection as well as an analysis of the size that could uncover all the relationships and causal mechanisms. The project team chose to put more weight on the data collection and tabulation and perform as much analysis as possible. This way, the collected data represent a standing resource that the traffic engineering community can use to produce deeper insights into the causal mechanisms related to pedestrian level of service and safety on crossings.

The initial goal of the Monte Carlo simulation was to develop a simulation model that would allow engineers to enter data describing traffic and roadway conditions at a site along with driver yielding rates from field studies and then predict the crash modification effect likely to result from installation of a HAWK. If successful, this model could then be extended to other treatments, such as RRFBs. However, while testing the validity of the model, it was found that to result in an injury severity distribution close to the one observed in the Twin Cities, it required us to assume that all, or almost all, simulated drivers attempt to brake when faced with a pedestrian conflict. Simulations where all drivers attempt to brake and where the fraction of careful pedestrians changes from between 0% and 40% to 80% give simulated crash modification factors that are similar to those reported for installation of HAWKs. These findings suggest that, while the percentage of yielding drivers might be a useful indicator of pedestrian level of service, it is less helpful as a safety surrogate. This could be because a driver’s yielding to a pedestrian, as observed in field studies, might not be the same behavior as a driver attempting to stop during a vehicle/pedestrian conflict.

The observational study of 38 individually controlled crossing sites in 34 separate locations aimed to evaluate the effectiveness of specific PACs under different conditions. The sites selected had a variety of treatment types (HAWK, RRFB, flashing LED, or standard signal), road geometries (island or no island and free right turn, midblock, T-intersection, or four-way intersection), speed limits (25 to 50 mph), and surroundings (urban, residential, school zone, or rural). At least one week of video was collected at each site, but in the interest of time, only a fraction of the events was analyzed. First, undergraduate research assistants (UGRAs) scanned through all of the videos and recorded the time of each crossing whether a vehicle was present while the pedestrian was crossing. The cases where at least one vehicle was present while a pedestrian was crossing the road were then examined more closely. Detailed data on the behavior of the pedestrians and drivers was collected for one full-day of crossings with pedestrian/vehicle interaction. If there were fewer than 100 crossings with pedestrian/vehicle interaction in that day, additional events from other days were examined until a minimum of 100 events with interaction had been recorded. Using vehicle yield rates as a surrogate for pedestrian safety, the effectiveness of the various PAC system options was analyzed for the different cases.

The observational study results were presented in separate sections, one for the HAWKs and one for all other systems. The following are some highlights of the results presented in this report. Consistent with earlier research by Hourdos et al. (2012) on roundabout crossings, driver yield rates were higher for interactions where the pedestrian was starting the crossing from an island than for interactions where the pedestrian was crossing to an island. This trend was most pronounced in the cases with activated signals and RRFBs where all or nearly all drivers yielded to pedestrians crossing from an island unlike the corresponding cases where the pedestrians were crossing to an island.

Based on the observations collected on sites with HAWKs, the average pedestrian wait time, or “delay,” is higher when the system is activated than when it is not activated. This difference is caused in large part by the system activation time (at least 7 seconds but often longer at sites with a variable system activation delay). However, the standard deviation of the pedestrian delay is lower when the system is activated. This suggests that pedestrians could value the wait time more predictability than with a less reliable shorter average waiting time to cross. Similar observations were made in Hourdos et al. (2012) for the case of roundabout pedestrian crossings.

RRFB delay times are considerably lower than those observed at HAWK sites given that RRFBs do not have a built-in delay prior to allowing the pedestrian to cross. Regardless, it is still observed that when the drivers do not yield, the resulting delay to cross is significantly higher and comparable to that of activated HAWKs. This suggests that, at locations where the driver yield rates are not high enough with an RRFB, installing a HAWK will result in better service quality, i.e., more predictable wait times. On the other hand, if yield rates with an RRFB are sufficient, installing a HAWK will result in higher delays, reducing service quality to both pedestrians and drivers. The analysis shows that, in terms of driver yield rate, the benefit of an RRFB increases with the number of lanes but is much more closely linked to the number of vehicle movements that conflict with the crosswalk.

Signals serving as PACs have shown to be counterproductive since, if they are not activated, driver yield rate is very low. This can be explained with the hypothesis that drivers are accustomed to signals being explicit determinants of priority. Therefore, if drivers are being shown a green signal and pedestrians are being shown a “don’t walk” sign, it implies that vehicles do not have to stop. The analysis results suggest that overhead placement of RRFBs may result in increased driver yield rates regardless of whether they are activated. This could imply that it may not be the overhead RRFB itself that is responsible for the improved yield rate but the accompanying static sign on the overhead mast.

An overall finding from the comparison of driver yield rates with and without an activated PAC is that good visibility, extra static signage, and advanced notice could be sufficient for raising the driver yield rate to a satisfactory level, in which case the cost of a PAC is unjustified. It is only at intersections with poor visibility that PAC systems increase the driver yield rate by a significant amount when activated.

MnDOT requested the before-and-after analysis of flashing LED pedestrian sign PACs. Due to the novelty of the system, only one site (with six individual crossings) was available to collect observations. The site only involved free right-turn lanes and low pedestrian volumes. Compounded by sidewalk and crossing alignment issues, the result was that most of the pedestrians crossed by following a path that did not bring them near the PAC activation button. Although the study did not provide sufficient insight regarding the effectiveness of the flashing LED pedestrian signs, it did highlight the importance of carefully planning the crossing geometry and alignment of the pedestrian path connected to it.

It is important to emphasize that this study, although comprehensive, does not include all of the possible information that can be gleaned from the collected observations. The delivered data set allows for further scrutiny and analysis, and it is hoped that, by offering it as a standing resource to the transportation community, additional benefit will be generated.

CHAPTER 1: INTRODUCTION

In the past decade, several different treatments aimed at improving pedestrian safety and mobility by positively affecting driver behavior have been designed and deployed. These treatments fall into the category of Pedestrian-Activated Crossing (PAC) systems, and in addition to standard actuated pedestrian signals, include the High intensity Activated crossWalK beacon (HAWK), the Rectangular Rapid Flashing Beacon (RRFB), and flashing LED crosswalk signs. Although prior studies have shown that these systems can have an aggregate positive effect on driver yielding rates, their effects on pedestrian crashes is less clear, and richer insight as to their selection and placement is needed to justify their cost. In Minnesota, several sites have had these treatments in place long enough for analyses to be performed. The scope of this analysis is limited to RRFBs, HAWKs, and flashing LEDs.

Prior research on pedestrian crossings has not adequately examined the influences of PAC treatments on vehicle yield rates. The classic study by Herms (1972) computed estimates of pedestrian crash rates at comparable pairs of marked and unmarked crosswalks and found distinctly higher crash rates at the marked locations. Herms interpreted this as evidence that marked crosswalks provide pedestrians with a "false sense of security." Similar results have been reported by Jones and Tomcheck (2000), while Zegeer et al. (2004) only found higher crash rates at marked crosswalks when they were located on roads with 3 or more lanes and Average Daily Traffic (ADT) of 12,000 or higher. If marked crosswalks do indeed lead to a greater tendency for pedestrian crashes, then either pedestrians, drivers, or both tend to behave differently at marked crosswalks. Although the above studies offer hypotheses as to what this behavior might be, none of them actually identify the mechanism(s) that cause the observed differences in crash rates. A number of field studies have looked at the behavior of drivers in the presence of pedestrians, (Howarth, 1985; Thompson et al., 1985; Katz et al., 1975; Varhelyi, 1998; Britt et al., 1995) and a smaller number have looked at the behavior of pedestrians (Van Der Molen, 1982; Knoblauch et al., 2000), but the crucial behavioral differences have yet to be identified. A recent study (Fitzpatrick et al., 2014) that focused on the effectiveness of two types of PACs, showed that compared to a 98% yield rate traffic signal crossing, RRFBs achieve an 86% rate. The study looked at 22 RRFBs with varying geometries and traffic characteristics. The results were based on staged pedestrian crossings with 20 such crossings for each direction at each site. Because each site was only sampled once and volumes were not measured, it was not possible to capture the effects of various traffic conditions. In the same study, a before-and-after comparison of four study sites with RRFBs and preexisting marked crosswalks showed a yielding range of 0-40% before and a range of 38-92% after. Results were based on 4-6 hours of before-and-after video with both staged and non-staged pedestrian crossings. Although this latest and most comprehensive of the PAC studies has provided some valuable insight, this study resulted in inconsistent yielding rates and was based on limited observations both in quantity and quality. Specifically, while general estimates of yielding rates have been available, estimates relating these to traffic conditions have been limited, both with and without the PAC treatments of interest.

The study presented in this report attempted to approach the subject from two different directions. The first such direction consisted of a statistical safety analysis, which used Monte Carlo simulation to develop a simulation model that would allow engineers to enter data describing traffic and roadway conditions at a site, along with driver yielding rates from field studies and then predicted the crash modification effect likely to result from installation of a HAWK. If successful, this model could then be extended to other treatments, such as RRFBs. This simulation used crash records to decide on driver and pedestrian characteristics; driver yielding and pedestrian caution were the two independent variables, and the simulated crash rate was the dependent variable.

The simulation showed that, to produce an injury severity distribution similar to those observed in the Twin Cities, it was necessary to assume that all, or almost all, simulated drivers attempted to brake when faced with a pedestrian conflict. Simulations where all drivers attempted to brake, and where the fraction of careful pedestrians changed from 0-40% to 80% gave simulated crash modification factors that were similar to those reported for installation of HAWKs. Together, these outcomes suggested that while the percentage of yielding drivers might be a useful indicator of pedestrian level of service it was less helpful as a safety surrogate. This could be because a driver's yielding to a pedestrian, as observed in field studies, might not be the same behavior as a driver attempting to stop during a vehicle/pedestrian conflict.

The simulation results also suggest that the crash reduction effects reported for HAWKs might result from modifying pedestrian behavior rather than, or in addition to, modifying driver behavior. At this point, though, before a simulation model can be used to support practical decision-making, a better understanding is needed of how HAWKs (and RRFBs) affect both driver and pedestrian behavior, especially as to how high-risk interactions are generated. Although more work is needed, simulation modeling can provide a framework for stating hypotheses about road-user behavior and then deriving consequences from these hypotheses, which can then be compared to observations.

The second component of the project was an observational study of pedestrian-vehicle interactions at crosswalks with particular treatments. The study sites were selected to cover a variety of treatment types, road geometries, speed limits, and surroundings. At least one week of video was recorded at each site. In two cases, video was collected before and after the PAC treatments were added. Video was collected by the Minnesota Traffic Observatory (MTO) using custom-made, self-contained camera systems. Originally, several more sites were going to be included in the study, but the videos collected at these sites using a commercially available video collection system were too blurry for use in the analysis.

The process of reducing the video collected into usable data on drivers' and pedestrians' behaviors was broken into two phases: pre-sorting and event logging. The pre-sorting phase consisted of scanning through one week of video from each site and recording hourly vehicle volumes as well as the time of each pedestrian crossing and whether there were any vehicles in the vicinity at the time of the event. The event logging phase focused on the larger of one full-day worth of pedestrian/vehicle interactions or 100 interactions. For each interaction, two types of data were recorded: event data and lane data. Event data consisted of information on the pedestrian and general information such as the time of the event, who yielded, and whether the system was activated. Lane data consisted of data on the behavior of drivers in a given lane such as the number of vehicles yielding and the total number of vehicles.

The data recorded during the data reduction process was then used to answer 23 questions about PACs that had been agreed on by the research team and the Technical Advisory Panel (TAP) to guide the investigation. Most of the questions were general, but due to the different nature of HAWKs as compared to RRFBs or flashing LEDs, some of the questions were specific to one of the two groups.

CHAPTER 2: LITERATURE REVIEW

This literature review is a collection of information from existing studies about pedestrian safety countermeasures used at crosswalks without traffic signals. The countermeasures include but are not limited to Pedestrian Hybrid Beacons, Rectangular Rapid Flashing Beacons, in-pavement flashing warning light systems, in-street stop-for-pedestrian signs, advance stop line markings, and LED-embedded signs.

There are multiple evaluations testing the effectiveness of pedestrian countermeasures. In collected articles and reports, surrogates of safety were used in lieu of the direct outcome of traffic safety such as reduction in pedestrian-vehicle crashes. The most commonly used criteria for evaluating pedestrian-driver interactions include:

- Percentage of drivers yielding to pedestrians
- Number of pedestrian-vehicle conflicts
- Stopping distance of vehicles ahead of the crosswalk
- Speed of drivers approaching the crosswalk
- Percentage of pedestrians who hesitated, rushed, or aborted a crossing
- Percentage of pedestrians using the crosswalk or pedestrian crossing facilities

Some evaluations, such as pedestrian-vehicle conflicts, have a direct relation with the outcome of safety, while others, such as the stopping distance ahead of the crosswalk, may not have clear relation with the traffic safety. Of these evaluations, percentage of drivers yielding to pedestrians is the most commonly used.

2.1 PEDESTRIAN HYBRID BEACONS

A Pedestrian Hybrid Beacon (PHB), often referred to as a HAWK (High-intensity Activated crossWalK) beacon, is a kind of crossing system used at unsignalized locations to help pedestrians cross marked crosswalks. As seen in Figure 2-1, the beacon consists of two circular red indicators side by side above a yellow indicator. This triangular configuration is used to keep drivers from confusing a HAWK for a standard traffic signal (Hunter-Zaworski et al., 2012). First included in MUTCD (the Manual on Uniform Traffic Control Devices) in 2009, HAWKs are now widely used in many states such as Georgia, Minnesota, Virginia, Arizona, Alaska, and Delaware (Chalmers, 2010). According to the MUTCD, a HAWK should be considered for installation if a location does not meet a traffic signal warrant or does meet warrants under section 4C.05 (Pedestrian Volume) or 4C.06 (School Crossing) but it was decided that a signal would not to be implemented.

Figure 2-1 Example of Pedestrian Hybrid Beacon (PHB)

As shown in Figure 2-2, the HAWK is all dark before it is activated by a pedestrian. After activation, the beacon begins to flash yellow then displays a steady yellow. During these three phases, the pedestrians are shown a “DONT WALK” indication. Following the steady yellow, the beacon displays a steady red and the pedestrians are given a “WALK” indication. This is the phase for pedestrians to walk through the crosswalk. It is followed by a clearance interval during which pedestrians are given a “DONT WALK” indication. The beacon then changes to a flashing red indication. Following the clearance indication, pedestrians are still given a Don’t Walk indication and the HAWK returns to all dark.

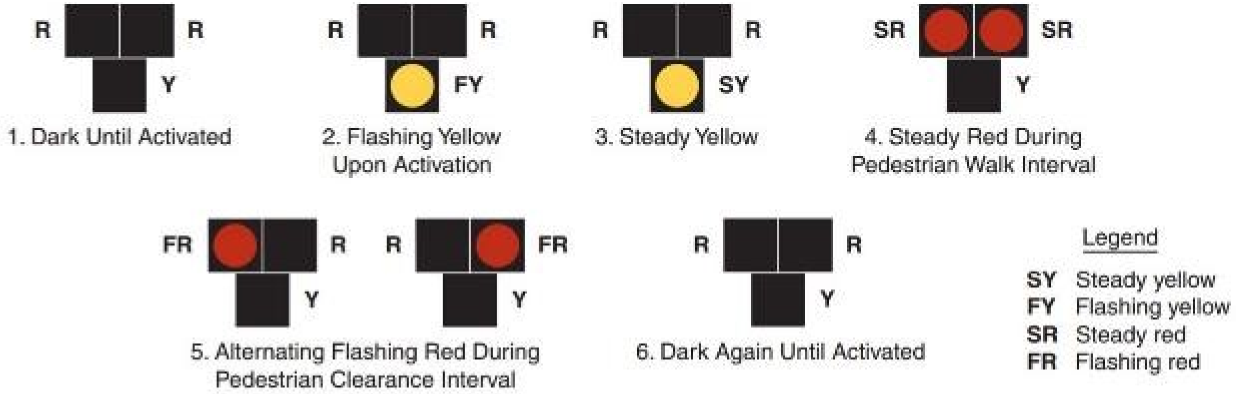

Figure 2-2 Phases of a HAWK system

The operation of HAWKs implemented in Portland, Oregon is slightly different from the operation laid out in the MUTCD. The difference is in the fourth phase where pedestrians are given a “WALK” indication two seconds after the drivers are given a steady red indication. The steady red indication is displayed through the pedestrian clearance interval after which a flashing red indication for drivers and a “DONT WALK” indication for pedestrians are displayed as per the recommendation of the MUTCD.

A typical HAWK beacon also includes other devices such as STOP signs on the minor street, a marked crosswalk on only one major street approach, a pedestrian signal head with a pedestrian interval countdown displays, and a pedestrian pushbutton with a supplemental educational plaque.

Two reports published by The Transportation Research Board (Turner et al., 2006; Fitzpatrick et al., 2006) detail a study that tested nine crossing treatments at 42 pedestrian crossings in different regions with a wide range of climates as well as urban and suburban design features across the country. Table 2.1 presents the ranges of speeds, ADTs, and numbers of lanes by site. Figure 2-3 shows the averages and ranges of yielding rates for each treatment. The pedestrian crossings were all marked crossings. Each crossing was evaluated before and after installation of the treatment to test the effectiveness of treatments.

Table 2.1 Site characteristics (Turner et al., 2006; Fitzpatrick et al., 2006)

City	Crossing Treatment	Number of Study Sites	Range in Through Lanes	Range in Speed Limit (mph)	Range in Peak Hour Vehicle Volumes (veh/h)
Tucson, AZ	HAWK signal beacon	5	4–6	30–40	2,700–4,350
	High-visibility markings and signs	2	4	25–35	600–2,400
Los Angeles, CA	Overhead flashing beacon (passive)	4	2–4	30–35	900–2,900
	Midblock signal	4	4–5	25–35	700–2,400
Santa Monica, CA	Median refuge island, high-visibility signs	2	4	30	2,400–2,600
Capitol Heights, MD	Overhead flashing beacon (continuous)	1	6	35	3,900
Towson, MD	Overhead flashing beacon (push button)	1	4	35	1,400
Portland, OR	Half signal	3	4	35	1,400–2,400
	Median refuge island, high-visibility signs	3	2–4	25–35	1,000–2,000
Austin, TX	High-visibility signs and markings	1	4	35	1,550
College Station, TX	Median refuge island, high-visibility signs	1	4	35	1,350
Salt Lake City, UT	Overhead flashing beacon (push button), pedestrian flags	3	4	30–35	1,300–1,800
	Pedestrian flags	3	4–6	30–35	700–2,500
Kirkland, WA	Pedestrian flags	3	2–4	25–35	1,050–1,700
Redmond, WA	In-street crossing sign	3	2–3	25–30	250–900
Seattle, WA	Half signal	3	3–4	35	700–2,050

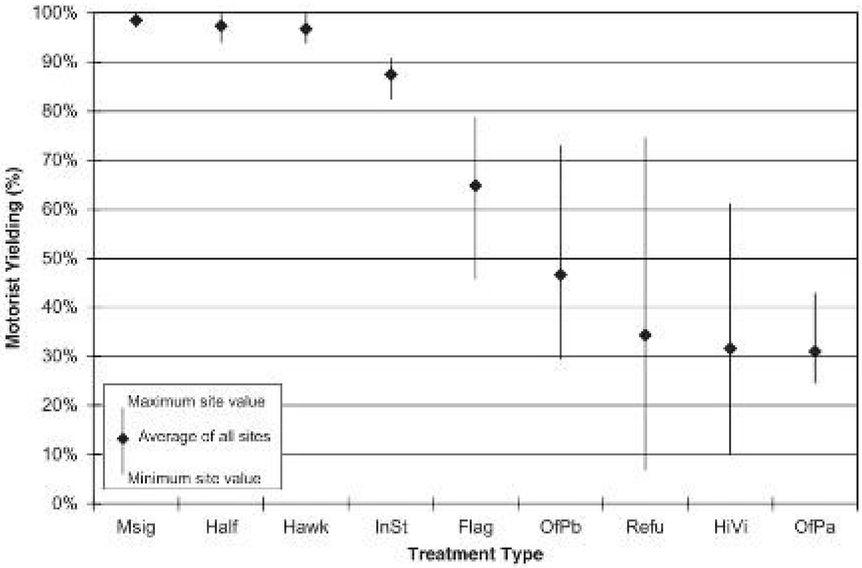

Figure 2-3 Average and range of yielding rate by crossing treatment (Turner et al., 2006; Fitzpatrick et al., 2006)

The treatment abbreviations as shown in Figure 2-3 are as follows:

- Msig: Midblock pedestrian signal
- Half: Half signals (major road is signalized, minor road is stop controlled)
- Hawk: HAWK system
- InSt: In-street pedestrian crossing sign
- Flag: Pedestrian crossing flags
- OfPb: Overhead flashing beacons, where an overhead pedestrian sign and two yellow flashing beacons are activated when a button is pushed by the pedestrian
- Refu: Pedestrian median refuge island
- HiVi: High-visibility markings and signs
- OfPa: Smart pedestrian warning, where an overhead pedestrian sign and two yellow flashing beacons are passively activated by an approaching pedestrian

Figure 2-3 shows the yielding rate of motorists following different treatments. The yielding rates for midblock pedestrian signals, half signals, and HAWKs were higher than 95% – much higher than the yielding rates for the other two categories of treatments. As most midblock pedestrian signals, half signals, and HAWKs are used on busy arterial streets, the researchers recommended that engineers use them to improve pedestrian crossing safety on busy arterial streets.

A report by Fitzpatrick and Park (Fitzpatrick et al., 2010) evaluates the effectiveness of HAWK systems using a before-after empirical Bayes approach. Data collection was conducted in 21 sites in Tucson, Arizona with 3-year study periods before and after the HAWKs were installed. The effectiveness of the HAWK beacons was evaluated by comparing the difference between observed and predicted crash rates with an empirical Bayes method. The result showed that, after the installation of HAWK, there were statistically significant reductions in total crashes and pedestrian crashes of 29% and 69%, respectively. There was also a statistically insignificant 15% reduction in severe crashes. The researchers were unsure if the same reductions in crash frequencies could be achieved at other locations with different road characteristics and pedestrian activities.

From the studies above, it can be seen that the effectiveness of HAWK systems is significant. Because the operation of a HAWK system resembles that of a standard traffic signal, most drivers treat them as traffic signals that need to be observed and stop for pedestrians when they see the HAWK shifting to red. However, the percentage of pedestrians who choose to activate this system when crossing the street has a very large impact the effectiveness of a HAWK system. One of the benefits to a HAWK system is the alternating flashing red phase, where motorists are allowed to proceed once all pedestrians have cleared their lane. Because the HAWK is a relatively new treatment and the alternating flashing red phase quite different than any phase in a standard signal, it is unclear if the operational benefits of motorists proceeding when allowed are being realized. The influences of additional factors such as median islands, the number of lanes, and time of day have not been discussed in prior works.

2.2 RECTANGULAR RAPID FLASHING BEACONS

RRFBs help pedestrians safely cross roads and uncontrolled intersections by drawing attention to crosswalk signs. RRFBs have not been included in the MUTCD but were given interim approval by the FHWA in July 2008 (FHWA, 2009). Note that this interim approval was briefly withdrawn in early 2018 as a result of legal conflicts. RRFBs are activated either by a pedestrian pushing a button on the curb or by a pedestrian detection system. Most RRFBs are designed to begin flashing without any waiting time following activation by a pedestrian. The duration of the pedestrian interval is the calculated by dividing the length of the crosswalk by the design pedestrian walking speed (Fitzpatrick et al., 2014). Shown in Figure 2-4, the RRFB has two yellow, rectangular LED indicators (roughly 6 in. wide, 2 in. tall, and spaced approximately 7 in. apart) positioned below a pedestrian sign to draw drivers' attention to the sign. Over the pedestrian sign, there is often a solar panel to supply energy for the system.

Figure 2-4 Example of RRFB (Photo courtesy of commuteorlando.com)

An article by van Houten, Ellis, and Marmolejo (Van Houten et al., 2008) discusses the effectiveness of RRFBs (referred to as "stutter-flash LED beacons") in enhancing the yielding behavior of drivers. Data was collected at two Miami-Dade County, Florida multilane crosswalks before and after the installation of the RRFB systems. Yielding rate, vehicle-pedestrian conflicts, trapped pedestrians, and motorist yielding distance were extracted from the collected data. Analysis showed that the yielding rate increased from 0% and 1% at the experiment sites to 65% and 92%, respectively. Vehicle-pedestrian conflicts, trapped pedestrians and motorist yielding distance also reduced after the installation of RRFB. The researchers concluded that the RRFB was effective in enhancing pedestrian's safety at multilane crosswalks.

RRFBs can be considered a modern incarnation of the older Roadside Flashing Beacons like the one in Figure 2-5. A report by Hua, Gutierrez, Banerjee, Markowitz, and Ragland (Hua et al., 2009) details the

San Francisco PedSafe project in which 13 countermeasures that have potential to enhance the pedestrian's safety in a 3-year period were implemented. Among these 13 countermeasures, six of them, including flashing beacons installed at uncontrolled crossing, proved to be successful. Data was collected by video camera before and after the installation. The flashing beacons activated by pushbuttons saw a significant reduction in vehicle-pedestrian conflicts (from 6.7% pre-treatment to 1.9% post-treatment) as well as a significant increase in vehicle yielding (from 70% pre-treatment to 80% post-treatment). While only 17% of pedestrians activated the beacon, an additional 27% of pedestrians crossed when the beacon was already activated. The automated flashing beacons saw a significant reduction in vehicle-pedestrian conflicts (from 6.1% pre-treatment to 2.9% post- treatment), a significant reduction in the percentage of trapped pedestrians (from 4.1% pre-treatment to 0% post-treatment), and a significant increase in vehicle yielding (from 82% pre-treatment to 94% post-treatment). Of the 13 countermeasures tested, both pushbutton-activated and automatic flashing beacons were among the six countermeasures that were considered to be the most effective in increasing pedestrian safety.

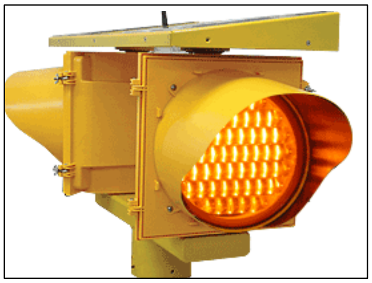

Figure 2-5 Traditional roadside flashing beacon

A report by Shurbutt, van Houten, Turner, and Huitema (Shurbutt et al., 2009) discusses the effects of RRFB in uncontrolled, marked crosswalks in three experiments. In the first experiment, the effects of two-beacon systems and four-beacon systems were evaluated in three sites. Two-beacon RRFB system includes two sets of RRFB on both sides of the crosswalk. Four beacons RRFB system includes four sets of RRFB on the median island and on both sides of the crosswalk. The average yielding rate in these sites increased from 18.5% to 81.2% after the installation of two-beacon system and increased to 87.85% after the installation of four-beacon system. The second experiment compared a traditional pedestrian overhead yellow flashing beacon and a traditional side-mounted yellow flashing beacon with the RRFB system at two sites. At the first site, RRFB system was installed following traditional overhead beacons (Figure 2-6). At the second site, RRFB system was installed following traditional side-mounted beacons on the same road. The results showed that overhead standard beacon increased the yielding rate by 4.6% while two-beacon and four-beacon RRFB systems increased the yielding rate by 70.6% and 77.8% respectively at the first location. At the second location, the side-mounted beacon increased the yielding rate by 11.48% and 17% after 7 days and 30 days, while two-beacon RRPB system increased the yielding rate by 63.4% and 72% after 7 days and 30 days. The research concluded that RRFB had better effect in increasing yielding rates than an overhead standard beacon and a side mounted beacon. In the third experiment, the effectiveness of RRFB was evaluated at 19 sites in St. Petersburg, Florida and 3 additional sites (two in the suburbs of Chicago, Illinois and one in the Washington, D.C. area). Follow-up data was collected from 19 sites after 7-day, 30-day, 60-day, and two-year periods. The results showed that yielding rate increased from an average of 2% before treatment to 86% after 60 days and was 85% at the 2-year follow-up.

Figure 2-6 Standard overhead yellow flashing beacon

A 2009 report by Pecheux, Bauer, and McLeod (Pecheux et al., 2009) evaluates the effect of RRFBs at two sites in Miami, Florida. Three measures of effectiveness were used: the percentage of pedestrians trapped in the roadway, yielding rate, and the percentage of pedestrian-vehicle conflicts. The results showed RRFB had effect on enhancing all of the aforementioned measures of effectiveness.

A report by Shurbutt and van Houten (Shurbutt et al., 2010) discusses the effectiveness of RRFBs at 22 multilane, uncontrolled crosswalks with high average daily traffic (ADT) in St. Petersburg, Florida, Washington, D.C., and Mundelein, Illinois. Data was collected in a 2-year follow-up period at 18 of these crosswalks to determine the long-term effect of the installation of a RRFB. The yielding rate before the installation of the RRFB was between 0% and 26% whereas the yielding rate after the installation of the RRFBs was between 72% and 96% at the two-year follow-up. The experiments also compared the effect of two-beacon RRFB systems and four-beacon RRFB systems; the four-beacon RRFB systems include RRFBs on the median. The average yielding rate under baseline conditions across four sites was 18.2%. After the installation of two-beacon systems, the yielding rate increased to 81.2%. After the installation of four-beacon systems, the yielding rate increased to 87.6%. The report also discusses the difference in the effects of RRFBs (side-mounted two- beacon RRFB system) with two types of LED lights. The first type of LED was aimed parallel to the approach roadway and the second type of LED was aimed at the eyes of approaching drivers. And average yielding rate after the installation of RRFB with two types of LEDs was about 80% after one year while the yielding rate under the baseline condition was zero in this experiment. The researchers concluded that RRFB appeared to be an effective tool for enhancing yielding behavior and pedestrian safety at uncontrolled crosswalks at high ADT multilane sites.

A report by Ross, Serpico, and Lewis (Ross et al., 2011) evaluates RRFBs installed at three crosswalks in Bend, Oregon. Two crosswalks were installed at Bend Parkway – a four-lane road with a median, bike lanes, sidewalks, and a posted speed limit of 45 mph. A second location was Green Avenue – a five-lane road with a two-way left turn lane and a posted speed limit of 35 mph. After the installation of an RRFB, the average yielding rate increased from 17.8% to 79.9%. The researchers recommended that RRFBs should be considered for installation on high-speed facilities with posted speed limits greater than 35 mph and that an RRFB installation needed to include other features to improve the visibility of the crossing, such as signs and markings in advance of the crosswalk.

A report by Foster, Monsere, and Carlos (Foster et al., 2014) examines driver and pedestrian behaviors at two enhanced midblock pedestrian crossings in Portland, Oregon. Instead of using a before and after method, this study compared the yielding rate when RRFB were activated and not activated in two sites with video recorded by video camera. The first site had a crosswalk with a median island that crossed a five-lane arterial. Eight RRFBs were installed around the crosswalk, of which six were placed at the crosswalk and two were placed ahead of the crosswalk. The second site was a crosswalk with a special median island with a path through it to let pedestrian face the traffic flow when walking through the median island. Four RRFBs were installed at this crosswalk. The sample sizes of crossings at the two sites were 484 and 330, respectively. Pedestrians activated the beacon 94% of the time at the first site and 83% of the time at the second site, so the sample size of the second site when RRPB was not activated was only 33. According to the results, the yielding rates were 92% and 91% respectively at two sites when the RRFB were activated. The researchers also tested the attraction of the crosswalk to crossing pedestrian by recording the number of pedestrians who used the crosswalk instead of taking the shortest path. Following the installation of the RRFBs, the average fraction of pedestrians crossing the roadway at the second site that chose to use the crosswalk increased from 71% to 84%. The researchers proposed that the installation of an RRFB encouraged more pedestrians to use the crosswalk in the second site.

A report by Fitzpatrick, Iragavarapu, Brewer, Lord, Hudson, and Avelar (Fitzpatrick et al., 2014) compares the effects of traffic control signals (TCS), HAWKs, and RRFBs on the yielding rate of drivers in Texas. Yielding rates were collected at 7 TCS sites, 22 RRFB sites, and 32 HAWK sites. TCSs in Texas had the highest driver yielding rates with an average of 98% for the seven sites. The average driver yielding rate for RRFBs with “School Crossing” signs was 86% and the average yielding rate for HAWKs was 89%. Because the RRFBs in this experiment were installed in conjunction with “School Crossing” signs near schools, the yielding rates of RRFBs in Texas were higher than average. Researchers used logistic regression model to represent the relation between yielding rates and several variables, such as speed limit, total crossing distance, one-way or two-way traffic, and city. The study indicated that the cities with more devices had higher yielding rates. The devices installed for longer times also had higher yielding rates. For HAWK sites, longer crossing distance was related with higher yielding rate. For RRFB sites, crosswalks with longer crossing distances were associated with lower compliance and higher posted speed limits were associated with higher yielding rates.

A 2015 report by The Federal Highway Administration (Fitzpatrick et al., 2015) details a closed-course study of drivers’ detection of pedestrian cutouts with RRFBs at different brightness levels, flash patterns, and LED locations. Some indices such as the time taken to correctly identify pedestrian walking direction and the participant’s rating of discomfort due to glare were used to measure the 98 licensed drivers’ ability to detect pedestrians. The four LED brightness levels the researchers used (0 cd, 600 cd, 1400 cd, and 2200 cd) were all lower than the normal brightness of an RRFB. The data showed that a lower LED brightness is associated with reduced disability due to glare and detection time increased when the LEDs were below the sign and the pedestrian was at the edge of the sign or when the pedestrian was shorter in height. Two of the six flash patterns tested increased the detection time (drivers would look away from RRFBs when the LEDs were constantly on) but appropriate dark periods between flashes gave drivers time to search for the pedestrian.

Table 2.2 Partial Summary of RRFB Studies

Year	Author	Road configuration	Main location	Before/After Yielding rate (%)
2006	Houten et al.	multilane	Miami, Florida	0 to 65, 1 to 92
2008	Hua	multilane	San Francisco, California	70 to 80, 82 to 94
2009	Pecheux et al.	multilane, median island	Miami, Florida	(2.5, 12.5) to (55.2, 83.4)
2009	Shurbutt et al.	multilane	St. Petersburg, Florida	18.5 (daytime) to 81.2 (2 beacons) to 87.9 (4 beacons) to 85 (two years)
2010	Shurbutt et al.	multilane	St. Petersburg, Florida, Washington, D.C., and Mundelein, Illinois	4.8 (nighttime) to 94.6 (2 beacons) to 99.5 (4 beacons)
2011	Ross et al.	multilane, median island	Bend, Oregon	17.8 to 79.9
2011	Foster et al.	multilane, median island	Portland, Oregon	45 to 91, 75 to 92
2014	Fitzpatrick et al.	multilane, median island	Texas	* to 86 (at school crossing)

*No lower level was indicated in study by Fitzpatrick et al.

Table 2.2 is a compilation of yielding rates (the most commonly used measure for effectiveness) from eight RRFB studies. While most studies only considered the short-term effects of RRFBs, some considered both short-term and long-term effects. Including short-term and long-term effects did make a difference. For example, in the 2009 study by Shurbutt et al., the yielding rate slightly declined after two years. It should also be noted that most studies only tested the yielding rate during daytime but, as shown in the 2010 study by Shurbutt et al., the data collected at night differed by as much as 10 % from the data collected during the day. Some of the experiment sites were located at roadways with median islands but the relation between median islands and the effect of RRFB was not fully understood.

When comparing initial yielding rates at all of the sites in all of the studies, the values vary widely (the lowest recorded rate was 0% and the highest rate was 82%). Similarly, the yielding rates after installation also differ greatly – in the 2014 report by Foster et al., the yielding rate reached 92% whereas, at one site in the 2008 report by van Houten et al., it only got as high as 65%. In the 2014 report by Fitzpatrick et al., cities with more devices had higher yielding rates because motorists were able adapt to the new device more quickly due to an increased familiarity with it. Fitzpatrick et al. also indicated that the devices installed for longer time had higher yielding rates but this conclusion was contradicted by the results of the 2009 study by Shurbutt et al. in which yielding rate declined by 2.9% two years after the installation. The effectiveness of RRFBs also varied when they were used with other beacons or signs. In the 2014 report by Fitzpatrick et al., RRFBs worked well when used with signs indicating that a school was nearby. Other factors that caused differences between the results were the lighting, weather, and measurement method. With the exception of this study, there has been little research on the impacts of RRFBs installed on a boom over the roadway, at high speed locations (over 40 mph), at rural cross-sections, or at wide, multi-lane crossings.

2.3 IN-PAVEMENT FLASHING WARNING LIGHT SYSTEMS

Much like RRFB systems, in-pavement flashing warning light systems increase drivers' yielding rate to pedestrians by drawing attention to the crosswalk. As the name suggests, in-pavement flashing warning light systems (see Figure 2-7) consist of lights embedded in the pavement at the edge of a crosswalk that can be activated by a pedestrian pressing a button or automatically by a pedestrian detection system and shut off after a predetermined amount of time.

Figure 2-7 Example of in-pavement flashing warning light system

A report by van Derlofske, Boyce, and Gilson (van Derlofske et al., 2003) compares the effects of an in-pavement light flashing system on pedestrian and driver behaviors to those of normal crosswalk striping at a four-lane divided highway and a two-lane road in Denville, New Jersey. The study employs an escalating series of before-and-after comparisons. At first, two crosswalks were striped and then in-pavement warning light system and associated pedestrian detectors were installed. Pedestrian surveys and observations were conducted and video data was recorded before the crosswalks were striped, before the warning system was installed, and after the warning system was installed. The behavior of drivers was measured from the collected data. The data showed that high-visibility marking of a crosswalk improved the conspicuity of the crosswalks and reduced the conflicts between drivers and pedestrians but the mean speed of vehicles approaching the crosswalk was unaffected. While adding an in-pavement flashing warning light system can reduce the mean speed of vehicles approaching a crosswalk and number of vehicle passing crosswalks while a pedestrian is waiting, the effect of adding an in-pavement light system to a striped crosswalk decreases over time.

A report by Whitlock and Weinberger Transportation (Whitlock & Weinberger transportation et al., 1998) details the effectiveness of in-pavement flashing warning light system in Orlando, California and Kirkland, Washington. Data was collected before and after the installation of an experimental system with extra lengths being taken to ensure that data was collected under similar weather and lighting conditions both during the daytime and at night. The yielding rate and stopping distance to crosswalks increased after the installation of the in-pavement flashing warning light systems thereby showing that the experimental system had a positive effect on drivers' awareness of crosswalks.

A report by Huang, Zegeer, and Nassi (Huang et al., 2000) details a study that tested the effectiveness of in-pavement flashing warning light systems in Gainesville and Lakeland, Florida. This system is automatically activated when pedestrians enter the microwave detection zone at one side of the crosswalk. The data was collected during daylight hours before and after the installation of this system. The measures of effectiveness were yielding behavior of motorists, pedestrians who benefit from motorists' yielding behavior, pedestrians who exhibited normal crossing behavior, and pedestrians who walked in the crosswalk. Following installation, there was a slight decline in the yielding rate in Gainesville from 80.6% to 74.6% but this may have been due to the fact that the data was collected soon after a new academic year had started when many newcomers were present. At the Lakeland site, however, the yielding rate increased from 18.2% to 29.7% though it should be noted that the yielding rate was still low and this increase was not statistically significant – both of which may be the result of insufficient data. It was also shown that pedestrians were more likely to cross within the crosswalk with this system. In the conclusion, the authors pointed out that more data from additional sites and at night was needed.

A report by Gadiel, Knodler, Collura, and Fischer (Gadiel et al., 2007) discusses the effectiveness of in-pavement warning light systems by evaluating the yielding rate of drivers before and after the installation at seven crosswalks in Amherst, Massachusetts area. The researchers used video cameras to collect data on pedestrian and driver behavior with partial and complete in-pavement warning light systems. Researchers also used a driving simulator including 576 crosswalk scenarios and an eye tracker to collect data on drivers' scan patterns when approaching a crosswalk with in-pavement warning light system. The results showed that the installation of this system led to an increase in yielding rates from less than 50% to more than 64% when partial systems were installed and to more than 90% when complete systems were installed. The simulation showed that most drivers would still scan for the pedestrian instead of the lights.

2.4 FLASHING LED SIGNS

A report by Ellis and Tremblay (Ellis et al., 2014) details a study that used a before-after study to test the effect of the Blinker Sign system produced by TAPCO. As shown in Figure 2-8, the Blinker Sign system consists of flashing LEDs and reflective sheeting. This system used in the study was activated by a pushbutton and powered by a solar panel mounted on top of the sign. Data was collected for vehicles traveling in both directions at two sites in Virginia with high traffic volume. The “before” data was collected two months prior to the installation of Blinker Sign system and the “after” data was collected about 7.5 months and 45 months after the installation of Blinker system. The measures of effectiveness were the average approach speed, decelerated speed, and yielding rate. Approach speed was the speed of vehicles when they were 300 to 500 feet from the crosswalk. Decelerated speed was the speed of vehicles when they were 100 to 300 feet from the crosswalk. The study showed that the installation of the Blinker Sign system was linked to a greater reduction in speed when drivers were approaching the crosswalk (this effect had not changed four years after the installation) and that the yielding rate increased from 56% to 80% one year after the installation but dropped to 64% after four years.

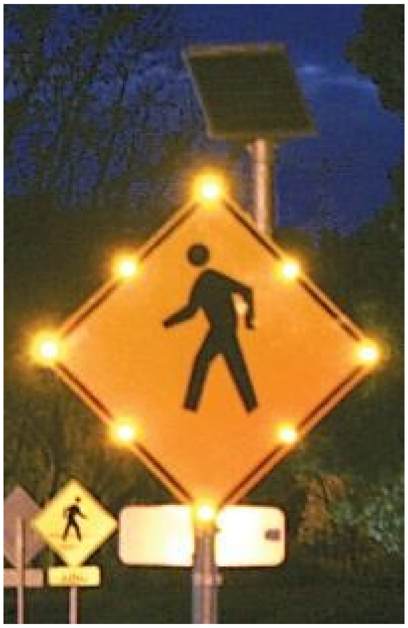

Figure 2-8 Flashing LED sign at night

2.5 IN-STREET “STOP FOR PEDESTRIANS” SIGNS

In-street “Stop for Pedestrians” signs are often installed on the centerline, on a lane line, or on the median of a roadway. As seen in Figure 2-9a, the signs are a reflective chartreuse yellow to increase the visibility of the crosswalk. The signs are included in the 2003 and 2009 editions of the MN MUTCD.

A report by Huang, Zegeer, Nassi (Huang et al., 2000) studies the effectiveness of an early version of the standard in-street sign (Figure 2-9b) installed at seven sites in New York state and Portland. The in-street sign was developed by New York State Department in Transportation in 1996 and was designed for use at marked intersections, unsignalized intersections, and at midblock locations. Using video data, researchers recorded the percentage of pedestrians to whom motorists yielded, the percentage of yielding motorists, the percentage of pedestrians who hesitated, rushed, or aborted a crossing, and the percentage of pedestrians who used crosswalk to cross the road. According to their findings, the pedestrian safety cones had the greatest effect on increasing the yielding rate as compared to an overhead crosswalk sign or pedestrian-activated overhead signs reading “Stop for Pedestrians in

Crosswalk”. The yielding rate increased from 69.8% to 81.2% thereby showing that the pedestrian safety cone was effective in enhancing pedestrian’s safety at low-speed two-lane roads.

(a) (b)

Figure 2-9 Current standard in-street sign in MN (a) and early version in-street sign (b)

A paper by Kamyab, Andrle, Kroeger, and Heyer (Kamyab et al., 2003) evaluates the effectiveness of in-street signs at reducing speed. Speed data was collected before and after the installation of pedestrian crossing signs and temporary pedestrian islands at two sites in rural Mahnomen County, Minnesota. The short-term (two weeks) and long-term (six weeks) assessments conducted with the collected data showed a decrease in mean speed and an increase in yielding rate at one site in Twin Lakes after the installation of in-street signs but showed no change in the mean speed at the second site in Bemidji Lake.

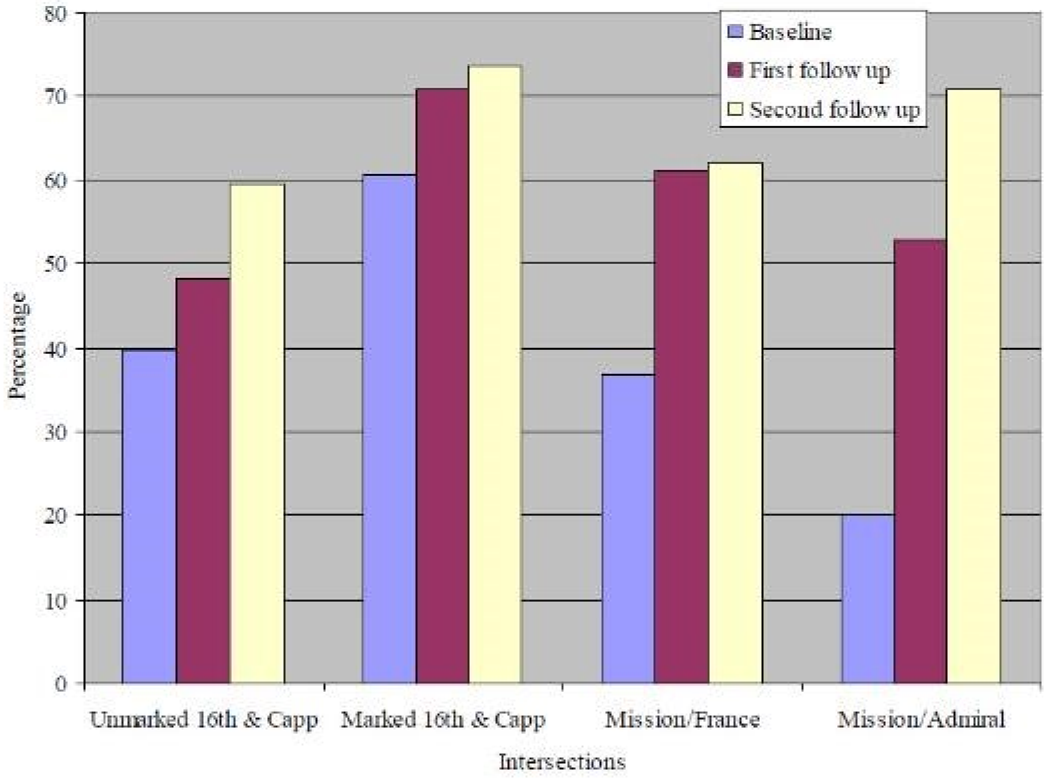

Figure 2-10 Increases in yielding rate at four sites (Banerjee et al., 2007)

A study by Banerjee and Ragland (Banerjee et al., 2007) evaluated the effect of in-street pedestrian signs on yielding rates at three intersections in San Francisco. There were two follow-up surveys conducted after the implementation to test both short-term and long-term effects. The results showed that the installation of in-street signs greatly enhanced drivers' compliance behavior. The compliance rates before installation and at each follow-up are shown in Figure 2-10.

A study by Ellis, van Houten, and Kim (Ellis et al., 2007) tested the effect of placing in-street signs in different numbers and at different distances from several crosswalks in Florida. The researchers placed single signs at the crosswalk, 20 feet ahead of the crosswalk, and 40 feet ahead of the crosswalk and also placed all three at once. The results showed that placing signs at the crosswalk had the same or greater effect as placing signs 20 or 40 feet in ahead of the crosswalk but placing all three signs at the same time had no greater effect than placing signs just at the crosswalk.

An article by Gedafa, Kaemingk, Mager, Pape, Tupa, and Bohan (Gedafa et al., 2014) evaluates the effects of in-street pedestrian signs in Grand Forks, North Dakota. Data was collected on yielding rates and average speeds with and without the in-street signs. The yield signs were placed at five locations: the edge of the crosswalk and 30, 60, 90, and 120 feet ahead of the crosswalk along the centerline in both directions. The result showed that when the signs were not present, the yielding rates were between 62% and 82% but, when the signs were present, the yielding rates were between 72% and 98%. The researchers also compared the yielding rate when signs were placed ahead of the crosswalk (72-98%) and when signs were placed at the crosswalk (97-98%). The mean vehicle speed was lower when signs were present at most of the locations. The researchers concluded that in-street pedestrian signs could increase the yielding rate and decrease the traffic speed and were most effective when signs were placed at the crosswalk.

2.6 OTHER STUDIES ABOUT PEDESTRIAN SAFETY COUNTERMEASURES

A report by Huang, Zegeer and Nassi (Huang et al., 2000) tests the effectiveness of three treatments used in conjunction with marked crosswalks aimed to improve pedestrian's safety. These three treatments used were an overhead crosswalk sign in Seattle, Washington, pedestrian safety cones reading "State Law: Yield to Pedestrians in Crosswalk in Your Half of Road" in New York State and Portland, Oregon, and pedestrian-activated overhead signs reading "Stop for Pedestrians in Crosswalk" in Tucson, Arizona. Video cameras were used to collect data on the behavior of drivers and pedestrian. The measures of effectiveness are used were the driver yielding rate, the percentage of pedestrians that had to run, hesitate, or abort their crossing, and the percentage of pedestrians that crossed in the crosswalk. The study showed that cones used in New York and the signs used in Seattle were effective in increasing the number of pedestrians who were yielded to. At one of the locations in Tucson, the overhead sign increased motorist yielding to pedestrians. The signs in Seattle and Tucson were effective in reducing the percentage of pedestrians who had to run, hesitate, or abort their crossing. None of the treatments had a clear effect on the percentage of pedestrians using the crosswalk. It should be noted that the results were not necessarily representative of all cases because the evaluation sites had different numbers of lanes and traffic volumes.

A report by Dougald, Dittberner, and Sripathi (Dougald et al., 2012) evaluates the effectiveness of two types of zig-zag pavement markings ahead of the crosswalks at W&OD Trail in Virginia. Figure 2-11 shows the zig-zag pavement marking chosen for the crosswalk on Belmont Ridge Road, a two-lane road. The zig-zag line runs down the center of one lane. Figure 2-12 shows the zig-zag pavement marking chosen for the crosswalk on Sterling Boulevard, a divided four-lane road. The zig-zag line runs down the centerline of the road and the southern lane. By comparing the crash data, average speed of vehicles, and attitudes and understanding of drivers before and after the installation of the pavement markings, researchers concluded that zig-zag pavement markings can enhance safety at mid-block crossing locations where there is a need to heighten motorist awareness.

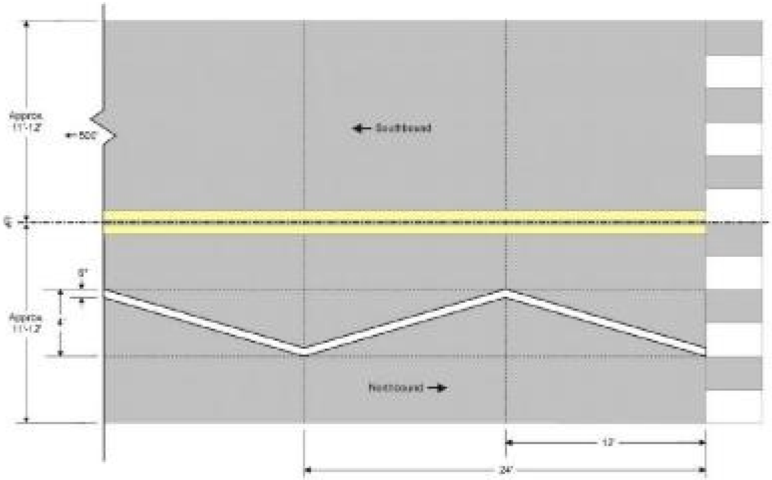

Figure 2-11 Schematic of zig-zag design chosen for Belmont Ridge Road

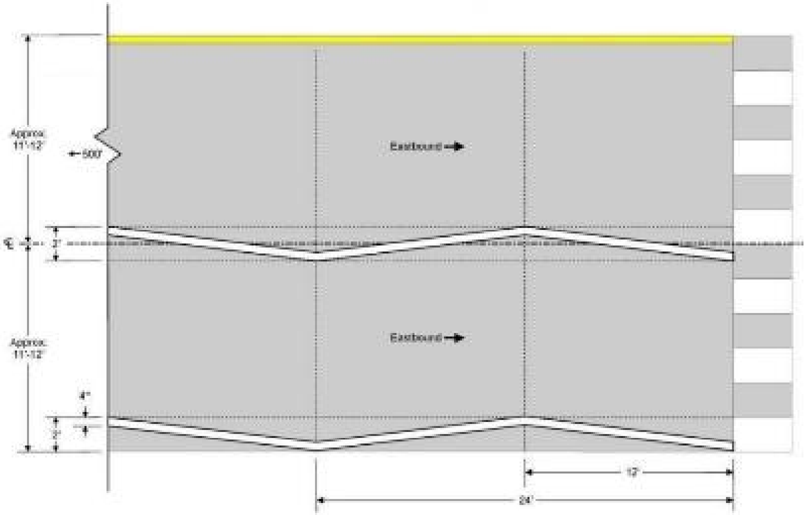

Figure 2-12 Schematic of zig-zag design chosen for eastbound approach of Sterling Boulevard

A report by Nitzburg and Knoblauch (Nitzburg et al., 2001) evaluates the effectiveness of an overhead illuminated crosswalk sign and high-visibility ladder-style crosswalk at unsignalized intersections in Clearwater, Florida. An experimental and control evaluation procedure was used. The two experimental sites had crossings at T-intersections. One of the control locations was a marked mid-block crossing with MUTCD signs and the other was an unmarked crosswalk without any warning signs. Data was collected during daytime and nighttime hours. Although the vehicle volumes and traffic gaps in the experimental and control sites were slightly different, the treatment was regarded as the main reason for the difference in the behavior of drivers and pedestrians. The data showed that the yielding rate increased from 30% to 40% during daytime, the change in yielding rate at night was insignificant (16.7% to 25.3%), the usage rate of pedestrian increased from 50% to over 80%, and pedestrians' aggressiveness did not change. It was concluded that this high-visibility crosswalk configuration enhanced the safety in the crosswalks studied. The researchers also recommended further research to test the effectiveness of this kind of high visibility crosswalks on wider streets with higher operating speeds.

A report by van Houten, Healey, Malenfant, and Retting (Van Houten et al., 1998) evaluates the effectiveness of two pedestrian treatments in increasing drivers' yielding rate at crosswalks equipped with pedestrian-activated flashing beacons, a flashing amber beacon suspended over the crosswalk (Figure 2-13). The second treatment was placing signs with the pedestrian symbol and an amber beacon star burst symbol (

Figure 2-14) that directed drivers to yield when the light was flashing 50 m ahead of the crosswalk. Data was collected at two crosswalks equipped with pedestrian-activated flashing beacons in the city of Dartmouth, Nova Scotia when the two treatments were installed separately and when they were utilized together. Observers recorded three things: the percentage of pedestrians that activated the beacon, the percentage of drivers yielding to pedestrians, and the number of pedestrian-vehicle conflicts. The data showed that both treatments increased yielding behavior but were more effective when employed together than they were when employed, and only the second treatment was effective in reducing the pedestrian-vehicles conflicts.

Figure 2-13 Example of illuminated sign with the standard pedestrian symbol

Figure 2-14 Example of "yield when flashing" sign

CHAPTER 3: USING SIMULATION TO PRIORITIZE SITES FOR TREATMENT

This chapter addresses using Monte Carlo simulation to provide a framework for hypotheses about road user behavior, specifically in the case of pedestrian and driver conflict. The chapter is largely based on the paper included in Appendix A: Pedestrian Injury Severity vs Vehicle Impact Speed: Calibrating a Relationship to Local Conditions Using Multiple Imputation.

3.1 CHARACTERIZING PEDESTRIAN SAFETY AT UNCONTROLLED CROSSINGS

Pedestrian actuated controls are not free. Installation costs for RRFBs are in the range of $10k - $15k per site while the costs for HAWKs are substantially greater. Given a set of candidate sites, but a budget insufficient to allow installation at all candidates, one can ask which sites should be given priority. Minnesota's Traffic Safety Fundamentals Handbook (Preston et al 2008) identifies two general approaches to solving this problem, called "reactive" and "proactive." In reactive approaches, crash experience is used to determine priority; one uses the crash histories from the candidate sites to estimate their individual tendencies to generate crashes and then compares these estimates to each other or to estimates of what is "typical." The critical rate method and empirical Bayes are commonly-used implementations of this idea. Reactive approaches generally require that crashes be frequent enough that acceptable sample sizes can be obtained in reasonable times, as is the case for multi-vehicle crashes at intersections or rear-ending crashes on urban freeways. Reactive approaches are less helpful when crashes tend to be serious but infrequent, such as road-departure crashes on rural highways or vehicle-pedestrian crashes.

Proactive approaches to safety planning involve first identifying crash risk factors, which are features that are over-represented in the population of sites having crashes compared to the population of similar sites not having crashes, and then identifying those sites having one or more risk factors. A classic example is the observation that, while the frequency of fatal crashes on any particular section of county road tends to be low, 40%-50% of rural fatal crashes occur on horizontal curves, even though curves make up only around 10% of the county road mileage. This suggest that curves are over-represented in the population of sites with crashes and that, other things being equal, curves should receive priority for safety-related improvements.

As originally proposed, this project intended to work along two roughly parallel tracks: (1) a field study of driver and pedestrian behavior at sites with and without pedestrian-activated crossing systems, and (2) a statistical study of risk factors associated with the occurrence of pedestrian crashes at uncontrolled crossings. Since it is well known that the frequency of pedestrian crashes tends to increase as both pedestrian and traffic volumes increase (e.g. Thomas et al 2018), a valid statistical study would require an adequate sample of locations where both vehicle and pedestrian counts have been performed. That is, historical crash data, vehicle volume data, and pedestrian count data would all be needed. Budget constraints limited the research team to using existing data sources, but unsignalized crossings with both pedestrian and vehicle counts tend to be rare. The city of Minneapolis does archive turning movement and pedestrian counts and to evaluate the feasibility of a prospective study, the Minnesota Crash Mapping Analysis Tool (MnCMAT) was used to compile pedestrian crashes at non-signalized locations in that city. A map showing these for the northeast portion of Minneapolis is shown in Figure 3-1. The city's traffic count management website was then used to identify non-signalized intersections where turning movement and pedestrian counts were available and these were then compared to the locations of the crashes shown in Figure 3-1. Of the 82 pedestrian crashes reported at non-signalized locations between 2005 and 2014 in northeast Minneapolis, only six of them occurred at locations where turning movement counts had been made during that same time period. Extrapolating this to the entire city gave an estimate of approximately 30 potential case locations for a case-control study, which is at best a marginally acceptable sample size. Also, during this stage, the research team became aware that National Cooperative Highway Research Program (NCHRP) Project 17-73 (Thomas et al. 2018) was in the process of developing guidance, with examples, for conducting proactive pedestrian safety studies. It was thus decided that a proactive study should be postponed until the NCHRP project was completed, but that this project might still make a contribution by exploring an alternative to the two standard approaches.

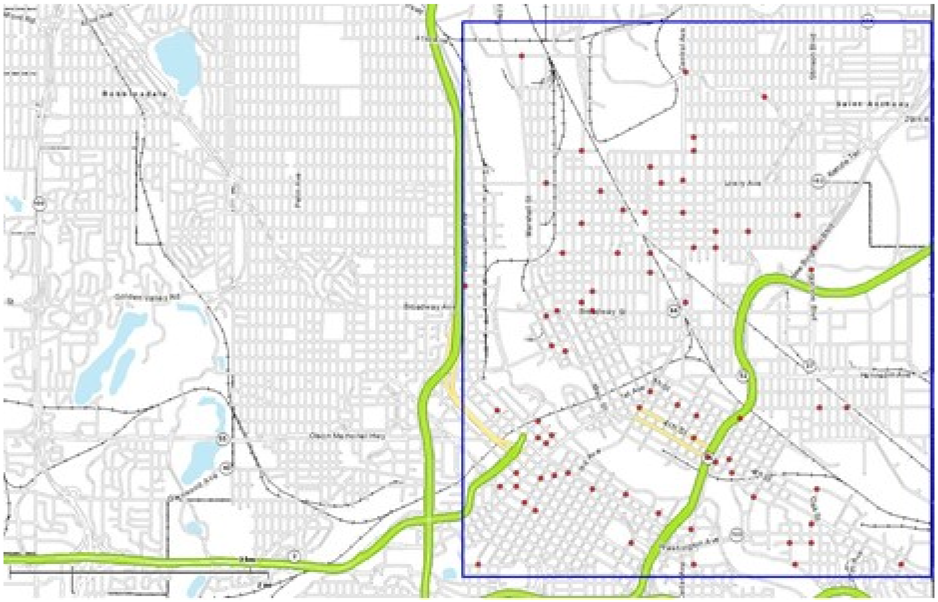

Figure 3-1 Pedestrian crashes at unsignalized intersections, Northeast Minneapolis

3.2 SIMULATION MODELING

This third option for prioritizing sites would be to use Monte Carlo (MC) simulation to rate pedestrian crash risk and to predict the change in crash risk that would follow deployment of a pedestrian-activated treatment. In MC simulation a computer is used to simulate a large sample of events (e.g. vehicle/pedestrian conflicts) and the fraction of them resulting in crashes is then an estimate of crash risk. MC simulation has been used in FHWA's Roadside Safety Analysis Program (RSAP) to evaluate roadside improvements (Mak and Sicking 2003), and a prototype for predicting the cost-effectiveness of a median barrier project has also been developed (Davis and Morris 2009). MC simulation is able to represent greater detail about individual sites than is usually possible in statistical studies but also requires a more detailed understanding of how crashes occur and how crash-related improvements achieve their effects. An earlier project (Davis, et al. 2002) described a Monte Carlo simulation model that rated the risk that traffic conditions on residential streets posed to child pedestrians and it was decided to update this model and adapt it to the problem of assessing candidate sites for pedestrian-activated controls.

3.2.1 Proposed Simulation Model

For the purposes of modeling an interaction between a vehicle and a pedestrian, a standard scenario is needed. Figure 3-2 shows a vehicle/pedestrian encounter at an uncontrolled crosswalk.

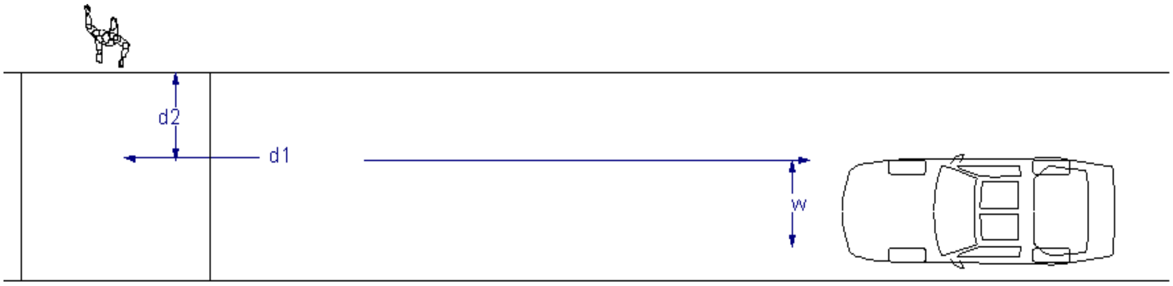

Figure 3-2 Vehicle/pedestrian encounter at an uncontrolled crosswalk.

The car, initially traveling at speed v_1, is a distance d_1 from the conflict zone when the pedestrian decides to initiate crossing. After a reaction time r_2 the pedestrian enters the road, traveling at speed v_2. The pedestrian enters the conflict zone after traveling a distance d2 from the pavement edge and exits the conflict zone after traveling a distance d_2+w from the pavement edge. If the driver does not attempt to brake, then the vehicle continues at its initial speed v_1. If the driver does attempt to brake then, after a reaction time r_1, the vehicle begins decelerating at constant rate a_1. A crash occurs if the vehicle arrives at the conflict zone while the pedestrian is in the zone. Otherwise, if the vehicle stops before reaching the conflict zone, or arrives either before the pedestrian enters or after the pedestrian exits the zone, a crash does not occur. If a crash occurs, then vi denotes the vehicle's speed at the point of impact. Formally:

Equation 3.1 Pedestrian's arrival time.

$$tped_1 = r_2 + d_2/v_2$$

Equation 3.2 Pedestrian's exit time.

$$tped_2 = r_2 + (d_2+w)/v_2$$

Equation 3.3 Vehicle's arrival time.

$$t_0 = \begin{cases} d_1 / v_1, if\ no\ braking\ or\ d_1 < r_1 v_1 \\ r_1 + \left(\dfrac{v_1 - \sqrt{v_1^2 - 2a_1(d_1 - v_1 r_1)}}{a_1} \right), if\ braking\ and\ r_1 v_1 \le d_1 \le r_1 v_1 + v_1^2 / 2a_1 \\ \infty, if\ braking\ and\ d_1 > r_1 v_1 + v_1^2 / 2a_1 \end{cases}$$

A crash occurs if $tped_1 < t_0 < tped_2$. The impact speed is then given by

Equation 3.4 Impact speed.

$$v_i = \begin{cases} v_1, if\ no\ braking\ or\ d_1 < r_1 v_1 \\ \left(\sqrt{v_1^2 - 2a_1(d_1 - v_1 r_1)} \right), if\ braking\ and\ r_1 v_1 \le d_1 \le r_1 v_1 + v_1^2 / 2a_1 \\ 0, if\ braking\ and\ d_1 > r_1 v_1 + v_1^2 / 2a_1 \end{cases}$$

If values for the variables d_1, v_1, r_1, a_1, d_2, v_2, r_2, w, and the driver's braking decision were known, then whether a collision occurs and the resulting impact speed could be computed. To link the impact speed to injury severity, an ordered logit model was developed using data from the National Highway and Transportation Safety Administration (NHTSA) Pedestrian Crash Data Study (Chidester and Isenberg 2001) supplemented with pedestrian crash records from MnDOT's Metro district. The development of this model is described in the Appendix. The following relationship, for pedestrians ages 15 to 60, is currently used in the simulation model.

Equation 3.5 Injury severity.

$$P(slight\ injury \mid v_i) = \frac{\exp(0.71 v_i - 1.89)}{1 + \exp(0.71 v_i - 1.89)}$$

$$P(serious\ injury \mid v_i) = 1 - P(serious\ injury \mid v_i)$$

Here v_i is now the impact speed in kilometers/hour.

3.2.2 Selection of Design Event(s)

In an earlier version of this model, the design pedestrian was fifth-grade boy running into a street independent of the location and speed of the vehicle, while the design driver always attempted to stop before colliding. If, as has been suggested in the literature, driver yielding rates are valid surrogates for pedestrian safety, (e.g. Schneider et al. 2018; Shaon et al. 2018) then the possibility of a driver's failing to yield (i.e. continuing at initial speed) should be included in the simulation model. Similarly, in the yielding studies that used staged pedestrian crossings (e.g. Brewer et al. 2015) the standardized event involved a pedestrian who did not initiate crossing if a vehicle's initial distance was less than a standard stopping distance, with different studies using the American Association of State Highway and Transportation Officials (AASHTO) or the Institute of Transportation Engineers (ITE) stopping distances.

So, to be comparable with the yielding rate studies, the simulation model should also include pedestrians who behave similarly.

To start, the decision was made to focus on a method for prioritizing sites for installation of HAWKs. This was because estimated crash modification factors (CMF) for HAWKs have been reported in the literature and these could be compared to the simulation model's output. Fizpatrick and Park (2010) found an estimated CMF of 0.31 (69% reduction in pedestrian crashes), while Zegeer et al. (2017) reported an estimate of 0.24 (76% reduction in pedestrian crashes). For RRFBs, on the other hand, crash modification effects remain somewhat uncertain (Zegeer et al. 2017). Also, the installations of HAWKs have been followed by substantial increases in driver yielding rates, as well as substantial use by pedestrians (e.g. Brewer et al 2015). These findings suggest the following method for prioritizing sites:

1. Using roadway, traffic, and driver yielding data collected at a candidate site, simulate the crash risk resulting from a sample of standardized pedestrian encounters;
2. Input yielding rates characteristic of HAWKs and again simulate the crash risk;
3. The ratio of these simulated risks gives a site-specific CMF for this site;
4. Prioritize a set of candidate sites according to their simulated CMFs.

This prioritization method assumes that the failure mode underlying vehicle/pedestrian crashes at uncontrolled crossings is drivers' failures to brake when encountering a crossing pedestrian. However, this is a hypothesis, not a finding, and should be tested by comparing its predictions to observed data. In particular, if the mechanism by which HAWKs achieve their estimated crash reductions is by increasing driver braking rates then, by changing these rates, it should be possible to simulate the reported CMFs. Also, using Equation 3.4 and Equation 3.5, it is possible to predict the distribution of pedestrian injury severities, and this prediction can be compared to a distribution from a crash database.

3.3 INITIAL SIMULATIONS

To start, it was decided to simulate an actual location with known traffic and geometric information. Figure 3-3 shows the intersection of Highland Parkway and Finn Ave, in St. Paul, MN, for which traffic data were available from an earlier study (Davis et al. 2002). A tube counter placed on the westbound lane of Highland Parkway had recorded individual vehicle speeds and headways during a summer afternoon peak-hour, which began at 5 PM. The westbound traffic volume during that hour was 125 vehicles and the volume for the entire day was 911 vehicles. The average vehicle speed during the 5 PM hour was 28.5 mph.

Figure 3-3 The intersection of Highland Parkway and Finn Avenue in St. Paul. North is up.

Video records of actual pedestrian crashes occurring in Helsinki (Pasanen and Salmivaara 1993) showed that the crashes tended to involve non-platooned, freely-moving vehicles, so a realistic simulation model should allow for a mixture of platooned and freely-moving vehicles. The Cowan M3 distribution (Cowan 1975; Luttinen 1999) is, arguably, the simplest model that explicitly allows does this. Cowan's M3 model assumes that the platooned vehicles follow at a constant headway Δ, while the headways for freely-moving vehicles follow a shifted exponential distribution. Letting α denote the proportion of freely-moving vehicles in the traffic stream and λ denote the vehicle arrival rate, the cumulative probability distribution for this headway model is

Equation 3.6 Cumulative probability distribution for Cowan's M3 headway model.

$$F(t) = \begin{cases} 0, & t < \Delta \\ (1-\alpha), & t = \Delta \\ 1-\alpha e^{-\lambda(t-\Delta)}, & t > \Delta \end{cases}$$

Published work (Sullivan and Troutbeck 1997) has suggested that Δ=2 seconds is reasonable for single-lane situations. Applying approximate maximum likelihood estimation to the headways observed on westbound Highland Parkway, with Δ=2 seconds, produced estimates of α=0.98 and λ=0.04 vehicles/second. That is, only about 2% of the vehicles were following in platoons. Figure 3-4 shows the empirical cumulative probability function constructed from the observed headways, together with the cumulative distribution function predicted by the fitted Cowan M3 model. A Kolmogorov-Smirnov goodness-of-fit test gave a computed test statistic D=0.08 which, being less than D_{crit}=0.124, the 5% critical value for a sample size of 120, indicates a reasonable fit between the Cowan M3 distribution and the data.

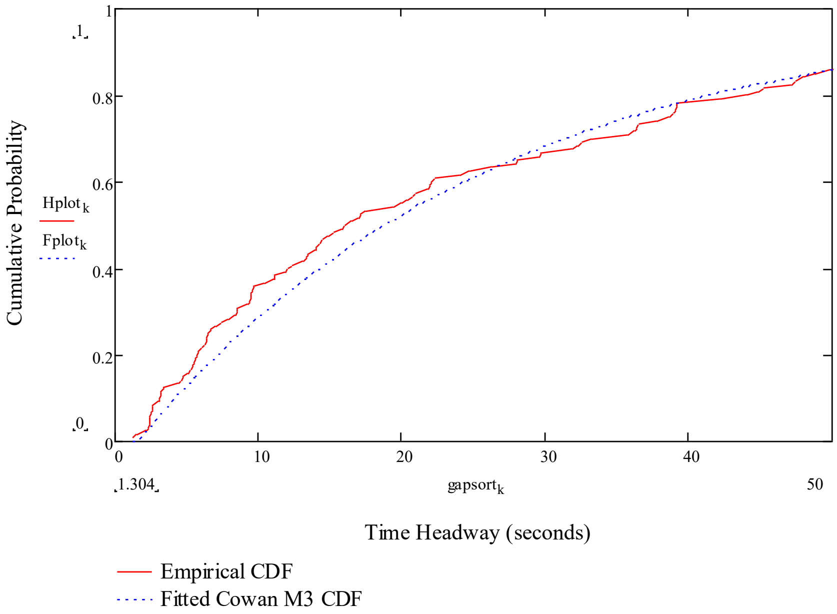

Figure 3-4 Empirical cumulative probability function and cumulative probability function from fitted Cowan M3 model.

As noted in Appendix A, 2764 police-reported collisions between adult (ages 15-60) pedestrians and either passenger cars, SUVs, pickups, or small vans were identified using MNCMAT. Of these, 1167 involved vehicles travelling straight (not turning). These collisions all occurred in MnDOT's Metro District during the years 2008-2015. The crash records included an estimate of injury using Minnesota's KABCN system, which were used to classify the collisions as shown in Table 3.1. That is, injury codes N (no injury) and C (possible injury) were coded as Slight, injury codes B (non-incapacitating injury) and A (incapacitating injury) were coded as Serious, and injury code K was coded as Fatal.

Table 3.1 Distribution of pedestrian injury severities: adults pedestrians, vehicles going straight.

Injury Category	KABCN Range	Frequency
Slight	N-C	573 (49.1%)
Serious	B-A	551 (47.2%)
Fatal	K	43 (3.7%
Total		1167

Because of the low frequency of fatal collisions, this category was combined with the Serious category to produce two categories: Serious/Fatal injury outcomes comprising 51% of the crashes, and Slight injury outcomes comprising the remaining 49%. One condition for a reasonable simulation then is that the distribution of simulated injury severities should be similar to those in Table 3.1.

The simulation model was coded to run within the WinBUGS program (Lunn et al. 2013) for simulating conditional probability distributions using Markov Chain Monte Carlo simulation. The initial test scenario involved an adult pedestrian crossing westbound Highland Parkway from the bump-out to the median, a distance of 12 feet. The conflict zone began four feet from the pavement edge and was six feet wide. Vehicle speeds were treated as normally-distributed random outcomes with a mean vehicle speed of

28.5 mph and a standard deviation of 4 mph, while vehicle headways were treated as Cowan M3 outcomes, with a traffic flow of 125 vehicles/hour and with 98% of the vehicles being free. Driver reaction times were treated as lognormal random outcomes with a mean of 1.07 seconds and a standard deviation of 0.248 seconds, consistent with findings reported by Koppa et al. (1996) in tests of surprised emergency braking. Driver braking decelerations were treated as lognormal outcomes with a mean of 0.63g and a standard deviation of 0.08G, again consistent with statistics from Koppa et al. (1996). Pedestrian walking speeds were taken to be normal random outcomes with a mean of 5.0 feet/second and a standard deviation of 0.9 feet/second, roughly consistent with the data for "non-elderly" pedestrians reported in Fugger et al (2001).

As noted above, a realistic simulation should reflect the driver and pedestrian behaviors that tend to occur in crashes. To start, two types of driver behavior were considered. Non-braking drivers, who continue at their original speeds without attempting to slow down, and braking drivers, who continue for a randomly-selected reaction time before decelerating at a randomly-chosen deceleration rate. Two types of pedestrian behavior were also considered. Careful pedestrians only accepted gaps where the initial distance was greater than the AASHTO stopping sight distance for the roads speed limit (200 feet for a 30 mph limit), emulating the staged crossings frequently used in field research. Careless pedestrians, on the other hand, accepted the first freely-moving gap regardless of the vehicle's position. For each combination of driver and pedestrian action 500,000 encounters where simulated, producing the results summarized in Table 3.2.

Table 3.2 Crash Probabilities and Injury Severity Distributions Simulated for Highland Parkway.

Driver Behavior	Pedestrian Behavior	Collision Probability	Proportion Slight Injury	Proportion Serious/Fatal
Non-braking	Careless	$1.7\cdot10^{-2}$	0.21	0.79
Non-braking	Careful	$2.8\cdot10^{-5}$	0.14	0.86
Braking	Careless	$3.7\cdot10^{-3}$	0.496	0.504
Braking	Careful	0	--	--

When all drivers braked and all pedestrians were careful, no simulated crash occurred in the 500,000 simulated encounters, while different combinations of less ideal behavior resulted in non-zero crash probabilities. The most striking feature of Table 3.2, however, is that both conditions involving non-braking drivers produced fractions of serious/fatal injuries that were noticeably higher than those in Table 3.1.

To expand on these results, another set of simulations was run, this time involving a hypothetical two-lane road. Both lanes were 12-feet wide and the interest here was on collisions occurring in the far lane. As before, the distribution of gaps between freely-moving vehicles followed a shifted exponential distribution, with a minimum headway of 2 seconds, and the traffic flow for freely moving vehicles was now 200 vehicles/lane/hour. The speed limit was 30 mph and vehicle speeds were treated as normal random variables with a mean speed of 35 mph and a standard deviation of 5 mph. All other features were the same as those used in the previous set of simulations. The results from this second set of runs are shown in Table 3.3.

Table 3.3 Summary of Results from Simulations of Hypothetical Two-Lane Road

Driver Behavior	Pedestrian Behavior	Collision Probability	Proportion Slight Injury	Proportion Serious/Fatal
Non-braking	Careless	$6.3 \cdot 10^{-2}$	0.12	0.88
Non-braking	Careful	$2.9 \cdot 10^{-2}$	0.09	0.91
Braking	Careless	$6.4 \cdot 10^{-3}$	0.60	0.40
Braking	Careful	$8.6 \cdot 10^{-5}$	0.51	0.49

As with Table 3.2, the most striking feature of Table 3.3 is that simulated situations where no drivers braked produced fractions of serious/fatal injuries that were substantially higher than those observed in the Twin Cities, while simulations where all drivers braked produced more reasonable injury distributions. To check and extend these results, the model was set to simulate collisions only, and the possibility of most, but not all, drivers braking was allowed for. 50,000 simulated collisions were generated for each selected condition and these results are summarized in Table 3.4.

Table 3.4 Results from 50,000 Simulated Collisions on a Hypothetical 2-Lane Road.

Driver Behavior	Pedestrian Behavior	Proportion Slight Injury	Proportion Serious/Fatal	Proportion Braking
0% Braking	100% Careful	0.09	0.91	0
90% Braking	100% Careful	0.10	0.90	0.03
90% Braking	0% Careful	0.34	0.66	0.46
100% Braking	0% Careful	0.60	0.40	1.0

The initial conditions for the first and fourth rows of Table 3.4 correspond to those of the second and third rows of Table 3.3, and produce similar injury severity distributions. The second row of Table 3.4 indicates that in a scenario where 90% of drivers brake, but all pedestrians are careful, simulated collisions were still dominated by non-braking drivers and 90% of simulated collisions resulted in serious/fatal injuries. On the other hand, the third row of Table 3.4 shows that, when initially 90% of simulated drivers braked, but no simulated pedestrians were careful, non-braking drivers were still over-represented in simulated collisions, but to a less extreme degree, and the injury severity distribution was less extreme.

The next set of simulations again used the hypothetical two-lane road, but looked at how crash rate and injury severity varied as the fraction of careful pedestrians varied, when all drivers attempted to brake. These results are summarized in Table 3.5.

Table 3.5 Variation in Simulated Collision Probabilities and Injury Severities with Respect to Change in Pedestrian Behavior When All Drivers Attempt to Brake.

Percent Careful Pedestrians	Collision Probability	Proportion Slight Injury	Proportion Serious/Fatal
0% Careful	$6.4 \cdot 10^{-3}$	0.60	0.40
20% Careful	$5.5 \cdot 10^{-3}$	0.60	0.40
40% Careful	$4.0 \cdot 10^{-3}$	0.60	0.40
60% Careful	$2.8 \cdot 10^{-3}$	0.61	0.39

80% Careful	$1.5\cdot10^{-3}$	0.60	0.40
99% Careful	$1.6\cdot10^{-4}$	0.56	0.44
100% Careful	$8.6\cdot10^{-5}$	0.51	0.49

Table 3.5 shows that, when all simulated drivers attempted to brake, the fraction of careful versus careless pedestrians had less effect on the distribution of injury severities. The collision probabilities listed in Table 3.5 can also be used to compute the simulated CMFs that would result from an intervention that changed pedestrian behavior. For example, when all simulated drivers attempted to brake, a change from 20% careful simulated pedestrians to 60% careful simulated pedestrians gave a simulated crash modification factor (CMF) of

$$\text{CMF} = (\text{Collision Probability After})/(\text{Collision Probability Before})$$

$$= (2.8\cdot10^{-3})/(5.5\cdot10^{-3}) = 0.51$$

Table 3.6 summarizes the simulated CMFs that result from different changes in pedestrian behavior.

Table 3.6 Simulated crash modification factors resulting from increases in percentage of careful pedestrians when all drivers attempt to brake.

		Percent Careful Pedestrians After						
		0%	20%	40%	60%	80%	99%	100%
Percent Careful Pedestrians Before	0%	1	.85	.63	.43	**.242**	.025	.014
	20%	-	1	.74	.51	**.27**	.029	.016
	40%	-	-	1	.68	**.37**	.040	.022
	60%	-	-	-	1	.54	.057	.031
	80%	-	-	-	-	1	.107	.058
	99%	-	-	-	-		1	.56
	100%	-	-	-	-	-	-	1

As noted earlier, another reasonable condition for a simulation model is that it should provide a plausible explanation for the CMFs observed in statistical studies. Also, as noted earlier, for two studies have provided estimated CMFs for installation of HAWKs: CMF=0.31 (Fitzpatrick and Park 2010) and CMF=0.24 (Zegeer et al (2017)). An FHWA study of 20 intersections in Tucson, Arizona and Austin, Texas found that 96% of drivers yielded when HAWKs were activated, that 91% of pedestrians who could have activated a HAWK in fact did so, and that "most of the observed conflicts were associated with noncompliant pedestrians" (FHWA 2016). Highlighted in bold face in Table 3.6 are changes in simulated pedestrian behavior that produce simulated CMFs similar to those reported in the literature. Increasing the fraction of careful simulated pedestrians from between 0% and 40% to 80% gives simulated CMFs consistent with those reported for installation of HAWKs.

3.4 CONCLUSIONS FROM SIMULATION STUDY

Our initial goal was to develop a simulation model that would allow engineers to enter data describing traffic and roadway conditions at a site, along with driver yielding rates from field studies, and then predict the crash modification effect likely to result from installation of a HAWK. If successful, this model could then be extended to other treatments, such as RRFBs.

In doing validation checks, however, we found that to produce an injury severity distribution similar to those observed in the Twin Cities it was necessary to assume that all, or almost all, simulated drivers attempt to brake when faced with a pedestrian conflict. This is not unreasonable since the events considered in the development of the original injury severity distribution were by default all cases where the pedestrian intersected the trajectory of a vehicle regardless of the origin of the infraction (pedestrian or driver). These events include no cases where drivers had yielded to pedestrians or pedestrians had yielded to drivers since neither of those cases results in a conflict.

Simulations where all drivers attempted to brake, and where the fraction of careful pedestrians changed from between 0% and 40% to 80%, gave simulated crash modification factors that were similar to those reported for installation of HAWKs. Together, these outcomes suggested that while the percentage of yielding drivers might be a useful indicator of pedestrian level of service it is less helpful as safety surrogate. This could be because a driver’s yielding to a pedestrian, as observed in field studies, might not be the same behavior as a driver attempting to stop during a vehicle/pedestrian conflict.

The simulation results also suggested that the crash reduction effects reported for HAWKs might result from modifying pedestrian behavior rather than, or in addition to, modifying driver behavior. At this point though, before a simulation model can be used to support practical decision-making, a better understanding is needed of how HAWKs (and RRFBs) affect both driver and pedestrian behavior, especially as to how high risk interactions are generated. Although more work is needed, this study has shown that simulation modeling can provide a framework for stating hypotheses about road user behavior and then deriving consequences from those hypotheses, that can then be compared to observations.

CHAPTER 4: OBSERVATIONAL STUDY SITES

Analysis of the PAC treatments in this study was an observational study of pedestrian-vehicle interactions at crosswalks with particular treatments. The study covered a minimum of two sites for each treatment with varying roadway conditions. At selected sites with the target treatments, a traffic conflict study based on pedestrian and vehicle trajectories was conducted to identify the individual effects of each treatment.

4.1 SITE SELECTION

Using the results of a survey sent to county engineers, city engineers, and private consultants in Minnesota requesting information on PAC system installations, a detailed list of PAC system installations throughout the state was compiled. For each site, the type of PAC system, intersection geometry, number of directions conflicting with the crosswalk, number of lanes crossed by the crosswalk, presence of a traffic island, the surrounding land use, speed limit, AADT, and number of crossings per day were recorded. This site data was used to categorize and prioritize the sites. The highest priority sites were the first sites considered when collecting and reducing data. The key features/risk factors for high-priority sites included:

- High speed (> 45 mph)
- High volume (based on AADT)
- 4+ lanes to cross
- Proximity to a school
- Presence of a traffic island
- HAWK installation

A scoring scheme was used to identify the sites with multiple features/risk factors of interest. To rank the importance of these features and risk factors, TAP members were asked to individually rank them based on their priorities and interests, and the rankings from all members were combined to generate an overall ranking. This, along with the expected pedestrian volume at a site, was used to select the sites that would provide the study with the most useful combinations of factors to study. The resulting site selections consisted of 38 sites of individually controlled crossings at 34 separate locations:

- RRFB: 24 sites at 20 separate locations
- Flashing LED: 7 sites
- HAWK: 5 sites
- Standard Signal: 2 sites

Of the sites selected, before/after analysis was possible at two of them (one with flashing LEDs and one with RRFBs). The sites selected had speed limits ranging from 25 to 55 mph, average hourly vehicle counts ranging from 11 to 1,978 vehicles, and between one and six lanes to cross. Of the 38 individually controlled crossings, seven had a traffic island within the crosswalk.

4.2 DATA COLLECTION

Data was collected at 34 locations over a total of 40 data collection periods (some locations had multiple crossings or had video before and after the system was installed). Due to video quality issues, video from five of the sites was not useable while on one of the planned before/after locations, although video before was collected, the HAWK was not installed on time to be considered in this study. A tabulation of sites and the usage of their respective video data can be found in Table 4.1. Images of each site included in the analysis and descriptions of their relevant features can be found in the Site Descriptions chapter on page 34. Video data was primarily collected in 2016 between the months of April and October (the before period for the Duluth site was collected in September 2015) using temporary battery-powered camera stations. Video data was collected from sunrise to sunset for at least seven days at each site.

Table 4.1 Summary of sites where video was collected and whether the video was analyzed

Site #	City	Location	Type	Analyzed?
1	Burnsville	TH-13, Cliff Rd E, & TH-13 & Co. Hwy 11	None (6) to LED (6)	Yes
4	Lewiston	CSAH 29 at Lewiston Elementary School	RRFB	Yes
6	Burnsville	Co Rd 11 & 140th St	HAWK	Yes
7	Maple Plain	TH-12 & Budd Ave	HAWK	Yes
8	Forest Lake	TH-61 & 2nd Ave NW	HAWK	No, video blurry
9	Red Wing	TH-61 between Franklin St & Hill St	HAWK	Yes
10	St. Cloud	TH-23 & 12th Ave S	HAWK	Yes
11	Anoka	TH-169 S of Main St	Standard Signal	Yes
12	St. Paul	Snelling Ave (TH-51) & Lincoln Ave	RRFB	Yes
13	Robbinsdale	CSAH 9 & Regent Ave	RRFB	No, video blurry
14	Richfield	66th St West of Lyndale Ave	RRFB	No, video blurry
19	Minnetonka	CSAH 3 & Woodhill Rd	RRFB	No, video blurry
20	Champlain	W River Rd & 109th Ave N	RRFB	Yes
23	Chanhassen	TH-101 & Pleasantview Rd	RRFB	Yes
24	Excelsior	TH-41 & Chaska Rd	RRFB	Yes
25	Wayzata	CSAH 15 & Kelly Ave	RRFB	Yes
26	St. Francis	TH-47 & Pederson Dr NW	RRFB	Yes
27	Lindström	CSAH 25 & 295th St	RRFB	Yes
34	Hutchinson	180th St & South Grade Ct SW	RRFB	Yes
38	Mankato	TH-169 & Belgrade Ave	RRFB	Yes
41	Lewiston	CSAH 25 & Williams St	RRFB	Yes
40	Wells	TH-22 & 2nd St SW	RRFB	Yes
45	Luverne	TH-75 & W Barck Ave	RRFB	Yes
46	Luverne	TH-75 & W Dodge St	RRFB	Yes
49	Duluth	E Superior St north of N 4th Ave E	None to RRFB	Yes
50	Bloomington	CSAH 017 & Heritage Hills Dr	RRFB	Yes
51	Anoka	E Main St between 2nd Ave & 3rd Ave	LED (Sign & In-road)	No, lights not visible
52	Anoka	W Main St & Franklin Ln	Standard Signal	Yes
U1	Bloomington	Old Shakopee Rd (CSAH 1) & Kell Ave	RRFB	Yes
U2	Wayzata	CSAH 15 & Tanager Lake	RRFB (2)	Yes
U3	Northfield	TH-3 & 3rd St	RRFB	Yes
U4	Winona	CSAH 32 & S Baker St	RRFB	Yes
U6	Hutchinson	MN-7 & Montana St NW	Future HAWK	No, not installed

4.3 SITE DESCRIPTIONS

To help contextualize the results of this report, images and brief descriptions of the sites where video data was collected and analyzed have been included. The letters denote the two (or three, in the case of crossings with an island) sides of the crossing, the numbers and arrows denote the lanes that intersect with the crossing, and the green lines represent the decision points (defined as the minimum distance from the stop line that a vehicle traveling at the speed limit would require to safely stop) for drivers in those lanes.

4.3.1 HAWK Sites

Site 6 is a two-lane crossing at a four-way intersection with a fixed-delay-activation HAWK system on the major road and stop signs on the minor road approaches. The crossing is in front of an elementary school in a residential neighborhood and, as such, sees peaks in the rate of crossings at the beginning and end of the school day. Drivers receive several advance warnings about the crossing ("school crossing ahead" and "school zone" signs) before arriving at it. The crossing is at a crest on a straight road.

Figure 4-1 Site 6 in Burnsville at Co Rd 11 & 140th St.

Site 7 is a midblock crossing on a two-lane road with a fixed-delay-activation HAWK system. The crossing is on a curve but drivers receive multiple advance warnings ("PED XING" pavement markings and "crossing ahead" signs). The crossing is in an urban area with a speed limit of 30 mph.

Figure 4-2 Site 7 in Maple Plain at TH-12 & Budd Ave.

Figure 4-3 Site 9 in Red Wing on TH-61 between Franklin St & Hill St.

Site 9 is a midblock crossing on a four lane road with a center island (two lanes between A and C, two lanes between C and B) and a fixed-delay-activation HAWK system with pushbuttons at A, C, and B. The road approaching the crossing is straight and there are pedestrian crossing signs 100 feet upstream of the crossing. The crossing is in an urban/commercial area with a reduced speed limit (30 mph) as TH-61 passes through Red Wing.

Figure 4-4 Site 10 in St. Cloud at TH-23 & 12th Ave S.

Site 10 consists of two three-lane crossings at a four-way intersection with through traffic prohibited for the minor street by a concrete median. The crossing has a variable-delay-activation HAWK system with pushbuttons at A and B only. The crossing is in a commercial/residential area with a reduced speed limit (30 mph) as TH-23 passes through downtown St. Cloud. The crossing is at the apex of a horizontal curve with straight approaches and there are pedestrian crossing signs 175 feet upstream of the crossing.

4.3.2 Flashing LED Sign Sites

Site 1 consists of two intersections with a total of 6 crossings between the curb and a channelizing island. The first intersection is at TH-13 and Co. Rd 11 with the second is nearby at TH-13 and Cliff Rd (all arterial roads). Crossings a, b, d, and e at Site 1 cross free right turn lanes where two roads meet at an acute angle thus forcing drivers to slow down as they approach the crossing. Crossings c and f, on the other hand, are located at corners where two roads meet at obtuse angles thereby allowing vehicles that are not stopping to maintain their speed through the turn. The three roads that make up the site all have fairly high speed limits (45 mph for Cliff Road and 50 mph for TH-13 and Co. Rd 11). Video was collected at each crossing before and after the installation of crosswalks and flashing LED PAC systems.

Figure 4-5 Aerial view of Site 1 Burnsville, MN, with major roads and crossings (a-f) labeled

Figure 4-6 Site 1a in Burnsville at the southwest corner of TH-13 & Co Rd 11 BEFORE the installation of a flashing LED sign.

Figure 4-7 Site 1a in Burnsville at the southwest corner of TH-13 & Co Rd 11 AFTER the installation of a flashing LED sign.

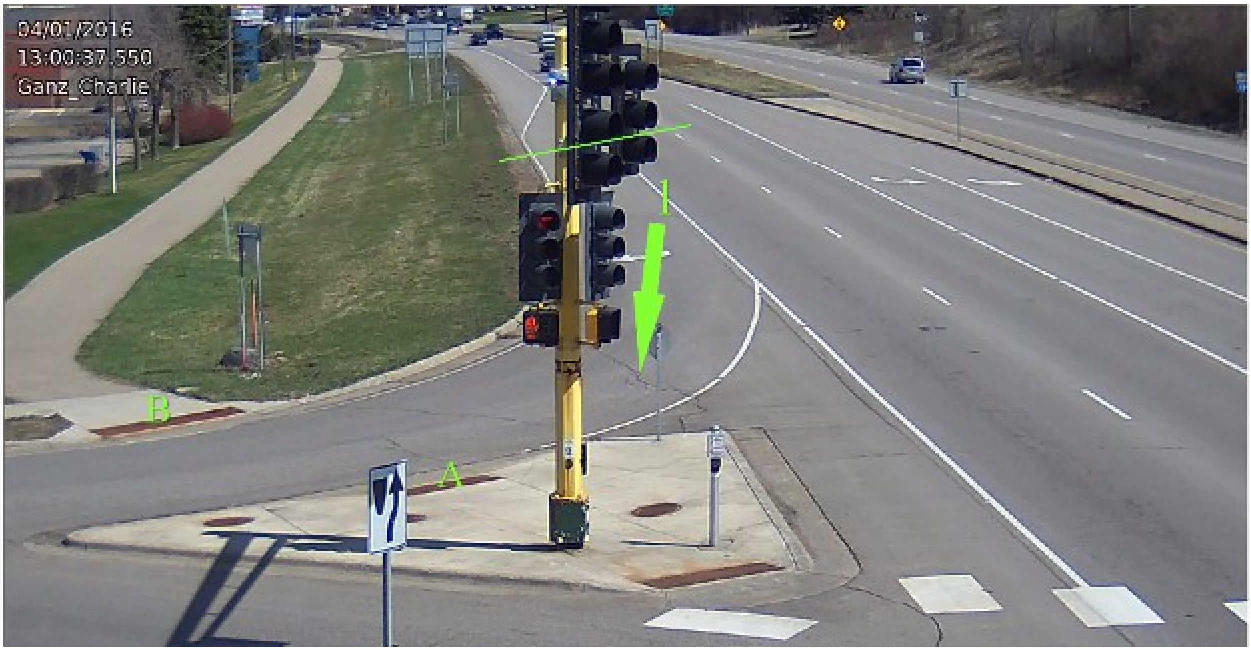

Figure 4-8 Site 1b in Burnsville at the northeast corner of TH-13 & Co Rd 11 BEFORE the installation of a flashing LED sign.

Figure 4-9 Site 1b in Burnsville at the northeast corner of TH-13 & Co Rd 11 AFTER the installation of a flashing LED sign.

Figure 4-10 Site 1c in Burnsville at the northwest corner of TH-13 & Cliff Rd BEFORE the installation of a flashing LED sign.

Figure 4-11 Site 1c in Burnsville at the northwest corner of TH-13 & Cliff Rd AFTER the installation of a flashing LED sign.

Figure 4-12 Site 1d in Burnsville at the northeast corner of TH-13 & Cliff Rd BEFORE the installation of a flashing LED sign.

Figure 4-13 Site 1d in Burnsville at the northeast corner of TH-13 & Cliff Rd AFTER the installation of a flashing LED sign.

Figure 4-14 Site 1e in Burnsville at the southwest corner of TH-13 & Cliff Rd BEFORE the installation of a flashing LED sign.

Figure 4-15 Site 1e in Burnsville at the southwest corner of TH-13 & Cliff Rd AFTER the installation of a flashing LED sign.

Figure 4-16 Site 1f in Burnsville at the southeast corner of TH-13 & Cliff Rd BEFORE the installation of a flashing LED sign.

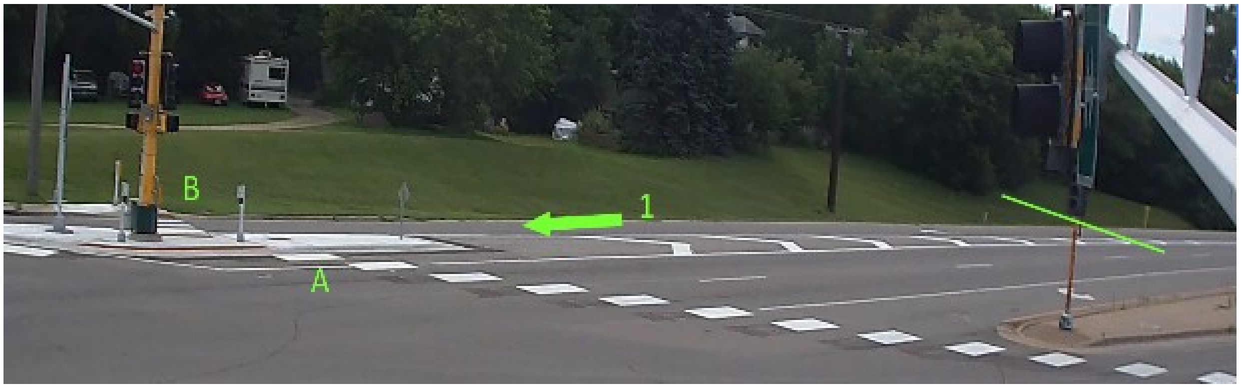

Figure 4-17 Site 1f in Burnsville at the southeast corner of TH-13 & Cliff Rd AFTER the installation of a flashing LED sign.

4.3.3 Traffic Signal Sites

Site 11 is a midblock crossing on a four lane road with a center island (two lanes between A and C, two lanes between C and B) and a standard signal with pushbuttons at A and B only. The signal appears to be coordinated with the nearby signals, sometimes causing long delays between the times the button is pushed and the signal is activated. The crossing is in a commercial/residential area with a reduced speed limit (30 mph) as TH-169 passes through downtown Anoka. The road approaching the crossing is relatively straight and there are overhead pedestrian crossings signs directly above the crosswalk.

Figure 4-18 Site 11 in Anoka on TH-169 south of Main St.

Site 52 consists of two two-lane crossings at an offset four-way intersection with a center island. The crossing has a standard signal with pushbuttons at A and B only. The crossing is in front of an elementary school in a residential neighborhood on a 35 mph road. Drivers receive several advance warnings about the crossing ("school crossing ahead" and "school zone" signs) before arriving at the crossing. The road approaching the crossing is straight and flat. Between the upstream signalized intersection to the east and the site, there is a dynamic speed limit sign for 35 mph, an S4-5 school speed limit sign for 25 mph, a school speed limit assembly sign (S4-3P, R2-1, and S4-1P), and a S1-1 School Ahead sign 200 feet from the crossing. The road geometry is similar to the west and the road has the same signage but without the initial dynamic speed warning sign.

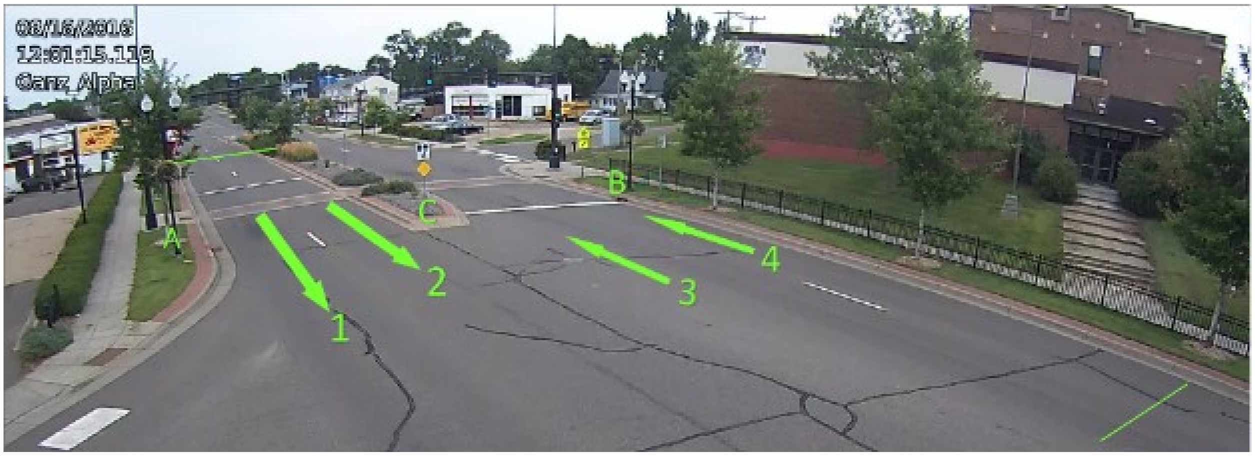

Figure 4-19 Site 52 in Anoka at W Main St & Franklin Ln.

4.3.4 RRFB Sites

Site 4 is a two-lane midblock crossing with an RRFB. The crossing is in front of an elementary school in a residential neighborhood and, as such, sees increased crossings at the start and end of the school day. The road approaching the crossing is straight and flat and has two advance warnings.

Figure 4-20 Site 4 in Lewiston on CSAH 29 near Lewiston Elementary School.

Figure 4-21 Aerial view of Site 4. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 12 consists of two two-lane crossings at a T-intersection with a center island and roadside RRFBs with pushbuttons at A, C, and B. The crossing is in an urban area with Macalester College on one side of the road and residential neighborhoods on the other. The speed limit is 30 mph. There are advance Pedestrian Crossing signs 175 feet upstream of the crossing in both directions but the sign to the north is obscured by a bus shelter.

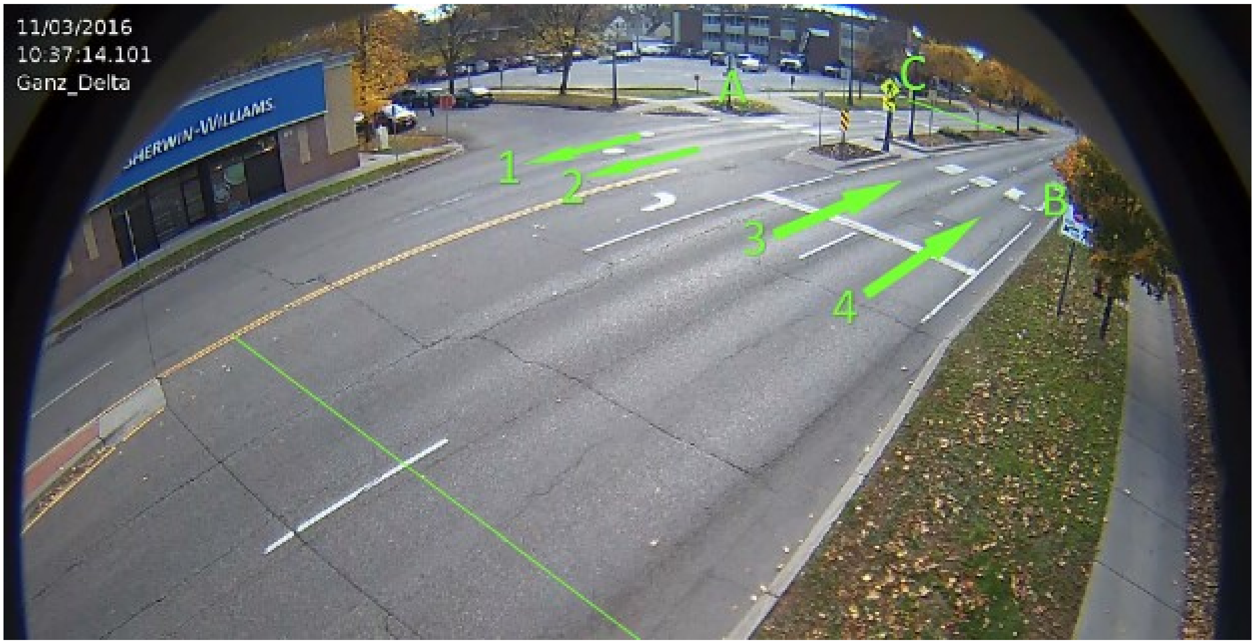

Figure 4-22 Site 12 in St. Paul at Snelling Ave (TH-51) & Lincoln Ave.

Figure 4-23 Aerial view of Site 12. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 20 is a three-lane crossing at a T-intersection with an RRFB at the crossing and advanced warning RRFBs 600 feet upstream of the crossing in both directions. The road is in a residential neighborhood half a mile away from a high school and middle school and, as such, has higher crossing rates at the beginning and end of the school day. The crossing also serves as the terminus of a bike trail. The road is straight and flat to the northwest but is curved to the south of the crossing. The speed limit is 50 mph.

Figure 4-24 Site 20 in Champlain at W River Rd & 109th Ave N.

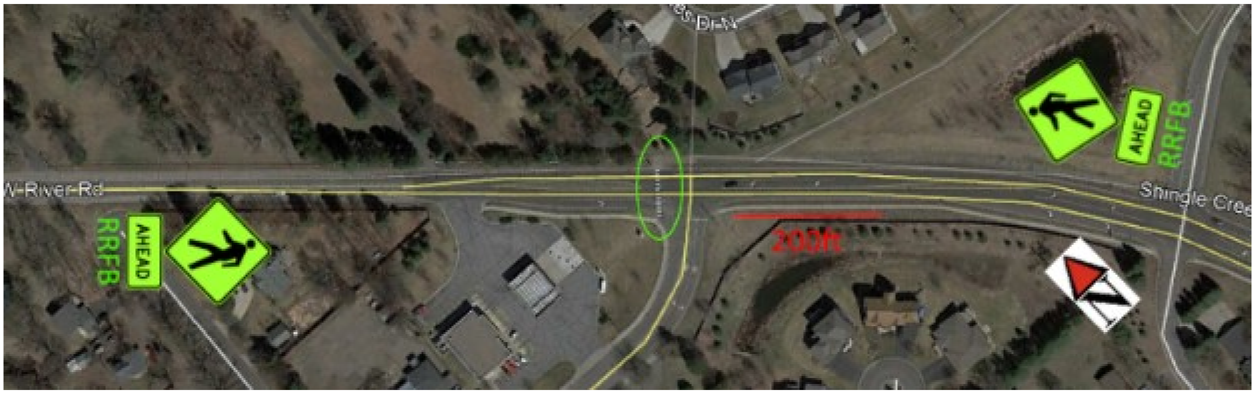

Figure 4-25 Aerial view of Site 12. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 23 is a four-lane crossing at a four-way intersection with overhead and roadside RRFBs. The crossing is on an arterial road with a speed limit of 45 mph and residential neighborhoods to either side. The road leading up to the intersection is straight and flat with pedestrian crossing signs 450 and 650 feet upstream of the crossing to the north and south, respectively.

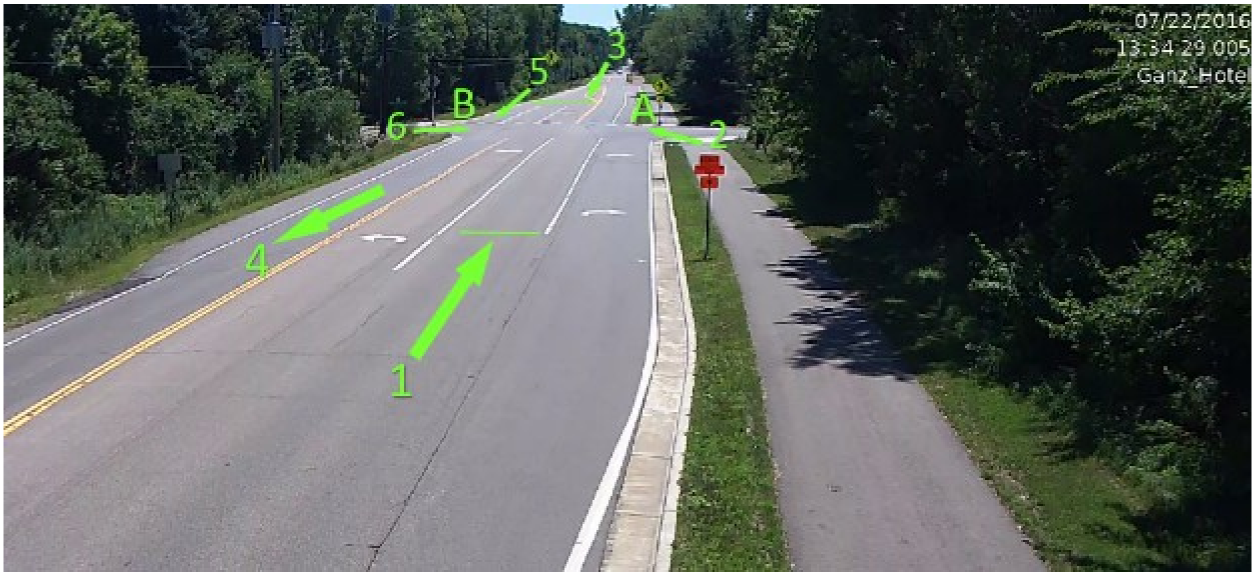

Figure 4-26 Site 23 in Chanhassen at TH-101 & Pleasantview Rd.

Figure 4-27 Aerial view of Site 23. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 24 consists of a two-lane crossing (A to C) and a three-lane crossing (C to B) at a T-intersection with a center island. The crossing has overhead and roadside RRFBs with pushbuttons at A and B only. The crossing is near a middle school and is on an arterial road with residential areas on either side. The crossing serves a mixed-use trail running parallel to the arterial road. The road leading up to the crossing is fairly straight with a speed limit of 45 mph (35 mph when school children are present according to the signs 350 feet upstream to the north and 950 feet upstream to the south). The road is relatively flat to the south but slopes upward as it approaches the crossing from the signalized intersection to the north. There are several school crossing signs at the site (500 feet upstream to the north and 400 and 1200 feet upstream to the south).

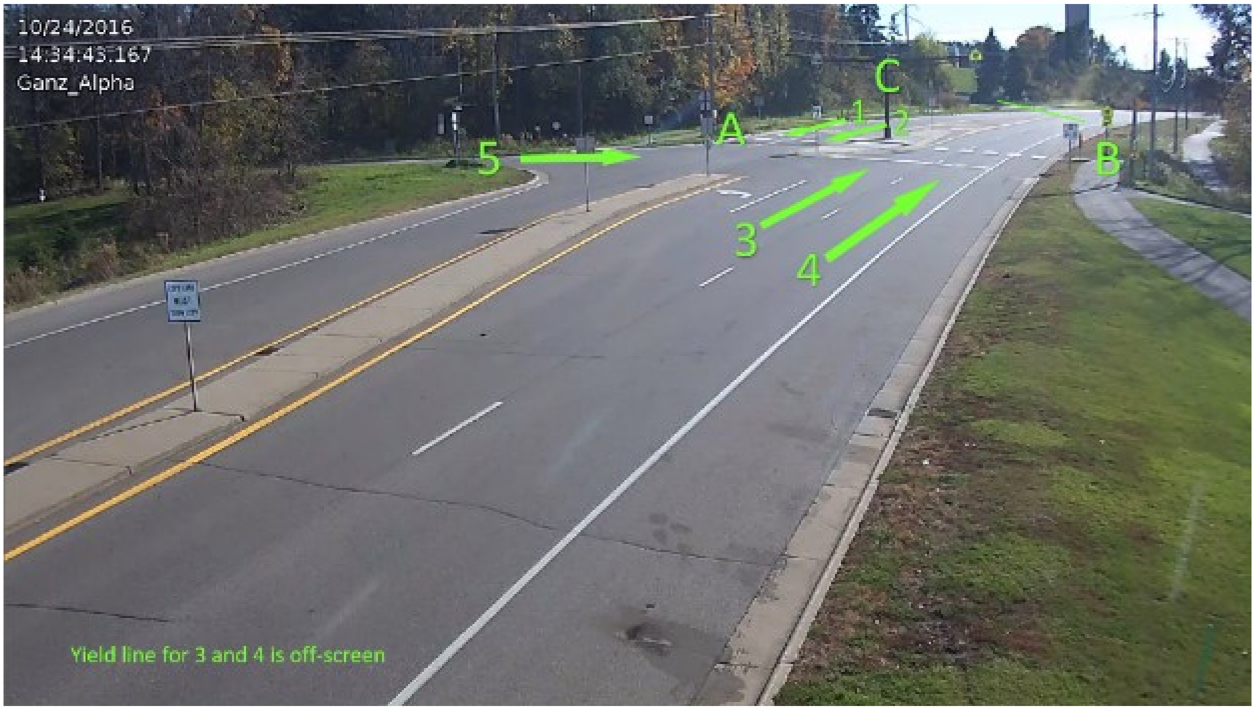

Figure 4-28 Site 24 in Excelsior at TH-41 & Chaska Rd.

Figure 4-29 Aerial view of Site 24. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 25 is a midblock crossing with a center island on a three-lane road, resulting in two one-lane crossings. The crossing has RRFBs at the crossing and, because of the limited sight distance caused by the uphill grade, an advance RRFB 400 feet upstream on the western approach. On the western approach, between the advanced RRFB and the actual crossing there is an additional, non-instrumented, marked crosswalk with a regular pedestrian crossing sign and a transit shelter 250 feet to the west. There is a signalized intersection approximately 500 feet to the east of the crossing. The road to the east is straight and flat and does not have any additional signage. The crossing is on an arterial in a commercial area with a speed limit of 35 mph.

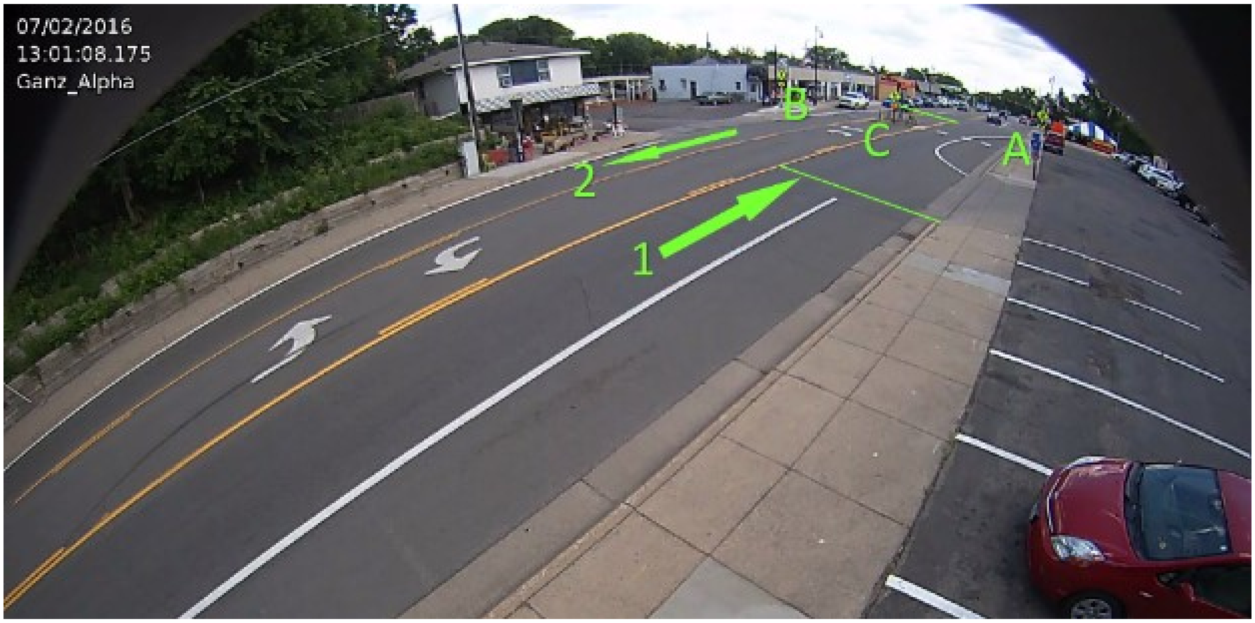

Figure 4-30 Site 25 in Wayzata at CSAH 15 & Kelly Ave.

Figure 4-31 Aerial view of Site 25. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 26 consists of a four-lane crossing (A to C) and a two-lane crossing (C to B) at a four-way intersection with a median. The crossing has overhead and roadside RRFBs with pushbuttons at A and B only. The minor road is stop-controlled. The crossing is on an arterial road with a middle school on one side of the road and a low-density commercial area on the other and, as such, has higher crossing rates at the beginning and end of the school day. The road leading up to the crossing is straight and flat with a speed limit of 50 mph. There are school crossing signs 700 feet upstream of the crossing in both directions.

Figure 4-32 Site 26 in St. Francis at TH-47 & Pederson Dr NW.

Figure 4-33 Aerial view of Site 26. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 27 is a three-lane crossing at a four-way intersection with roadside RRFBs. The crossing is on an arterial with a high school on one side of the road and residential areas on the other. The road leading up to the crossing is straight and flat with a speed limit of 30 mph as it passes through Lindström. There is no additional signage.

Figure 4-34 Site 27 in Lindström at CSAH 25 & 295th St.

Figure 4-35 Aerial view of Site 27. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 34 is a two lane crossing at a T-intersection with roadside RRFBs. There are also pedestrian crossing signs 700 feet upstream to the west and 800 feet upstream to the west. The crossing is on a rural highway with a field on one side and residential area on the other. The crossing serves a mixed use trail that runs along the north side of the highway before crossing south to the residential area. The road leading up to the crossing is straight and flat with a speed limit of 45 mph. The crossing sees very little pedestrian or vehicle traffic – an average of 83 vehicles and 0.5 crossings per hour. Over the course of seven days, only 48 crossings were observed – 6 of which involved interactions with vehicles.

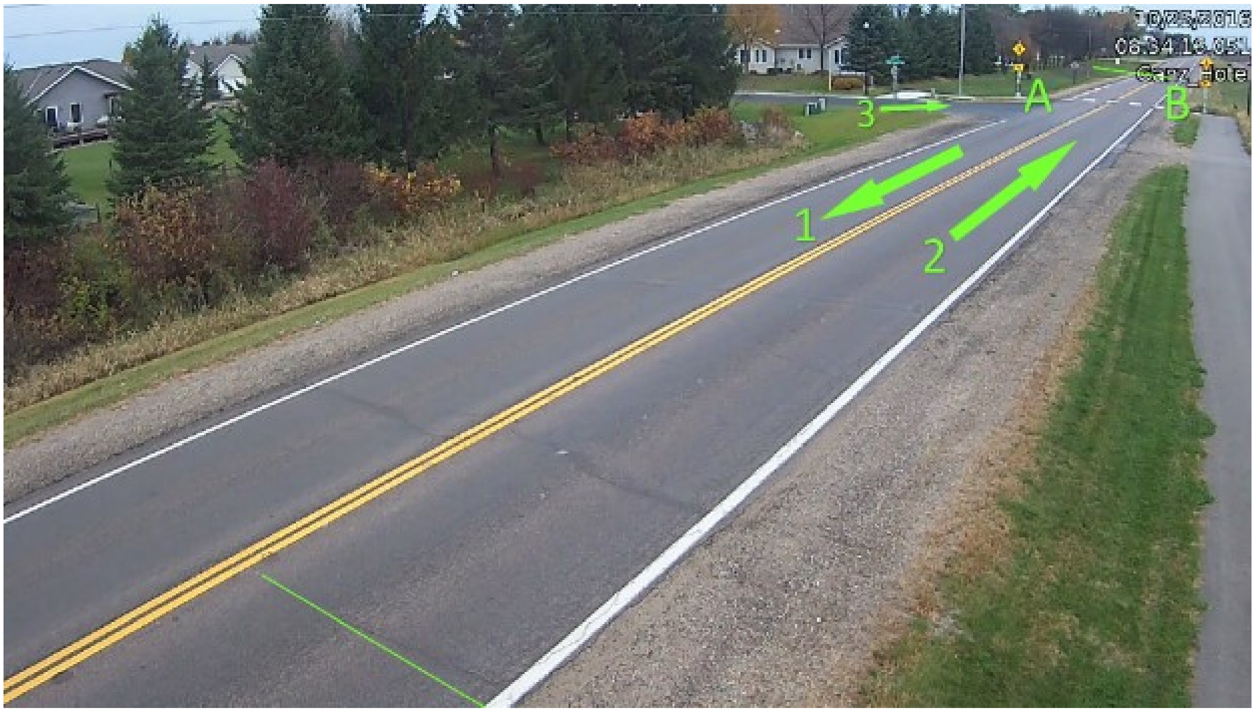

Figure 4-36 Site 34 in Hutchinson at 180th St & South Grade Ct SW.

Figure 4-37 Aerial view of Site 34. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 38 is a one-lane crossing on a free right turn lane with an automatic roadside RRFB. The system is designed to detect pedestrians as they approach the crossing and automatically activate the RRFB. The crossing is on the free right turn lane of a six-lane highway with a 30 mph speed limit but 200 feet upstream of the crossing there is an advisory speed of 15 mph for the free right turn. There is no advance signage regarding the pedestrian crossing.

Figure 4-38 Site 38 in Mankato at TH-169 & Belgrade Ave.

Figure 4-39 Aerial view of Site 38. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 40 is a two-lane crossing at a T-intersection with automatically activated roadside RRFBs. The crossing is on an arterial road with a reduced speed limit (30 mph) as it passes through a residential area of Wells. There is no advance signage. The site includes school signs but the school is more than a mile away and not clearly related to this intersection.

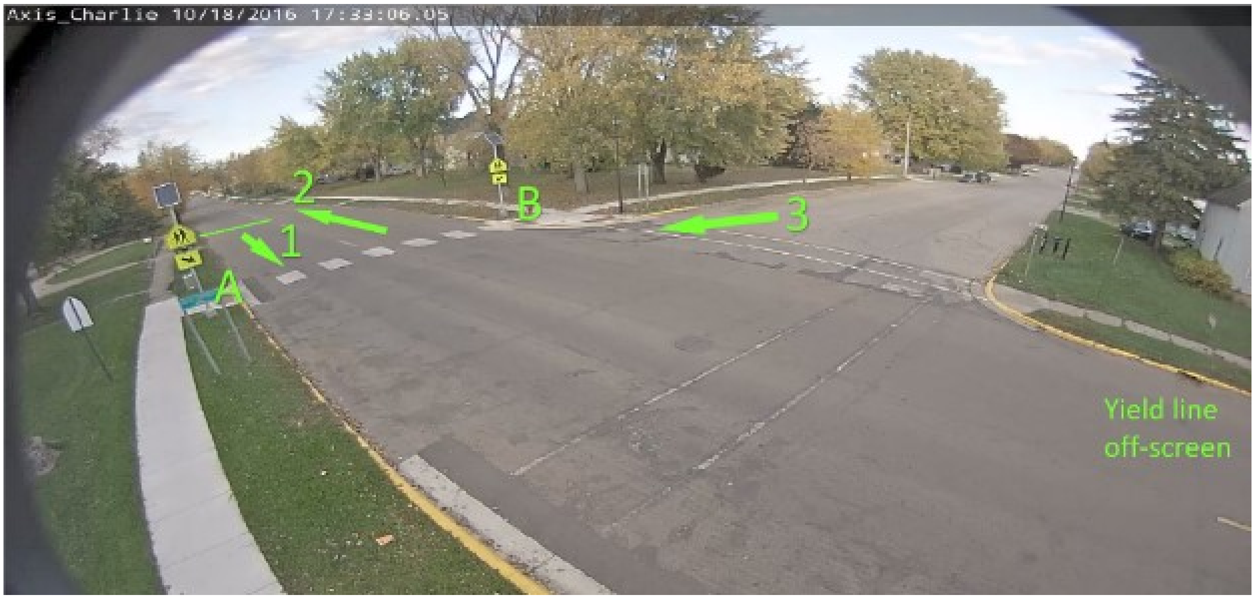

Figure 4-40 Site 40 in Wells at TH-22 & 7th St SW.

Figure 4-41 Aerial view of Site 40. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 41 is a two-lane crossing at a T-intersection with roadside RRFBs on the major road. The minor road is stop-controlled. The crossing is on highway with a reduced speed limit (30 mph) as it passes through Lewiston. The highway has a high school on one side and residential areas on the other and, as such, has higher crossing rates at the beginning and end of the school day. The road approaching the crossing is straight and flat with school crossing signs.

Figure 4-42 Site 41 in Lewiston at CSAH 25 & Williams St.

Figure 4-43 Aerial view of Site 41. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site 45 is a three-lane crossing at a T-intersection with roadside and overhead RRFBs on the major road. The RRFBs are automatically activated as pedestrians approach the crosswalk. The minor road is stop-controlled. The crossing is on a highway with a reduced speed limit (30 mph) as it passes through Luverne. The highway has a high school on one side and residential areas on the other and, as such, has higher crossing rates at the beginning and end of the school day. The road approaching the crossing is straight and slopes downhill as it runs north. There is a school crossing sign 800 feet upstream to the north and two sets of “School Xing” pavement markings 250 and 800 feet upstream to the north. There are no additional signs or road markings to the south but the site is only two blocks (1100 feet) north of the crossing at Site 46.

Figure 4-44 Site 45 in Luverne at TH-75 & W Barck Ave.

Before a 3-lane conversion, the major road used to have two marked pedestrian crossings between Sites 45 and 46. These pavement markings and signage were not replaced after the conversion was completed but the sidewalks still have outlets to the road at those locations. As a result, there are many pedestrians that cross the major road between the two sites.

Figure 4-45 Aerial view of Sites 45 (right) and 46 (left). Advanced warning sign icons correspond to the sign locations. The crossing are highlighted by the green oval.

Site 46 is two blocks to the south of Site 45 and has the same characteristics except that it is at a four-way intersection. The minor approaches are stop-controlled. There are no advance signs related to this pedestrian crossing on the approach from the north but there is a school crossing sign 800 feet to the south.

Figure 4-46 Site 46 in Luverne at TH-75 & W Dodge St.

Site 49 is a three-lane crossing at a T-intersection that had roadside RRFBs installed. The crossing is in a commercial area on a curving road with a 30 mph speed limit. The crossing has high vehicle and pedestrian volumes – an average of 585 vehicles and 19.5 crossings per hour. The minor road is stop-controlled and the major road has no advance signage. Prior to the installation of the RRFB at the site, there was no signage at the crossing.

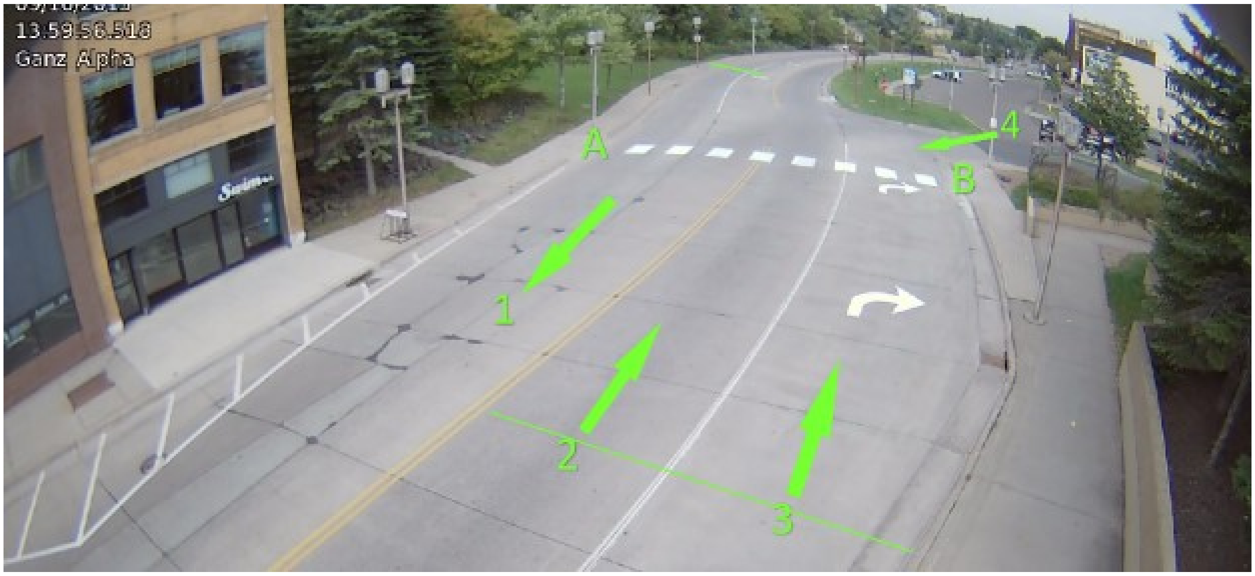

Figure 4-47 Site 49 in Duluth on E Superior St north of N 4th Ave E BEFORE the installation of an RRFB.

Figure 4-48 Aerial view of Site 49. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

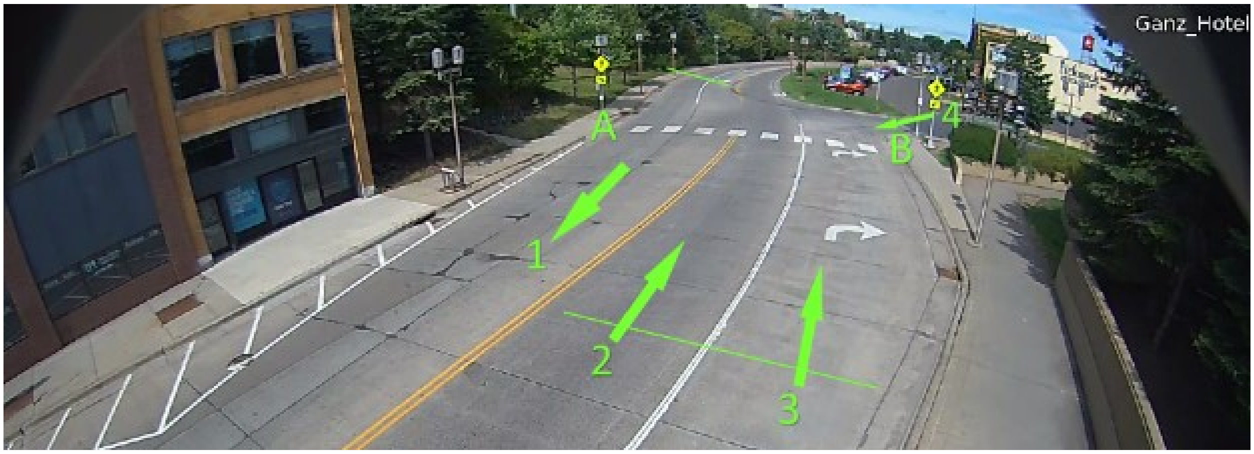

Figure 4-49 Site 49 in Duluth on E Superior St north of N 4th Ave E AFTER the installation of an RRFB.

Site U1 is a four-lane crossing at a four-way intersection with roadside and overhead RRFBs at the crossing and advanced warning RRFBs upstream of the crossing in both directions. The road is slightly curved but flat with a speed limit of 35 mph. The only additional signage is an advance RRFB 400 feet upstream to the east.

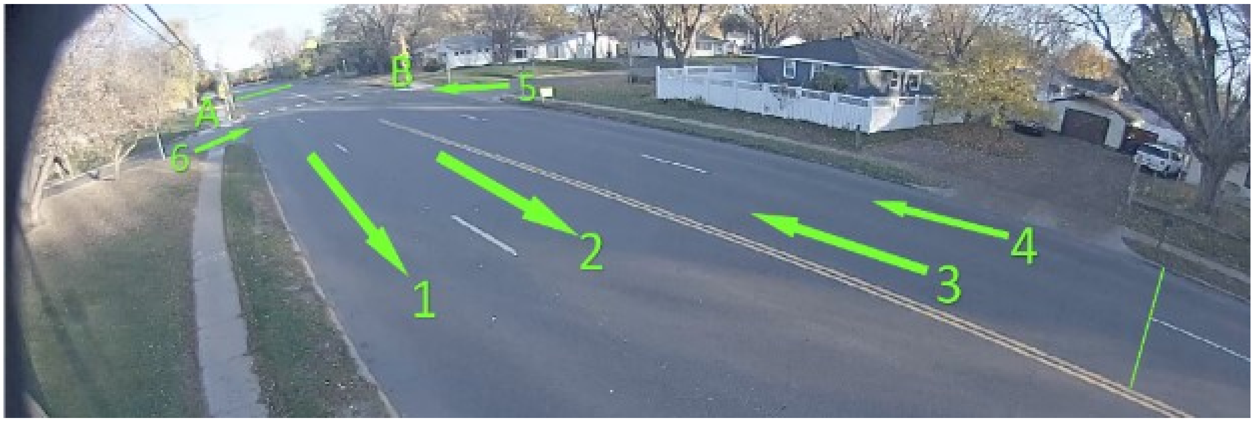

Figure 4-50 Site U1 in Bloomington at Old Shakopee Rd (CSAH 1) & Kell Ave.

Figure 4-51 Aerial view of Site U1. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site U2 consists of two two-lane midblock crossings (U2a from A to B and U2b from C to D). The site is on isthmus in Lake Minnetonka and has a marina on each side. There are no sidewalks leading to the site so the only pedestrian traffic is between the two marinas. The speed limit is 35 mph. The road approaching U2a from the south is flat but with a sharp curve resulting in limited sight distance of no more than 300 feet. The following signs are posted on the northbound approach: a speed limit sign for 30 mph, an advance RRFB linked to the RRFBs at the crossing, and a curve speed warning for 30 mph. The road approaching U2b from the north is straighter, resulting in a sight distance of about 450 feet. In regards to signs, this approach also has an advance RRFB about 500 feet upstream. Note that both advance RRFBs are frequently partially obscured by vegetation (as was the case during data collection). The two crossings each have roadside RRFBs with pushbuttons but both sets (and their respective advance RRFBs) are activated when any pushbutton is pressed.

Figure 4-52 Sites U2a (near side) and U2b (far side) in Wayzata on CSAH 15 near the marina on Tanager Lake.

Figure 4-53 Aerial view of Sites U2a (right) and U2b (left). Advanced warning sign icons correspond to the sign locations. The crossings are highlighted by the green ovals.

Site U3 is essentially a midblock crossing (there are no turning movements conflicting with the crosswalks) with two two-lane crossings and a median. The site has roadside and overhead RRFBs at the crossing. The crossing is on a highway with a reduced speed limit (30 mph) as it passes through a commercial area of Northfield. The road approaching the crossing is flat in both directions but curves when approaching from the north.

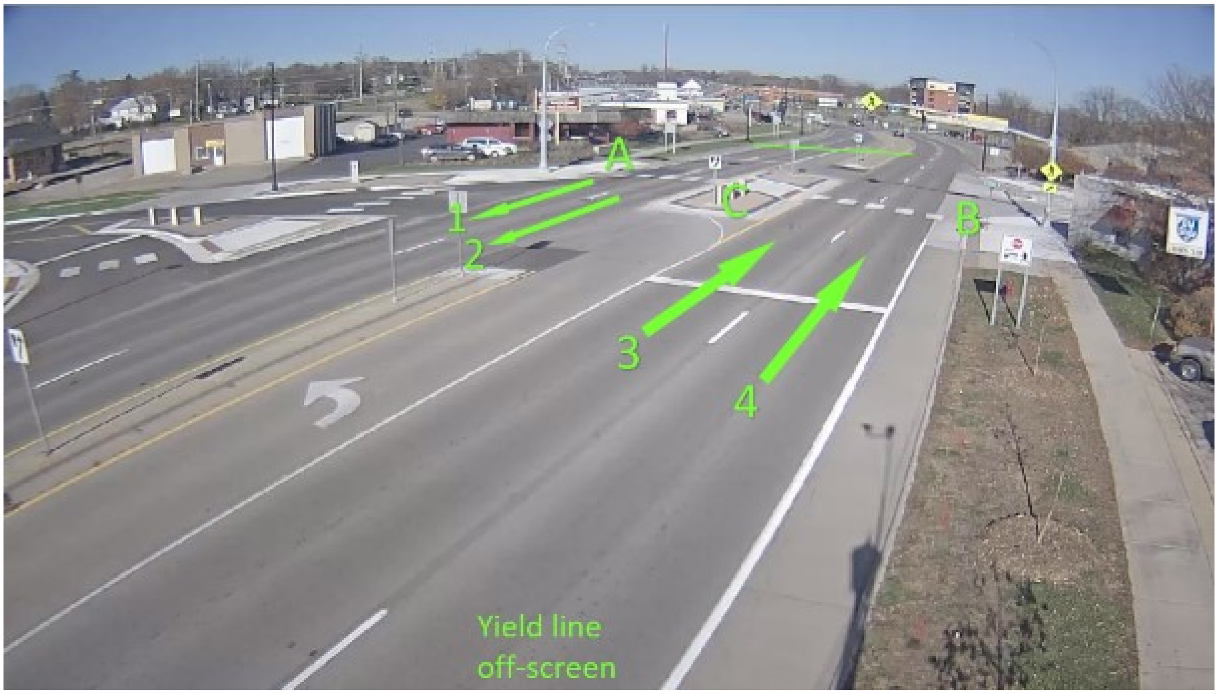

Figure 4-54 Site U3 in Northfield at TH-3 & 3rd St.

Figure 4-55 Aerial view of Site U3. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

Site U4 consists of a one-lane crossing (B to C) and a three-lane crossing (C to A) at a four-way intersection with roadside RRFBs and school crossing signs upstream of the crossing. The crossing is on an arterial that has a high school on one side and residential areas on the other and, as such, has higher crossing rates at the beginning and end of the school day. The site has high pedestrian volumes and moderate vehicle volumes. The road approaching the crossing is flat in both directions but curves when approaching from the east. The speed limit is 30 mph but drops down to 20 mph when school children are present as per the signs 125 upstream to the east and 275 feet upstream to the west. There are also school crossing signs 275 feet upstream to the east and 400 feet upstream to the west.

Figure 4-56 Site U4 in Winona at CSAH 32 & S Baker St.

Figure 4-57 Aerial view of Site U4. Advanced warning sign icons correspond to the sign locations. The crossing is highlighted by the green oval.

CHAPTER 5: DATA REDUCTION

Following the collection of video data at the selected sites, one week of video was selected from each site for data reduction. Days were selected in such a way as to avoid days where any video data was missing or unusable. The data reduction process consisted of two passes per site – one pass to get hourly vehicle counts and identify all crossings at the site by time and date and note whether there were any vehicles in the vicinity during the crossing and a second pass to further examine the crossings where pedestrians interacted with vehicles.

5.1 PRE-SORTING

The first pass of the data reduction process, the pre-sorting pass, not only provided hourly vehicle counts for the relevant directions at the site, it allowed researchers to quickly find crossings and mark the events where vehicles and pedestrians may have interacted for further investigation. This time savings was especially apparent at intersections with low pedestrian and vehicle volumes because the pre-sorting process allowed researchers to navigate to the rare interactions. At sites with a traffic island, the crossing from one curb to the other was broken up into two crossings – one from the curb to the island and a second from the island to the opposite curb – because, unlike crossings without an island, pedestrians could safely wait for vehicles to yield halfway through crossing the road.

5.2 EVENT LOGGING

The second pass of the data reduction process, the interaction logging pass, involved collecting detailed data for every interaction, both for the pedestrian crossing road and for each lane of traffic that they interacted with. Note that the term “pedestrian” refers to both a single person crossing the road and a group crossing the road.

The data collected for the pedestrian consisted of the following:

- The manner in which the pedestrian used the crosswalk (started in crosswalk and stayed in crosswalk, started in crosswalk and left outside of crosswalk, started outside of crosswalk and finished in crosswalk, or never used crosswalk)
- Whether the system was activated
- Whether the pedestrian was on a bike or on foot
- Who yielded (only drivers, only pedestrians, or some combination of the two)
- The time the first pedestrian showed their intent to cross the road (either by activating the system or by using body language)
- The time the first pedestrian entered the road
- The time the last pedestrian reached the other side of the road
- The number of pedestrians making the crossing
- The pedestrian’s origin
- The pedestrian’s destination

- Whether the pedestrian was forced to stop before reaching a traffic island or the opposite curb after leaving the curb

Under Minnesota law, “Where traffic-control signals are not in place or in operation, the driver of a vehicle shall stop to yield the right-of-way to a pedestrian crossing the roadway within a marked crosswalk or at an intersection with no marked crosswalk. The driver must remain stopped until the pedestrian has passed the lane in which the vehicle is stopped. No pedestrian shall suddenly leave a curb or other place of safety and walk or run into the path of a vehicle which is so close that it is impossible for the driver to yield.” (Minn. Stat. § 169.21) Because determining whether a vehicle is “so close that it is impossible for the driver to yield” is quite subjective and difficult to judge from video, a decision point was defined as the minimum distance from the stop line that a vehicle traveling at the speed limit would require to safely stop. The AASHTO design guidelines were used to compute this distance from the respective stop lines for all lanes that intersected with the crosswalk but did not have a stop sign (see Equation 5.1). A deceleration of 11 ft/sec^2 was used but excluded the reaction time distance traveled to balance the fact that this is not an emergency stop.

Equation 5.1

$$d = \frac{u_{SL}^2}{30(\frac{a}{g} \pm G)}$$

Where

d is the minimum distance from the crosswalk at which a driver can safely stop (ft)
u_{SL} is the speed limit (mph)
a is the acceleration due to gravity (11 ft/sec^2)
g is the acceleration due to gravity (32.2 ft/s^2)
G is the grade (assumed to be 0)

For the purposes of determining whether a driver yielded, the Minnesota statute was interpreted as exempting drivers from yielding if they were between the conflict point (the point where the respective trajectories of the vehicle and the pedestrian intersect) and the decision point at the time that the pedestrian showed their intent to cross. For the purposes of this analysis, all vehicles that were upstream of the decision point at that time that the pedestrian showed their intent to cross are considered as having interacted with the pedestrian. If all interacting vehicles yielded to the pedestrian, the yielder for the crossing is recorded as “vehicle”. If none of the interacting vehicles yielded, the yielder for the crossing is recorded as “pedestrian”. If some but not all of the interacting vehicles yielded, the yielder for the crossing is recorded as “both”.

To serve as a reference while event data was being recorded, a screenshot of the video for each site was saved and labeled. The image annotations consisted of labels for the sides of the road (and median if applicable), the lanes intersecting the crosswalk, and the driver decision point. Figure 5-1 shows an example of an annotated screenshot.

For each site, data for instances of pedestrian-vehicle interactions was recorded until a minimum of 100 interactions were observed and all hours of the day between sunrise and sunset were covered. In total, 11,440 crossings were identified (1145 at HAWK Intersections). Of those crossings, 5,401 had pedestrian-vehicle interactions (780 at HAWK intersections).

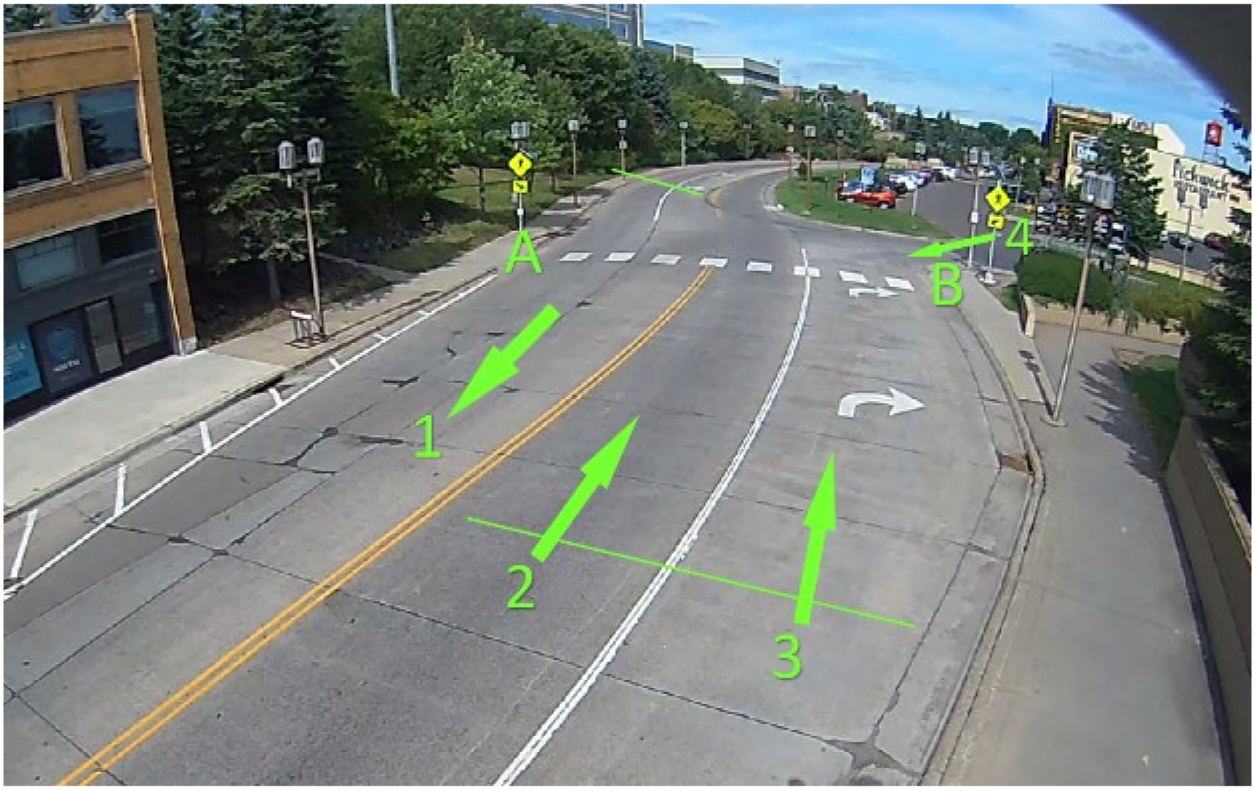

Figure 5-1 Sample annotated site view showing decision points (green lines), sides of road (A and B), and lanes (1 through 4)

5.2.1 Lane Information – HAWK Sites

For each lane that conflicted with the crosswalk at a site with a HAWK system, the data collected consisted of the following:

- The total number of vehicles in the given lane that were upstream of the decision point when the pedestrian showed intent to cross that crossed or stopped at the conflict point while the pedestrian was crossing or the system was activated
- The number of vehicles in the given lane that crossed the conflict point while the system was displaying a solid (Prepare to Stop) or flashing (Slow Down) yellow light
- The number of vehicles in the given lane that crossed the conflict point while the system was displaying a solid red light (Stop)
- Whether the first stopped vehicle in the given lane crossed the conflict point after the system was displaying flashing red and the pedestrian had cleared the lane, demonstrating following the “Flashing Red – Proceed if Clear” rules correctly

5.2.2 Lane Information – Non-HAWK Sites

For each lane that conflicted with the crosswalk at a site without a HAWK system, the data collected consisted of the following:

- The number of vehicles in the given lane that did not yield
- The time the first vehicle in the given lane reached the decision point
- The time that the first vehicle reached the conflict point (if all of the vehicles in that lane yielded to the pedestrian) or the time that the last vehicle cleared the conflict point (if not all of the vehicles in that lane yielded to the pedestrian)
- Whether at least one vehicle in the given lane yielded to the pedestrian
- The manner in which the first yielding vehicle in the given lane yielded to the pedestrian (e.g. full stop, roll-through, or lane change).

The difference between the event specific data collected on HAWK and Non-HAWK sites is because at HAWK sites there were no clear violations of the HAWK. On these cases attention was drawn in the HAWK signal phase on which the vehicles yielded and separately started moving again. In difference, at non-HAWK sites the emphasis was in the yielding behavior of the drivers as well as evidence trying to gage the distance the drivers noticed the pedestrian and/or the PAC system, when activated.

CHAPTER 6: ANALYSIS & RESULTS

Following the reduction of the collected video, an extensive data set of metrics describing in a uniform manner all vehicle-pedestrian encounters became available. Through this data set the research team attempted to identify and quantify the effect different factors like the presence of an island, number of lanes crossed, or PAC system type, have on metrics such as yield rate, activation rate, and pedestrian delay. Early in the project, in cooperation with the project advisory panel, 23 guiding questions were identified. These questions aimed in guiding the investigation and improve the utility of the project results by practitioners. Although, given the nature of the observations, some of these questions cannot have literal answers, the following analysis was guided by these questions and aimed in providing direct or indirect answers. The following is a list of guiding questions:

1. What was the rate of pedestrians using the crossing system?
2. What were pedestrian waiting times?
3. How does a delayed activation affect the compliance of pedestrians in waiting to cross a street?
4. Which system results in the lowest pedestrian delay?
5. How do refuge islands impact yielding to pedestrians?
6. How do traffic islands impact wait times for pedestrians?
7. How does a Flashing LED sign impact the yielding rate of vehicles at free right turns?
8. How does the number of lanes influence yield rates?
9. How do yield rates differ per lane on multilane road crossings?
10. If not all vehicles yield to a pedestrian, how many vehicles did not yield to pedestrian by system?
11. Does the presence/type of the PAC affect the yield rate of far lanes on multilane roads? By far lane(s) we refer to the parallel, same direction, lane(s) next to the lane where the crossing started.
12. Which system is more effective at midblock crossings?
13. Which system performed best at busy intersections?
14. What was the rate of vehicles yielding to pedestrians by type of intersection (right turn, midblock, 3-way, 4-way)?
15. What was the rate of vehicles yielding to pedestrians by treatment type?
16. What was the rate of vehicles yielding to pedestrians with and without overhead RRFBs?
17. What was the rate of vehicles yielding to pedestrians by traffic volume?
18. What was the rate of vehicles yielding to pedestrians on bikes?
19. What was the rate of vehicles yielding to pedestrians by speed limit?
20. What was the rate of vehicles yielding to pedestrians by conflict direction (left turn, right turn, near side through, far side through, etc.)? During the course of the study, this question was rephrased to be more general.
    a. How is the rate of vehicles yielding to pedestrians by the number of conflicts encountered?
21. What was the rate of vehicles yielding to pedestrians by environment (school zone, rural, residential, or commercial)?

22. How often were HAWKs used properly by pedestrians?
23. How often were HAWKs used properly by drivers?

For assistance, the applicable questions are placed in bold before each relevant analysis. In some cases, the analysis pertains to more than one question, while in other cases, the same question can be relevant to more than one analysis section. This method avoids repetition of the results.

6.1 HAWK SITES

The following section covers the analysis of the four HAWK sites included in the study. The results for the HAWK sites are discussed separately because they cover some unique aspects that are irrelevant to non-HAWK sites. In addition to the general questions regarding yield rates and delay, there are two questions seeking to quantify the level of comprehension regarding the proper use of the HAWK PACs by pedestrians and drivers.

6.1.1 System Usage

Guiding questions addressed:

1. ***What was the rate of pedestrians using the crossing system?***
3. ***How does a delayed activation affect the compliance of pedestrians in waiting to cross a street?***
10. ***If not all vehicles yield to a pedestrian, how many vehicles did not yield to pedestrian by system?***
22. ***How often were HAWKs used properly by pedestrians?***
23. ***How often were HAWKs used properly by drivers?***

The phases of a HAWK PAC are shown in Figure 6-1. The resting state of the system is dark beacons and a “don’t walk” sign for pedestrians. When a pedestrian pushes the button, the signal flashes yellow to attract drivers’ attention and then displays solid yellow to direct drivers to prepare to stop. The top two beacons then display solid red while the pedestrian signal head displays “walk”. Unlike standard signals, when the “don’t walk” sign begins to flash, the top two beacons begin to flash directing drivers to treat the system like a stop sign and proceed if the crosswalk is clear of pedestrians. When the pedestrian signal head goes from flashing “don’t walk” to a solid “don’t walk” sign, the beacons go dark again. For the purposes of this analysis, the two yellow phases were combined because they have the same general meaning.

The vast majority of pedestrians (320 out of 376) used the HAWK systems appropriately. Only in a few cases (56 out of 376) did pedestrians start their crossings before the HAWK had reached the solid red phase, i.e. after pressing the button, they crossed either before or during the yellow phases. In almost all of the 56 cases, there was a vehicle yielding to the pedestrians, which suggests that, because the vehicles had already yielded, the pedestrian did not see any reason to wait for the HAWK to reach the appropriate phase before starting their crossing.

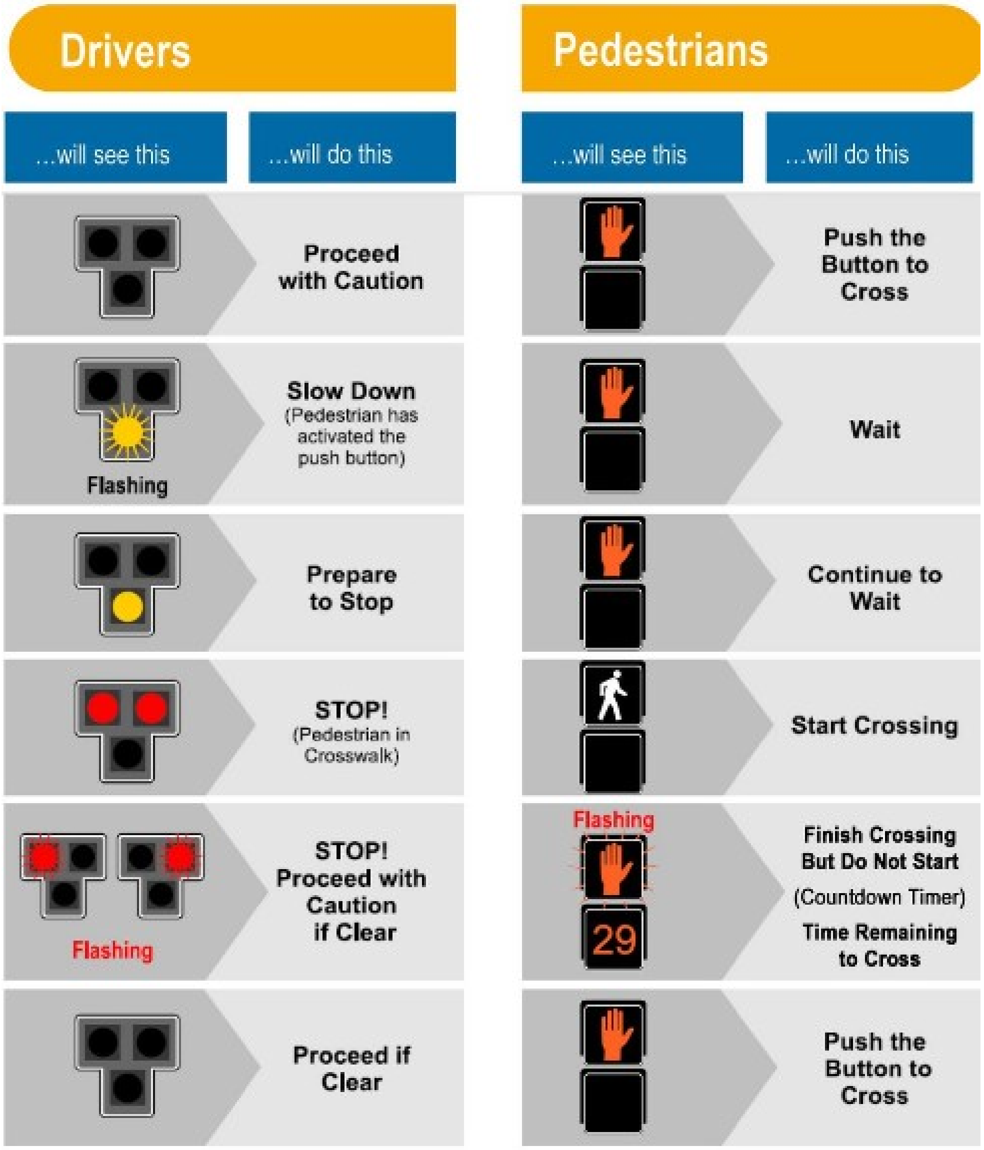

Figure 6-1 HAWK phases and meanings

Table 6.1 shows the percentage of interactions where pedestrians activated the signal. Events where no vehicles interacted with the pedestrian were omitted because the lack of an interaction implies an empty road, which is not relevant to the study. The activation rates for the HAWK systems are relatively high but not the same on all sites, suggesting some external influence on the pedestrian behavior. At Sites 7 and 9, the system is activated at more than 90% of the crossings. There is no clear reason for the difference in behaviors – it is unclear if public education campaigns or resident outreach programs occurred or what role they may have played.

Table 6.1 HAWK activation rates by site

Site	Activation rate when vehicles were present
10 - St. Cloud	70%
6 - Burnsville	66%
7 - Maple Plain	92%
9 - Red Wing	91%

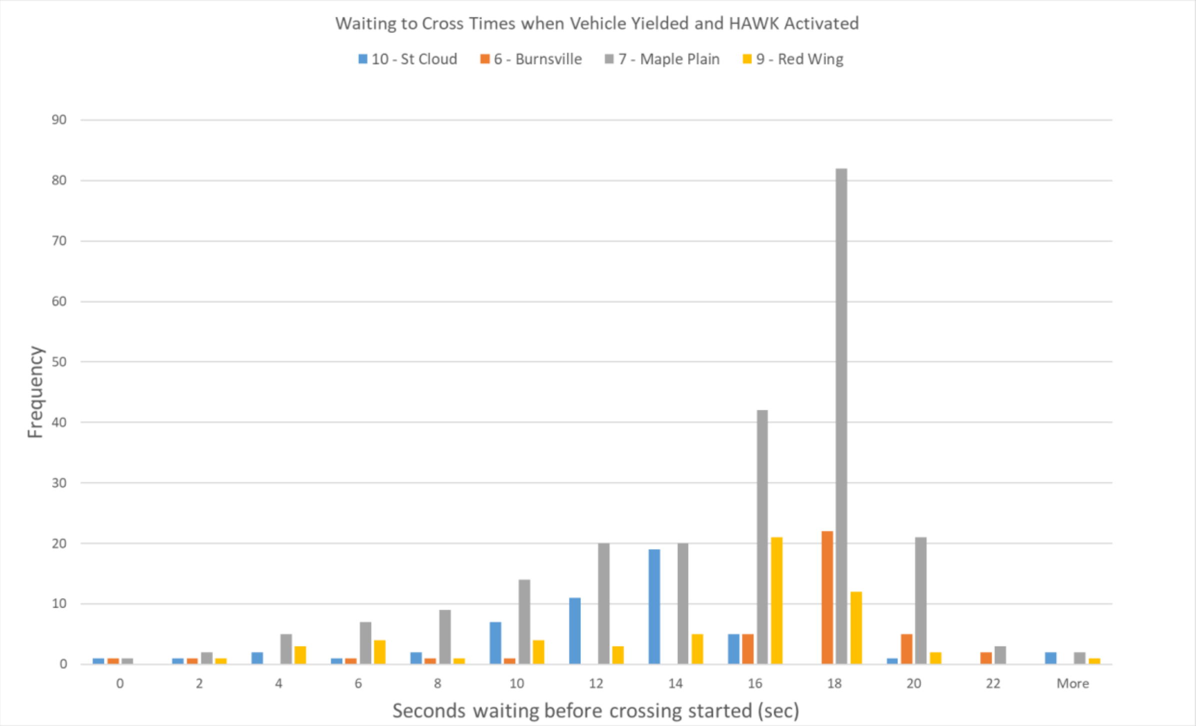

Figure 6-2 Waiting to Cross Times when Vehicle Yielded and HAWK Activated

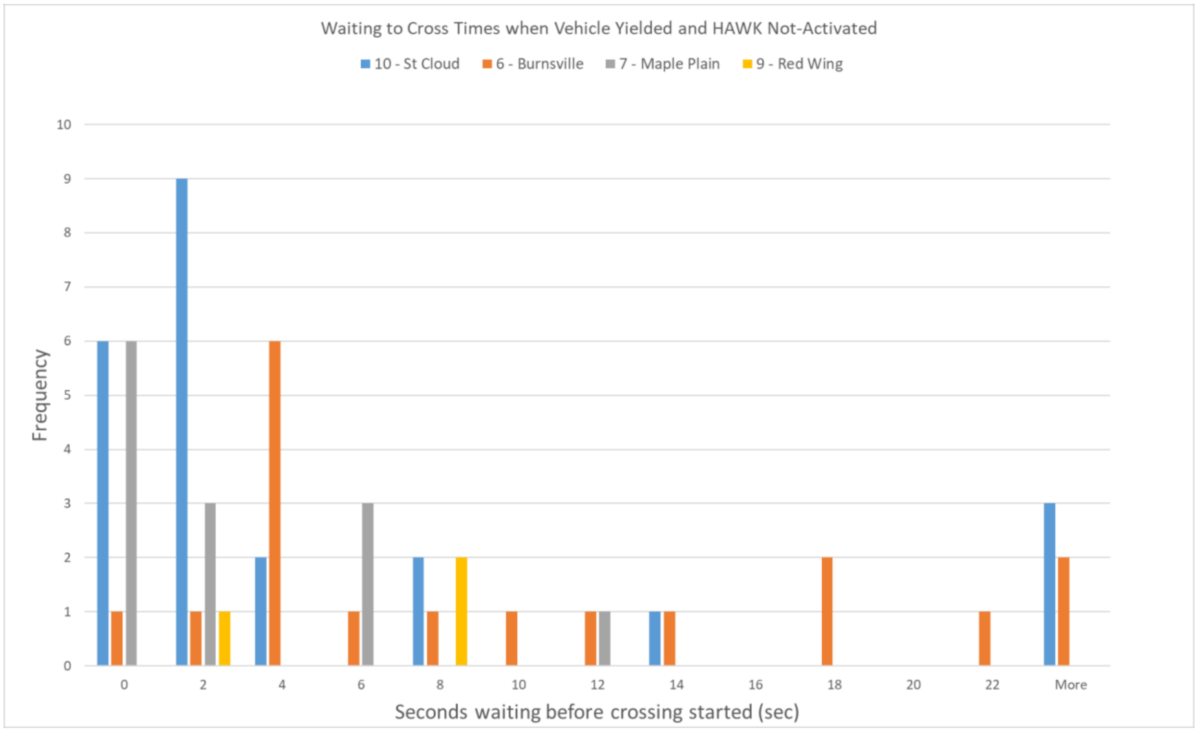

Figure 6-3 Waiting to Cross Times when Vehicle Yielded and HAWK Not-Activated

One question posed by the project panel inquired if the pedestrians where crossing before the “Walk” indication was activated. Figure 6-2 and Figure 6-3 present the waiting times of the pedestrians in the case where the HAWK was activated and the one when it was not respectively. The site in St Cloud (10) had a delayed activation rate of approximately 30 seconds similar to a semi-actuated signal. The pressing of the button places a call for the HAWK activation phase but the actual serving of the phase depends on the gaps between vehicles passing over a detector on the pavement. If the road is busy, then the HAWK will be activated after the maximum phase duration is reached otherwise a large gap between two vehicles can activate it earlier. Because the button is at least 10 feet away from the curb, it was not possible to reliably mark the time the pedestrian pressed the button making it impossible to measure the time between phase call and phase activation on each individual event. The times reported are measured from the time the flashing yellow indication is activated in the HAWK. This brings site 10 at the same context as the other three which had immediate activation. Note that since the delay in site 10 is related to the traffic on the road, it was not possible for the pedestrians to cross safely anyway until the system was activated. From the first graph we see that on all sites a significant amount of pedestrians cross as soon as the vehicles have yielded and they do not wait till the activation of the “Walk” indication. In sites where there is only one conflicting lane per direction this is not a problem but on locations like Site 9 (two lanes) and Site 10 (three lanes) starting the crossing before the completion of the sequence may result on a vehicle in an inner lane not stopping. This is only a hypothetical since no such event was observed. Normally when the system was not activated, the waiting time was considerably smaller although as seen from the graph the sample size is small since the activation rates where very high.

There are three aspects of the HAWK activation cycle that were observed to have low compliance rates by drivers. Normally, following the pressing of the button by the pedestrian the HAWK begins the two yellow phases. The expected behavior during yellow is for the drivers who are upstream of the yield line to decelerate and stop at the stop line before the crossing. Table 6.2 shows that the best behavior is observed at Site 10 where the average number of vehicles per event not stopping on yellow is only 0.367. Numbers less than 1 indicate that on average the majority of the vehicles stopped for the yellow or red resulting in zero violators. At Site 7, however, more than one vehicle fails to stop at the yellow during the average event. There is no clear indication why the behavior is so different at Site 7 and to lesser degree at Site 9. Visibility is adequate on all sites but Sites 7 and 10 are both on a curve while Sites 6 and 9 are on straight segments.

The second indication when activated is solid red. The expected behavior during solid red is for all vehicles to come to a stop and not to cross the stop line at all during solid red and to only cross the line during flashing red if the crosswalk is clear and the vehicle has already stopped first. Although, Site 7 is again the site with the worst compliance of the four HAWK sites the number of vehicles violating the red is very low.

Table 6.2 Average number of vehicles per event that did not stop at each phase

Site	Avg. number of vehicles not stopping per event	
	Yellow Phases	Red Phases
10 - St. Cloud	0.367	0.113
6 - Burnsville	0.576	0.011
7 - Maple Plain	1.440	0.236
9 - Red Wing	0.816	0.154

During the blinking red phase, the expected behavior is for vehicles to come to a full stop if not already stopped during solid red and only cross the stop line if there are not any pedestrians in the crosswalk anymore. This is the most phase with the lowest driver compliance and, as shown in Table 6.3, with the exception of Site 9 in Red Wing, at least half of the drivers that could have crossed the stop line during the blinking red phase did not do so but instead waited until the HAWK turned off. The Site 9 outlier has no clear explanation.

Table 6.3 Percent of events where all vehicles started moving during blinking red when able

Site	Percent of events where vehicles moved during blinking red phase (sample size)
10 - St. Cloud	41% (247)
6 - Burnsville	25% (70)
7 - Maple Plain	47% (275)
9 - Red Wing	76% (188)

6.1.2 Pedestrian Delay

Guiding question addressed:

2. What were pedestrian waiting times?

The results presented in Figure 6-2, Figure 6-3, and Table 6.4 show that when the system is activated, the waiting or delay time is higher than the cases where the system was not activated. Pedestrian delay is defined as the difference in the time the pedestrian activated the system or showed their intent to cross and the time the pedestrian actually left the curb – this includes the duration of the two yellow phases (see Figure 6-1). This difference in delays when activated vs not activated is caused in large part by the system activation time (at least 7 seconds but often longer at sites with a variable system activation delay). In the cases when the system is not activated, the experienced wait times can vary dramatically, in which case the average delay is not informative anymore. The contradiction between these two observations may suggest that pedestrians favor a more predictable wait time than a decreased average delay, a similar finding to the one described in Hourdos, et al. (2012).

Table 6.4 Average waiting time in seconds with standard deviation

Site	Avg. Delay in seconds (Std. Dev.)	
	Activated	Not Activated
10 - St. Cloud	13 (9)	8 (15)
6 - Burnsville	16 (5)	10 (10)
7 - Maple Plain	15 (4)	3 (4)
9 - Red Wing	15 (8)	6 (4)

6.1.3 Driver Yield Rates

Guiding questions addressed:

15. What was the rate of vehicles yielding to pedestrians by treatment type?
18. What was the rate of vehicles yielding to pedestrians on bikes?

The yield rates on HAWK sites seem to fluctuate considerably, an observation not in line with other studies (Turner et al., 2006; Fitzpatrick et al., 2006) in which HAWK systems were found to have yield rates between 95% and 100%. The patterns shown in Table 6.5 follow the general trends presented later at the non-HAWK PACs; namely, that yield rates are higher for crossings where the system is activated or the crossing starts from a traffic island.

Table 6.5 HAWK yield rates per island destination, number of lanes, and activation

Site	Island Origin	Lanes Crossed	All Driver Yield Rate to Pedestrians	
			Activated	Not Activated
10 - St. Cloud	Yes	3	94.5%	58.3%
10 - St. Cloud	No	3	64.2%	62.1%
6 - Burnsville	n/a	2	81.2%	75.0%
7 - Maple Plain	n/a	2	88.5%	56.5%
9 - Red Wing	Yes	2	93.0%	100%
9 - Red Wing	No	2	66.2%	42.8%

In the cases where the event involved a bicyclist (Table 6.6), yield rates to bicyclists using the crosswalk have a greater variability between sites, although this can be expected given the smaller sample size of available observations (251 out of 780). Apart from that, in general yield rates follow the same trend as the ones involving pedestrians at the same sites.

Table 6.6 HAWK yield rates to bicyclists per island destination, # of lanes, and activation

Site	Island Origin	Lanes Crossed	All Driver Yield Rate to Bicyclists	
			Activated	Not Activated
10 - St. Cloud	Yes	3	89.5%	58.8%
10 - St. Cloud	No	3	82.3%	66.6%
6 - Burnsville	n/a	2	60.0%	60.0%
7 - Maple Plain	n/a	2	92.3%	72.7%
9 - Red Wing	Yes	2	100%	100%
9 - Red Wing	No	2	77.7%	33.0%

6.2 NON-HAWK SITES

The following section covers the analysis of the remaining PAC sites covered by this research. Regular signals, Flashing LED Pedestrian Crossing signs, and RRFBs are presented in the same tables as well as compared to each other and to different operational features of the same PAC type. The project directed more resources on the investigation of non-HAWK PAC sites because, signals excluded, they present higher ambiguity in regards to their message, do not indicate a regulatory requirement, and present a larger variety of implementation characteristics. On the latter, for example, RRFB sites may or may not include overhead signs, advanced warning controlled by the device at the actual crosswalk, or mid island buttons to name a few implementation varieties.

6.2.1 System Usage

Guiding questions addressed:

1. ***What was the rate of pedestrians using the crossing system?***
3. ***How does a delayed activation affect the crossing behavior of pedestrians?***

The frequency at which the system was activated by pedestrians is an important metric because, especially for LED and RRFB if not activated they are not much different than just static signs. During the data analysis, crossings involving an island were broken up into two events. As such, the number of lanes for the resulting events is not indicative of the total number of lanes a pedestrian needed to cross. For example, a pedestrian crossing a three-lane road with an island only has to cross one or two lanes at a time but will probably not perceive the crossings the same way they would a one, two, or three lane crossing at a site without an island. For this reason, interactions that took place at sites with an island were kept separate from the interactions from sites that did not have an island. Note that sites with traffic signals were separated from the other sites (and denoted by a second +) because they only give pedestrians the right of way when activated – unlike LED signs and RRFBs which draw attention to the fact that the pedestrian has the right of way.

Inspection of Figure 6-4 supports the hypothesis that pedestrians treat island crossings different than single crossings of the same length. An observation also encountered in Hourdos, et al. (2012) for roundabout pedestrian crossings. The activation rate increases with the number of lanes crossed. This is likely because pedestrians' certainty that all vehicles will yield decreases as the number of lanes they must cross – and thereby length of the crossing and number of vehicles that must yield – increases; activating the system helps assure that all drivers can clearly register the pedestrian's intent. At sites with a signal (all 2++ crossings), the average activation rate was 92.3%. This high activation rate is likely due to the fact that drivers have the right of way until they are shown a red light – something that will only happen after the pedestrian pushes the button. The volume of traffic on the two standard signal sites was comparable to the rest of the sites. The direct relationship between number of lanes to cross and system activation rate – likely a proxy for pedestrian uncertainty – is a compelling argument for the prioritization of sites with long crossings when considering potential sites for PAC system installations.

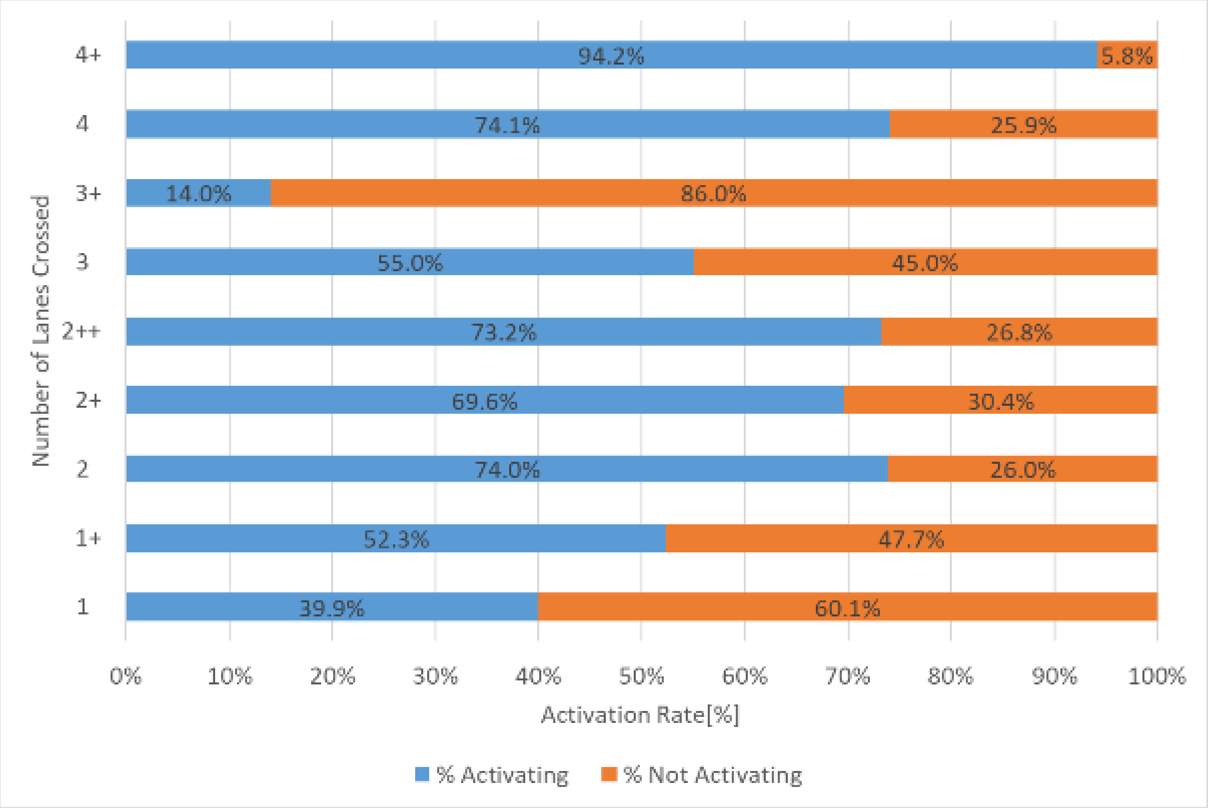

Figure 6-4 Plot of the percent of PAC system activation by number of lanes (+ denotes crossings with an island, ++ denotes island and signal with activation delay)

At four RRFB sites (Sites 38, 40, 45, and 46), activation is automated – i.e. there is some sort of detection device that activates the system when a pedestrian is detected. As shown in Table 6.7, the sites with automatically activated RRFBs have higher activation rates when vehicles are present than those where the pedestrian is responsible for activating the system. Both sites with a signal had a manual delayed activation. On those sites, the activation rate was approximately equal to that of the manually activated RRFBs. The sites with flashing LEDs had a very low activation rate but that was likely due to the site geometry and low vehicle volumes.

Table 6.7 Activation rates by PAC type and method of activation

Treatment	Activation Method	Activation Rate
LED	Button - Immediate	15.9%
RRFB	Automatic - Immediate	90.2%
RRFB	Button - Immediate	72.5%
Signal	Button - Delayed	75.5%

Perhaps unsurprisingly, the activation rate would be lower when it is optional for pedestrians as compared to sites with automatic activation that represent a decreased responsibility for the pedestrian. As it will be discussed in more detail later, overall, driver yield rates at sites with RRFBs are slightly higher when the system is activated than they are when it is not activated (79% vs 68%, respectively). Therefore, at sites, such as those with limited visibility, an automatic activation system might increase the chances the pedestrian is detected and yielded too by the drivers. At sites where the activation rate is already high or the relative benefit of system activation is less pronounced, the benefit of automatic activation is likely decreased.

6.2.2 Pedestrian Delay

Guiding questions addressed:

2. ***What were pedestrian waiting times?***
6. ***How do traffic islands impact wait times for pedestrians?***

The next set of relationships examined consisted of those between the number of lanes crossed, activation, and delay. To examine the impacts of the number of lanes crossed, the inherent delay was calculated for every interaction before aggregating the delays by the number of lanes crossed and whether the system was activated. The inherent delay was defined as the difference between the time the first pedestrian showed their intent to cross and the time the first pedestrian began crossing after all drivers yielded. Table 6.8 shows how delay is influenced by yielder (Driver if all drivers yielded, Both if some – but not all – drivers yielded, and Pedestrian if no drivers yielded) and activation.

Table 6.8 Delay by yielder and activation

Yielder	Activated?	Avg. Delay [s]
Driver	Yes	4.1
Driver	No	2.8
Both	Yes	10.0
Both	No	11.5
Pedestrian	Yes	9.6
Pedestrian	No	10.7

The delay is lowest when all drivers yielded to the pedestrian after they signaled their intent to cross (see Table 6.8). This confirms the assumption that the inherent delay to pedestrians is determined by the average delay when all drivers yield. When all drivers yield, the average delay to pedestrians who did activated the PAC was 1.3 seconds longer than the cases where the system was not activated. This may be caused by the pedestrians observing that drivers are already coming to a stop even before they set foot in the road. Anecdotal cases supporting this were observed but the analysis level performed did not allow for this to be accurately quantified. This confidence that drivers will yield likely precludes the tendency to wait or activate the system. However, when either a fraction of the drivers or no drivers yielded, the average delay was approximately one second shorter when the system was activated than when it was not. This is the reverse from what was observed when all drivers yielded.

Inspection of the plot showing the average inherent delay by number of lanes crossed and activation (Figure 6-5) supports the earlier observation that interactions at sites with islands (number of lanes with a plus sign) are different than interactions at sites without an island, even when adjusting for the number of lanes crossed.

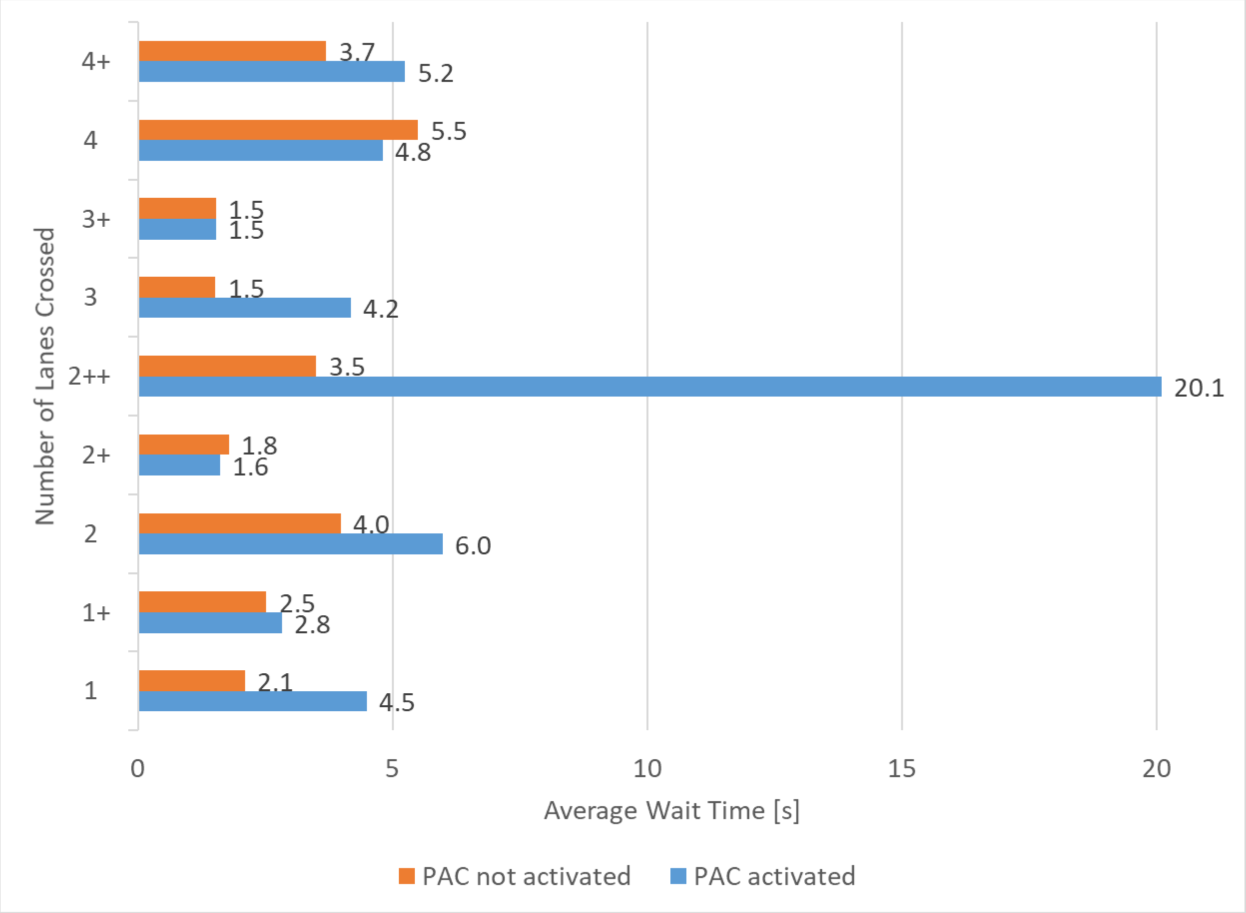

Figure 6-5 Plot of delays when all drivers yielded and the PAC system was activated vs was not activated by number of lanes (numbers with + denote crossings with an island, ++ denotes island and signal with activation delay)

In all cases, the average delay for a crossing that is part of a two-phase island crossing is higher than that for a crossing of the same length that does not take place at a site with an island (i.e. 2+ vs 2). Additionally, the delay for one part of a crossing with an island is still higher than the delay for a crossing without an island of the same length (i.e. 2+ vs 4). No clear pattern can be seen to the relative differences in delay for interactions where the system was or was not activated for a given number of lanes. It does appear however that, for shorter crossings (three or fewer lanes), the delay is longer when not activated whereas that trend fades or even reverses for the longer crossings (four or more lanes).

At sites with a signal (all 2++ crossings), the average inherent delay when activated was much higher than the average for all other 2+ sites (20.1 seconds versus 1.6 seconds). The average delay when not activated was much closer to that of the other 2+ sites (3.5 sec vs 1.8 sec). The higher delay when activated can be explained by the long delay at signals caused by non-immediate activation of the "walk" sign following the button at the crosswalk being pressed.

6.2.3 Before/After Studies

Guiding questions addressed:

7. ***How does a flashing LED sign impact the yielding rate of vehicles at free right turns?***
15. ***What was the rate of vehicles yielding to pedestrians by treatment type?***

Coordinating filming for data collection around the installation of a system is difficult – not only because finding upcoming installations at sites with characteristics of interest is difficult but also because aligning the timeline of the installation work with the timeline of a research project often proves quite difficult. For these reason, only two sites (Sites 49 and 1) with a total of seven crossings were filmed both before and after the installation of a PAC system. At those seven crossings, a before/after study following the methods recommended by Ezra Hauer (1997) was conducted to determine the changes in yield rates following the treatment thereby providing a test and control case. Neither site had any signage prior to the installation of the PACs (the T-intersection had a painted crosswalk). The introduction of flashing LEDs at six one-lane free right turns and an RRFB at a three-lane T-intersection corresponded to mixed results.

Following the installation of an RRFB, Site 49 showed no significant difference in Driver yield rates between activation and no-activation cases (see Table 6.9). Regardless, the installation of the RRFB resulted in a minimum 24% increase in driver yield rates suggesting that the additional static signage that accompany the RRFB may be the critical factor instead of the flashing lights.

Table 6.9 Average yielding rates before and after the installation of an RRFB at the Duluth site.

			Avg. Yield Rate by Yielder		
	Treatment	**Activated?**	**Driver**	**Both**	**Pedestrian**
Before	Uncontrolled	No	30.2%	37.0%	32.7%
After*	RRFB	No	58.6%	20.7%	20.7%
After	RRFB	Yes	54.5%	33.3%	12.2%

1 The row with the asterisk denotes a lower number of instances where the RRFB was not activated.

In Table 6.10, the changes in yield rates are shown for the cases of the free right turns. It is important to note that there were 101 out of total 118 events where the pedestrian did not use the crosswalk and didn't go near the activation button. Usage of the PAC systems was very low at all six crossings at Site 1 with an average of 12% of pedestrians activating the LED PACs. The natural geometry of more than half of the free right turn crossings requires the pedestrians to walk a few feet longer to reach the crossing and since the volume of vehicles was low, a significant number of pedestrians just walked on a straight line from the sidewalk. Arithmetically the numbers show a counter-intuitive reduction in driver yield rates but the small sample sizes prevent serious analysis.

Table 6.10 Average yielding rates with and without system activation before and after the installation of a flashing LED PAC system

			Avg. Yield Rate by Yielder		
	Treatment	Activated?	Driver	Both	Pedestrian
Before	Uncontrolled	No	69%	9%	21%
After	LED	No	58%	13%	29%
After	LED	Yes	44%	13%	44%

6.2.4 Driver Yield Rates

Guiding questions addressed:

5. ***How do refuge islands impact yielding to pedestrians?***
8. ***How does the number of lanes influence yield rates***
11. ***Does the presence/type of the PAC affect the yield rate of far lanes on multilane roads?***
12. ***Which system is more effective at midblock crossings?***
14. ***What was the rate of vehicles yielding to pedestrians by type of intersection (right turn, midblock, 3-way, 4-way)?***
16. ***What was the rate of vehicles yielding to pedestrians with and without overhead RRFBs?***
17. ***What was the rate of vehicles yielding to pedestrians by traffic volume?***
19. ***What was the rate of vehicles yielding to pedestrians by speed limit?***
21. ***What was the rate of vehicles yielding to pedestrians by environment (school zone, rural, residential, commercial, etc)?***

The first relationships evaluated were those between yield rate, PAC system type, and activation. These relationships were evaluated by grouping interactions by PAC system and activation before calculating the portion of the total interactions for each group that were made up by each yield type. The results are plotted in Figure 6-6.

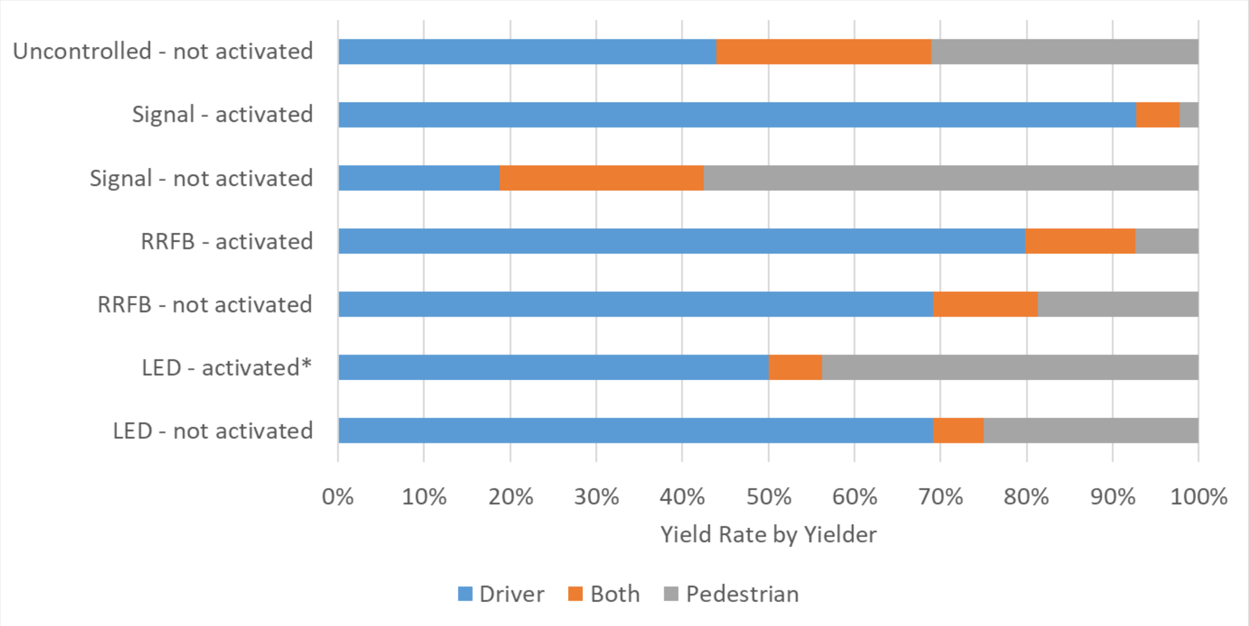

Figure 6-6 Yield rates by PAC system type and activation (* Indicates too few observations)

Upon inspection of Figure 6-6, several trends emerge. The signal has the highest yield rate when activated but the lowest yield rated when not activated. This is likely due to the fact that the signal is a well-recognized system that drivers and pedestrians are both required to follow though it should be noted that far more pedestrians disobeyed the signal than did drivers (the vast majority of non-yields by drivers occurred in the first five seconds of the red phase). The RRFB and LED have much smaller disparities in the yield rates when they are activated versus not activated. The reason for the effectiveness of the RRFBs and LEDs when not activated is likely the fact the law still requires drivers to yield and even when not activated, the PAC systems still serve as a large sign reminding drivers to yield to pedestrians in the crosswalk. While it is counterintuitive for the driver yield rate to be lower for the sites with LEDs when the LEDs were activated, the sample size was so small that this result is non-statistically significant; as was mentioned previously, the system was activated for only 16 out of the 136 interactions at sites with LEDs, likely because of the placement of the pushbuttons, the short crossing distance, and the low vehicular volume.

To continue the evaluation of the relationships between yield rate, PAC system type, and activation, the interactions that occurred at sites with islands were grouped by PAC system type, activation, and pedestrian origin/destination before calculating the portion of the total interactions for each group that were made up by each yield type. The results are plotted in Figure 6-7. As is consistent with earlier research by Hourdos, et al. (2012), driver yield rates were higher for interactions where the pedestrian was starting the crossing from an island (second part of crossing) than for interactions where the pedestrian was crossing to an island (first part of crossing). This trend is most pronounced in the cases of activated signals and RRFBs where all or nearly all drivers yielded to pedestrians crossing from an island unlike the corresponding cases where the pedestrians were crossing to an island. Note that uncontrolled sites and sites with LED systems do not appear in the plot because they were not present at any sites with an island.

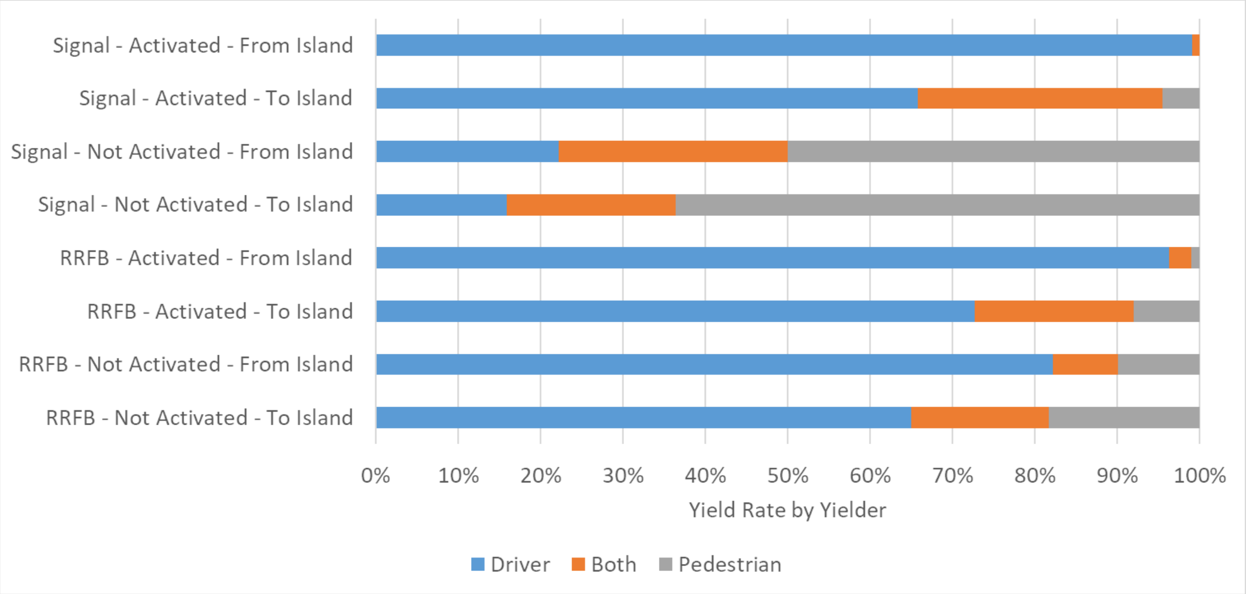

Figure 6-7 Yield rates by PAC system type, activation, and island origin/destination

Table 6.11 specifically addresses the relationship between yield rate, activation, and number of lanes crossed. Note that interactions from the site with flashing LED signs was left out due to the previously discussed anomalies. As will be described in the following sections, there is a strong influence from the road geometry and amount of signage that reduces the clarity of these result but they suggest, nonetheless, that, for RRFBs, the benefit from the system increases with the number of lanes. The table also suggests that yield rates decrease by ~50% on crossings with 4 lanes when the system is not activated. On such crossings, the use of the system is highly warranted. In difference, in one lane crossings the difference in yield rates is marginal suggesting that the cost of installing an RFFB on one or two lane crossings may not be justified. The change in yield rates does not suggest a cap or big change between number of lanes. Less than two may be considered such a cap but it is more of a policy decision rather than an engineering one.

Table 6.11 Yield rates by number of lanes crossed and treatment

	Lanes	Avg. Yield Rate	
Treatment	**Crossed**	**Activated**	**Not Activated**
RRFB	1	72.3%	66.2%
RRFB	2	78.0%	60.4%
RRFB	3	79.1%	59.2%
RRFB	4	60.5%	34.8%
Signal	2	80.5%	26.9%

The number of lanes covered by the pedestrian crossing is also not representative of the number of conflicts between vehicle movements and pedestrians. Table 6.12 shows the same type of information as Table 6.11 but grouped also by the number of conflicting movements and the relation of the crossing to an island. In this table, the importance of the PAC is further highlighted by the low yield rates at sites with high number of conflict sites when the system is not activated. There is a similar drop in all-driver yield rates when the system is active but not as pronounced. When reviewing the following table, consider the influence of the island, otherwise the trend is not clear. The last column shows the difference in yield rates on each case. This helps normalize the information since some sites may have higher yield rates for other reasons. From that column we see that four and more conflicts show a higher benefit for installing a PAC than locations with less than 4 conflicting movements.

Table 6.12 Yield rates by number of conflicting movements and treatment

Treatment	Number of Conflicts	Island Origin	All Driver Yield Rate		Change in Yield Rate
			Activated	Not Activated	
RRFB	1	Yes	69.4%	52.1%	17.3%
RRFB	2	No	67.8%	51.1%	16.7%
RRFB	2	Yes	80.8%	67.4%	13.4%
RRFB	3	Yes	85.4%	68.4%	17%
RRFB	4	No	63.2%	42.9%	20.3%
RRFB	5	No	78.0%	53.3%	24.7%
RRFB	6	No	59.1%	20.6%	38.5%
Signal	2	Yes	83.9%	25.0%	58.9%

What was the rate of vehicles yielding to pedestrians by type of intersection (4-way)?

When looking at the driver yield rates at individual sites, there is a large disparity in the rate at which all drivers yield to a pedestrian when the system was activated. The second and third columns of Table 6.13 shows all driver yield rates (sample size in parentheses) at five crossings in four-way intersections. The rates range from 44.7% to 100%. The cause of the disparity is not initially apparent indicating a more complex causality mechanism. Sites U1 and 23 are busy intersections with complicated geometries and little advanced notice of the crossings. Sites U4 and 46 have better line of sight and much more signage to warn drivers of an upcoming crossing. Site U4 in particular is a three lane crossing to an island with two of these lanes being exclusive left or right/bike lanes and only one lane through. Due to the island and the bike lane there is an abundance of signs with all sorts of warnings. Site 46 in Luverne is a three-lane road with a shared middle lane and bike lanes on both sides, is straight and level at the location of the crossing, and includes overhead mounted RRFBs. Site 46 does not have as much advance warning as U4 but a lot of clues regarding the crossing and perfect visibility both for drivers and pedestrians.

The site with the worst yield rate in both cases (outlier), Site U1, has a four-lane crossing with one direction that includes a curve with an advance RRFB to deal with the lack of visibility. Interestingly, the direction with the lowest yield rate is the one with the best visibility but no advance warning. The worst yielding behavior at the site was observed on the far lane of the good visibility approach.

Table 6.13 All-driver-yield rates at four-way intersections by system activation (with sample size)

Site	All Driver Yield Rate		Treatment	Lanes Crossed	Intersection Type
	Activated	Not Activated			
U4 - Winona	100.0% (30)	93.1% (175)	RRFB	3	Four-Way
46 - Luverne	93.5% (185)	66.7% (3)	RRFB	3	Four-Way
27 - Lindström	81.0% (100)	60.0% (30)	RRFB	3	Four-Way
23 - Chanhassen	65.9% (44)	29.4% (34)	RRFB	4	Four-Way
U1 - Bloomington	44.7% (76)	12.5% (8)	RRFB	4	Four-Way

Initially, this correlation between visibility and yield rates might suggest that the differences in yield rates are dependent on visibility and not on the PAC system. If this were the case, the same trend in yield rates would apply when the system is not activated. However, as shown in the third column of Table 6.13, the magnitudes of some of the yield rates change dramatically. For example, the yield rates at Sites 23 and U1 decrease dramatically when the system is not activated. At U4, however, the decrease in yield rate is much less significant. These differing effects of activation suggest that, at crossings with good visibility, extra signage, and advanced notice, an RRFB may be redundant. It is only at intersections with poor visibility that PAC systems are needed to increase the driver yield rate by a significant amount.

Which system is more effective at midblock crossings?
What was the rate of vehicles yielding to pedestrians by type of intersection (midblock)?

Table 6.14 presents results from five midblock crossings. U2b and U2a in Wayzata are isolated midblock crossings with no overhead signs and poor visibility requiring advance RRFBs. Site 25 also in Wayzata is in a busy crossing, sign wise, that includes an island. It also has an advance RRFB on the west side of the crossing. Site 4 in Lewiston does not follow the current hypothesis; t is a crossing near a school but with no special signs and warnings. Site 11 in Anoka has a particularly high yield rate when activated and a particularly low yield rate when not activated; these extremes can be explained not only by the clear delineation of right-of-way but also the legal obligation of drivers and pedestrians to stop and stay stopped when shown a red light or Don’t Walk signal, respectively.

Table 6.14 All-driver-yield rates at midblock crossings by system activation (with sample size)

Site	All Driver Yield Rate		Treatment	Lanes Crossed	Intersection Type
	Activated	Not Activated			
4 - Lewiston	81.8% (22)	50.0% (6)	RRFB	2	Midblock
11 - Anoka	98.0% (151)	14.7% (61)	Signal	2	Midblock
25 - Wayzata	73.1% (130)	55.1% (49)	RRFB	1	Midblock
U2a- Wayzata	72.1% (172)	66.7% (30)	RRFB	2	Midblock
U2b - Wayzata	68.2% (198)	35.5% (107)	RRFB	2	Midblock
7 - Maple Plain	88.5%	56.5%	HAWK	2	Midblock
9 - Red Wing from Island	93.0%	100%	HAWK	2	Midblock
9 - Red Wing	66.2%	42.8%	HAWK	2	Midblock

Much like the four-way intersections, midblock crossings showed a similar trend in the added benefit of a PAC system. The sites that still had relatively high driver yield rates when the system is not activated (Sites 4, 25, and U2a) all had a long sight distance and/or a great deal of signage alerting drivers of an upcoming crosswalk. It should be noted, however, that the system was activated at Site U2a for only 30 of the 202 crossings so the 66.7% driver yield rate when the system was not activated may not be completely representative of the yielding behavior. The sites that only had satisfactory driver yield rates when the system was activated (Sites 11 and U2b) saw this trend for one of two reasons. In the case of Site 11, it was because the system in place was a standard signal which is a well-recognized traffic control device that clearly gives one party or the other the right-of-way; when pedestrians attempted to cross when they did not have the right-of-way, drivers were much less likely to yield. In the case of Site U2b, the low driver yield rate when not activated was likely due to a short sight distance on a curve – as compared to a straight stretch of road, drivers were much closer to the crosswalk when they had a clear view of the crosswalk and any pedestrians that might be waiting there. Site 4 in Lewiston does not follow the current hypothesis. It is a crossing near a school but with no special signs and warnings.

What was the rate of vehicles yielding to pedestrians with and without overhead RRFBs?

What was the rate of vehicles yielding to pedestrians by type of intersection (3-way)?

Given the already highlighted interrelationships between number of conflicting movements, number of main lanes crossed, etc. the effect of the overhead RRFBs as compared to roadside only systems cannot be illustrated in isolation. The following table groups sites by characteristics and compares similar groups with and without overhead signs. The table only includes groups that have a combined sample count of more than 30 to avoid non-statistically significant results to distort the analysis. These sections are combined for brevity and to reduce the overall number of tables.

Table 6.15 Yield rates on paired groups with and without overhead RRFB

Intersection Type	Speed Limit (mph)	Lanes Crossed	# of Conflicts	Treatment	Overhead RRFB?	All Driver Yield Rate	
						Activated	Not Activated
Four-Way	30	3	5	RRFB	Yes	91.30%	66.67%
Four-Way	30	3	5	RRFB	No	78.00%	53.33%
T-Intersection	30	2	2	RRFB	Yes	72.01%	50.79%
T-Intersection	30	2	2	RRFB	No	88.70%	82.93%
T-Intersection	50	2	4	RRFB	Yes	92.86%	66.67%
T-Intersection	50	3	4	RRFB	No	71.93%	27.27%

Table 6.15 makes a weak suggestion that overhead placement of RRFBs may result in increased driver yield rates regardless if they are activated or not. The latter suggests that it may not be the RRFB alone once is activated, that is responsible for the improved yield rates but the accompanying static sign on the overhead mast. Two out of three groups show an average 15% increase in yield rate when active. Similar behavior but with larger differences, is observed on the same sites when the pedestrian did not activate the RRFB. The middle group that does not follow this trend is the one that includes sites with the least amount of lanes and least amount of conflicts. One can hypothesize that the positive effect of overhead warning signs dynamic or static is observable when there is complexity and/or higher speeds involved. A closer inspection of the non-conforming group reveals that there are only two actual sites involved, Site U3 in Northfield (with overhead RRFB) and Site 12 in St. Paul (without overhead RRFB). U3 has a moderate pedestrian traffic, approximately 9.6 crossings per hour and relatively high vehicle traffic with an average of 1030 vph. Site 12 has a very high pedestrian traffic, approximately 48 crossings per hour and higher vehicle traffic with an average of 1260 vph. Site 12 is also near a school and therefore it has additional signage as well as advance RRFBs while U3 is a much more open location with pedestrian crossing signs only at the crossing itself. These differences may account for the change in trend and reinforce the hypothesis that overhead warning signs introduce a measurable benefit to the operation of the crossing.

What was the rate of vehicles yielding to pedestrians by environment (school zone, rural, residential, commercial, etc)?

Although from the results of the following table can support the claim that crossings in rural areas experience better yield rates than comparable sites in urban or commercial sites, the difference to ones in urban or commercial areas is small and under the level of statistical significance. On the other hand, RRFB crossings inside or near school zones experience significantly higher yield rates. One major difference in the general road environment inside school zones is the considerably higher density of warning signs (pedestrian, speed limit, school zone in general, etc). it is not possible to completely separate the two effects and even if it was the additional “bonus” on school zones is not enough to negate the benefit from the RRFBs but it may be an argument for not installing enhanced versions like overhead or advanced RRFB.

Table 6.16 Percent Yield by Environment

Area Description	School	Treatment	Average Yield Rate
Commercial	No	None	59%
Urban	No	None	30%
Urban	No	RRFB	52%
Urban	Yes	RRFB	84%
Commercial	No	RRFB	59%
Rural	No	RRFB	62%
Rural	Yes	RRFB	86%
Urban	No	LED	78%
Commercial	No	LED	63%
Urban	No	Signal	63%
Urban	Yes	Signal	69%

What was the rate of vehicles yielding to pedestrians by speed limit?

Given the already highlighted interrelationships between number of conflicting movements, number of main lanes crossed, etc. the effect of the speed limit cannot be illustrated in isolation. Site 12 (signal) was excluded from Table 6.17 since it will only confuse given that the yield rates are dramatically different when it is not activated. The results suggest, based on the difference in yield rates when the PAC is activated and when it is not, that for speeds above 30mph the speed is not a good predictor of driver yielding behavior. As highlighted above, and emphasized here, the number of conflicting movements is a much stronger influence and hence reason for implementing a PAC.

Table 6.17 Yield rates by intersection type, speed limit, and conflicts.

Intersection Type	Speed Limit (mph)	Lanes Crossed	# of Conflicts	Treatment	All Driver Yield Rate		Difference
					Activated	Not Activated	
T-Intersection	25	3	4	RRFB	54.5%	58.6%	-4.10%
Midblock	30	1	1	RRFB	69.4%	52.1%	17.30%
Midblock	30	2	2	RRFB	67.8%	51.1%	16.70%
T-Intersection	30	2	2	RRFB	80.4%	66.9%	13.50%
Four-Way	30	3	5	RRFB	78.0%	53.3%	24.70%
Four-Way	45	4	6	RRFB	59.1%	20.6%	38.50%
T-Intersection	50	3	4	RRFB	71.9%	27.3%	44.60%
T-Intersection	55	2	2	RRFB	82.3%	69.6%	12.70%
T-Intersection	55	2	3	RRFB	85.4%	68.4%	17.00%

What was the rate of vehicles yielding to pedestrians by traffic volume?

One of the questions raised by the TAP was the effect of the traffic volume, how busy the road is, on the yielding behavior of drivers. The results are first sorted by treatment type and second by number of conflicts. (*) denotes locations where the sample is too small to support statistically correct findings. The colors on the table rows are an attempt in organizing groupings to assist the readers. Uncontrolled and LED sites don't have enough locations with good sample size to offer informative findings. On sites with signals, higher volumes show a weak correlation with higher yield rates. In general, the RRFBs when activated generate a yield rate that is controlled only by the number of conflicts while the traffic volume doesn't seem to be introducing a significant influence.

Table 6.18 What was the rate of vehicles yielding to pedestrians by traffic volume?

Treatment	Island?	Speed Limit (mph)	# of Conflicts	Average Volume (vph)	Average Driver Yield Rate
LED	No	45	1*	264	75%
LED	No	50	1	109	33%
LED	No	50	1	308	50%
LED	No	50	1*	93	25%
LED	Yes	25	2	1026	79%
LED	Yes	25	2	1026	88%
None	No	25	4	582	35%
None	No	45	1*	17	100%
None	No	45	1*	36	91%
None	No	50	1	119	88%
None	No	50	1	345	50%
None	No	50	1*	13	100%
None	No	50	1*	99	96%
RRFB	No	25	4	591	52%
RRFB	No	30	1	146	42%
RRFB	No	30	2	1248	72%
RRFB	No	30	2	1248	64%
RRFB	No	30	3	171	82%
RRFB	No	30	4	426	84%
RRFB	No	30	5	381	96%
RRFB	No	30	5	431	74%
RRFB	No	30	2*	154	68%
RRFB	No	30	3*	178	69%
RRFB	No	35	6	1386	25%
RRFB	No	45	6	474	60%
RRFB	No	50	4	367	72%
RRFB	Yes	30	1	1092	87%
RRFB	Yes	30	1	1092	82%
RRFB	Yes	30	2	1029	75%
RRFB	Yes	30	2	1029	60%
RRFB	Yes	30	2	1263	93%
RRFB	Yes	30	2	1263	96%
RRFB	Yes	30	3*	536	100%
RRFB	Yes	30	3*	536	100%
RRFB	Yes	50	4	500	93%
RRFB	Yes	50	4	500	97%
RRFB	Yes	55	2	976	82%
RRFB	Yes	55	3	976	85%
Signal	Yes	25	2	953	91%
Signal	Yes	25	2*	953	87%
Signal	Yes	30	2	1978	91%
Signal	Yes	30	2	1978	84%

How do yield rates differ per lane on multilane road crossings?

Does the presence/type of the PAC affect the yield rate of far lanes on multilane roads? If not all vehicles yield to a pedestrian, how many vehicles did not yield to pedestrian by system?

The following four tables show the number of non-yielding vehicles per lane the crossing is going over when the PAC had been activated and not-activated. Note that cases where the sample size was low were removed to simplify the tables. The full tables can be found in appendix B. In earlier discussions, the influence of the number of conflicts was emphasized, as such, these tables are sorted by the number of conflicting movements on each crossing. In all tables, the lanes are sorted in the order in which the pedestrian encounters them during the crossing from the starting point. For example, Lane 1 vehicles is the number of vehicles that didn't yield to the pedestrian on the first lane he/she had to cross, Lane 2 vehicles is the next one over, and so on. The tables were split in two groups based on average vehicle flow. Table 6.19 and 6.20 cover sites where the hourly flow is less than 700vph and Table 6.21 and 6.22 cover sites where the hourly flow is more than 700 vph. The Volume Standard Deviation is included to show that the presented average does not include large differences in traffic between sites of similar geometry. The number of samples included in each row is included. In cases where there were so few samples that the results are not statistically correct, the first columns are marked with an asterisk. Finally, the number of vehicles on each lane is a sum and not an average. This was selected to highlight the general trend better. The average can be calculated by dividing the per lane number with the sample size.

The first question above, asks for the yield rate per lane. This is not feasible to estimate since the location of vehicles is not homogeneous and the sites have a number of special lanes. In most cases the far lane is a left turn pocket. Further breakdown can be done to separate these cases but this has not been a priority.

In general, on all sites regardless of average vehicle volume, we observe that the far lanes generate higher numbers of non-yielding vehicles. This observation is stronger at sites with higher vehicle volumes. This is consistent with earlier observations and anecdotal evidence. It is interesting to note that in the case of un-controlled crossings, (Treatment listed as "none") the numbers of non-yielding drivers on far lanes are much higher. This is a significant observation and an argument for using PACs on multilane/multiconflict crossings since the most severe and fatal pedestrian crashes happen when the pedestrians starts crossing because the vehicle on the near lane yields but the vehicle on the farther lane fails to stop.

Regarding the question on how the system type affects the number of vehicles non-yielding, the numbers on the aforementioned tables do not indicate any large differences after the number of conflicts and volume is controlled for and low-sample size locations are removed.

Table 6.19 Non-Yields per lane for different numbers of conflicting movements, # of lanes crossed, and Activated treatment for sites with less than 700 vph

# of Conflicts	# of Lanes	Treatment	Island Start?	Who Yielded?	Average Volume	Average Volume StD	# of Samples	Lane 1 # of Non-Yielding Veh	Lane 2 # of Non-Yielding Veh	Lane 3 # of Non-Yielding Veh	Lane 4 # of Non-Yielding Veh	Lane 5 # of Non-Yielding Veh
1	1	None	No	Both	261	129	9	19				
1	1	None	No	Pedestrian	250	121	20	51				
1	1	RRFB	No	Both	146	0	11	22				
1	1	RRFB	No	Pedestrian	146	0	54	98				
4	3	None	No	Both	582	0	147	97	76	156		
4	3	None	No	Pedestrian	582	0	130	73	96	122		
4	4	RRFB	No	Both	544	86	86	19	35	46	54	
4	4	RRFB	No	Pedestrian	550	83	30	9	17	13	13	
5	3	RRFB	No	Both	409	25	32	7	10	3	10	9
5	3	RRFB	No	Pedestrian	414	26	6	3	0	0	2	3

Table 6.20 Non-Yields per lane for different # of conflicting movements, # of lanes crossed, and Non-Activated treatment for sites with less than 700 vph

# of Conflicts	# of Lanes	Treatment	Island Start?	Who Yielded?	Average Volume	Average Volume StD	# of Samples	Lane 1 # of Non-Yielding Veh	Lane 2 # of Non-Yielding Veh	Lane 3 # of Non-Yielding Veh	Lane 4 # of Non-Yielding Veh	Lane 5 # of Non-Yielding Veh
1	1	None	No	Both	261	129	9	19				
1	1	None	No	Pedestrian	250	121	20	51				
1	1	LED	No	Both	215	113	14	33				
1	1	LED	No	Pedestrian	211	115	30	87				
4	4	None	No	Both	582	0	147	97	76	156	115	
4	4	None	No	Pedestrian	582	0	130	73	96	122	123	
4	4	RRFB	No	Both	463	114	14	9	6	23	9	
4	4	RRFB	No	Pedestrian	428	101	22	10	16	12	25	
5	3	RRFB	No	Both	431	0	9	5	2	0	3	5
5	3	RRFB	No	Pedestrian	423	20	6	0	8	1	12	1

Table 6.21 Non-Yields per lane for different number of conflicting movements, # of lanes crossed, and Activated treatment for sites with more than 700 vph

# of Conflicts	# of Lanes	Treatment	Island Start?	Who Yielded?	Average Volume	Average Volume StD	# of Samples	Lane 1 # of Non-Yielding Veh	Lane 2 # of Non-Yielding Veh	Lane 3 # of Non-Yielding Veh	Lane 4 # of Non-Yielding Veh	Lane 5 # of Non-Yielding Veh	Lane 6 # of Non-Yielding Veh
1	1	RRFB	No	Both	1092	0	27	46					
1	1	RRFB	No	Pedestrian	1092	0	13	21					
2	2	RRFB	No	Both	1162	111	176	141	179				
2	2	RRFB	No	Pedestrian	1149	112	67	41	55				
2	2	RRFB	Yes	Both	1129	120	14	7	15				
2	2	RRFB	Yes	Pedestrian	1185	120	6	10	11				
2	2	Signal	No	Both	1698	463	33	42	46				
6	4	RRFB	No	Both	1386	0	55	14	29	24	21	30	27
6	4	RRFB	No	Pedestrian	1386	0	2	1	0	0	0	0	1

Table 6.22 Non-Yields per lane for different # of conflicting movements, # of lanes crossed, and Non-Activated treatment for sites with more than 700 vph

# of Conflicts	# of Lanes	Treatment	Island Start?	Who Yielded?	Average Volume	Average Volume StD	# of Samples	Lane 1 # of Non-Yielding Veh	Lane 2 # of Non-Yielding Veh	Lane 3 # of Non-Yielding Veh	Lane 4 # of Non-Yielding Veh	Lane 5 # of Non-Yielding Veh	Lane 6 # of Non-Yielding Veh
1	1	RRFB	No	Both	1092	0	6	17					
1	1	RRFB	No	Pedestrian	1092	0	15	39					
2	2	RRFB	No	Both	1143	120	27	25	39				
2	2	RRFB	No	Pedestrian	1224	72	75	36	54				
2	2	RRFB	Yes	Both	1070	92	17	15	11				
2	2	RRFB	Yes	Pedestrian	1055	82	16	22	19				
2	2	LED	No	Both	1026	0	34	23	55				
2	2	LED	No	Pedestrian	1026	0	12	5	13				
2	2	Signal	Yes	Both	1875	323	10	3	6				
2	2	Signal	No	Pedestrian	1795	399	28	15	7				
2	2	Signal	Yes	Pedestrian	1636	496	18	4	11				

CHAPTER 7: CONCLUSIONS

Pedestrian-Activated Crossing (PAC) systems such as the High intensity Activated crossWalK beacon (HAWK), the Rectangular Rapid Flashing Beacon (RRFB), and flashing LED crosswalk signs have been shown to have an aggregate positive effect on driver yielding rates. However, their relative effects on pedestrian safety are less clear, and richer insight as to their selection and placement is needed to justify their cost. This study estimated the effects of PACs on pedestrian crash rates using Monte Carlo simulation and examined the relationships between driver yield rates and a variety of treatments and site designs by conducting an observational study using video data from 31 crossings. This study represents one of the most extensive data collection efforts to date. The funding provided for this study, a reality on all past studies, could not satisfy both an extensive data collection effort and an analysis effort that uncovered all the relationships and causal mechanisms. The project team chose to put more weight on the data collection and tabulation and perform as much analysis as possible given the available funds. That way, the collected data would represent a standing resource that the traffic engineering community could share and use to produce deeper insights into the causal mechanisms related to the pedestrian level of service and safety at crossings.

The Monte Carlo simulation originally was going to be used to develop a simulation model that would allow engineers to enter data describing traffic and roadway conditions at a site, along with driver yielding rates from field studies and then use it to predict the crash modification effect likely to result from installation of a HAWK.

However, it was determined during validation that to produce an injury severity distribution similar to those observed in the Twin Cities, it was necessary to assume that all, or almost all, simulated drivers attempted to brake when faced with a pedestrian conflict. Simulations where all drivers attempted to brake, and where the fraction of careful pedestrians changed from 0-40% to 80% gave simulated crash modification factors that were similar to those reported for installation of HAWKs. Together, these outcomes suggested that while the percentage of yielding drivers might be a useful indicator of the pedestrian level of service, it was less helpful as a safety surrogate. This could be because a driver’s yielding to a pedestrian, as observed in field studies, might not be the same behavior as a driver attempting to stop during a vehicle/pedestrian conflict.

The simulation results also suggested that the crash-reduction effects reported for HAWKs might result from modifying pedestrian behavior rather than, or in addition to, modifying driver behavior. At this point, though, before a simulation model can be used to support practical decision-making, a better understanding is needed of how HAWKs (and RRFBs) affect both driver and pedestrian behavior, especially as to how high-risk interactions are generated. Although more work is needed, simulation modeling can provide a framework for stating hypotheses about road-user behavior and then deriving consequences from these hypotheses, which can then be compared to observations.

The statistical analysis part of this study helped guide the analysis of the results from the collection of observations in the field. The observational study results were presented in separate sections, one for the HAWKs and one for all other systems. The following are some highlights of the results presented in the previous chapter.

- Based on the observations collected on sites with HAWK PACs, the pedestrian wait, or delay, time is relatively high because it includes the system activation time. The results, though, show that when a HAWK is activated, the experienced delay, and to a certain extent pedestrian LOS, has a more stable standard deviation as compared to the cases when the system is not activated. This is a positive aspect of the HAWK since crossing time reliability can be considered a bonus to the overall LOS.

- RRFB delay times are considerably lower than the ones observed on HAWK sites given that RRFBs do not have a delay in allowing the pedestrian to cross. Regardless, it is still observed that when the drivers do not yield, the resulting delay to cross is significantly higher and comparable to that of activated HAWK PACs. This suggests that at locations where, for various reasons, the driver yield rates are not high enough with an RRFB, installing a HAWK will result in better LOS. On the other hand, if with the RRFB, yield rates are sufficient, installing a HAWK will result in higher delays and therefore reduced service to the pedestrians and drivers.

- On the one site with an automatically activated RRFB that was included in this study, the delay was similar to that of a HAWK. At this study site, there was no evidence pedestrians initiated their crossing before the PAC was active. Therefore, if the concern was the level of activation of an RRFB, but the resulting yield rate when activated was sufficient, installing an automated activation mechanism will result in a cheaper solution with similar LOS, compared to a HAWK.

- Consistent with earlier research by Hourdos et al. (2012) on roundabout crossings, driver yield rates were higher for interactions where the pedestrian was starting the crossing from an island (second part of crossing) than for interactions where the pedestrian was crossing to an island (first part of crossing). This trend was most pronounced in the cases of activated signals and RRFBs where all or nearly all drivers yielded to pedestrians crossing from an island unlike the corresponding cases where the pedestrians were crossing to an island.

- The analysis shows that for RRFBs the benefit from the system, in terms of driver yield rate, increases with the number of lanes or more importantly the number of conflicting movements.

- Signals serving as PACs have shown to be counterproductive since, if they are not activated, driver yield rate is very low. This can be explained with the hypothesis that drivers are accustomed to signals that are explicit determinants of priority; therefore, if they are not red, it implies vehicles do not have to stop. Crosswalk markings and other static signs seem to be of lesser relevance in the presence of a signal head, even a blank one.

- The analysis results suggest that overhead placement of RRFBs may result in increased driver yield rates regardless if they are activated or not. This could imply that it may not be the overhead RRFB itself that is responsible for the improved yield rate but the accompanying static sign on the overhead mast. It would be interesting to investigate a case where there is a static overhead sign without the RRFB. Regardless, common logic dictates that after the initial cost of installing an overhead mast arm, adding one instead of two RRFBs represents a small additional installation cost although it may add more in maintenance.

- An overall finding from the comparison of driver yield rates with and without an activated PAC is that good visibility, extra static signage, and advanced notice could be sufficient for raising the driver yield rate to a satisfactory level in which case the cost of a PAC is unjustified. It is only at intersections with poor visibility that PAC systems increase the driver yield rate by a significant additional amount when activated.

MnDOT, the agency that funded this research effort, specifically requested the before-and-after analysis of flashing LED pedestrian sign PACs. Due to the novelty of the system, only one overall site was available from which to collect observations. Unfortunately, the site involved only cases of free right-turn lanes, and a small number of pedestrian traffic compounded by sidewalk/crossing alignment issues resulted in most pedestrians crossing by following a path that did not bring them near the PAC activation button. Although the study did not provide sufficient insight regarding the effectiveness of the flashing LED pedestrian signs, it did highlight the importance of carefully planning the crossing geometry and alignment to the pedestrian path connected to it.

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APPENDIX A

PEDESTRIAN INJURY SEVERITY VS VEHICLE IMPACT SPEED: CALIBRATING A RELATIONSHIP TO LOCAL CONDITIONS USING MULTIPLE IMPUTATION.

Pedestrian Injury Severity vs Vehicle Impact Speed: Calibrating a Relationship to Local Conditions Using Multiple Imputation.

Gary A. Davis, Christopher Cheong

INTRODUCTION

Cities in both North America and Europe have seen, over the past 30 years or so, a growing interest in making walking and other non-motorized transport modes more attractive options for a greater number of people. As pedestrian volumes increase, however, one can expect, other things being equal, an increase in vehicle/pedestrian conflicts and crashes. This had led to new interventions, such as pedestrian hybrid beacons (PHB) and rectangular rapidly flashing beacons (RRFB), aimed at reducing conflicts where traditional traffic signals are unwarranted. Initial empirical work has shown crash reduction effects for HAWKs (Zegeer et al 2017; Fitzpatrick and Park 2010) while the effect of RRFBs is, at present, less clear (Zegeer et al 2017). This empirical work is, of course, descriptive of the current mix of driver and vehicle capabilities and we can expect this population to change, possibly significantly, as automated vehicle technologies increase in both sophistication and market penetration. Awareness of this trend has led to interest in alternative methods for predicting effects on pedestrian safety, such reconstruction-based prediction (Rosen et al 2010) and Monte Carlo-based simulation (Helmer et al 2011). A key component in both these approaches is an empirical relationship between the speed of a vehicle when it strikes a pedestrian and the resulting severity of the pedestrian's injuries. Although it has long been recognized that impact speed shows a definite association with pedestrian injury severity (e.g. Ashton, Pedder, and McKay 1977), identifying a reliable quantitative relationship has proved difficult. Rosen et al (2011) reviewed that state-of-art in this area, and identified several methodological concerns. First, the primary data sources for developing this relationship are samples of vehicle/pedestrian crashes that have been investigated in sufficient detail to provide both an estimated impact speed and a characterization of pedestrian injuries. Unfortunately, the sampling scheme for such studies tends to be outcome-based, with crashes showing more serious injuries being more likely to be included. Although outcome-based samples can reliably identify injury risk factors they will, unless appropriately corrected, produce biased predictions of injury prevalence. Second, after developing a severity vs impact speed relationship one can expect that, as with all statistical methods, some residual uncertainty will remain, so in addition to providing point predictions of injury risk the analyst should also provide confidence intervals for these predictions. Third, greater attention should be paid to the fact that impact speeds estimated from crash reconstructions will also tend to be uncertain and if this uncertainty cannot be eliminated it should also be quantified.

Several years ago, researchers at the University of Minnesota developed a prototype simulation model for rating traffic conditions on local streets with regard to risk to pedestrians (Davis et al 2002). A component of this model was an empirical relationship between impact speed and injury severity developed using data collected in Great Britain during the 1970s. As part of a current ongoing project it was decided to update this relationship using recent, and local, data. The remainder of this paper describes an estimation method that explicitly addresses the three issues raised in Rosen et al (2011).

METHOD

Data

Two sources provided the data for this study. The first was the National Highway Traffic Safety Administration's (NHTSA) Pedestrian Crash Data Study (PCDS) (Chidester and Isenberg 2001). The PCDS data contains results from detailed investigation of 521 vehicle/pedestrian collisions, occurring in six U.S. cities during 1994-1998. Among the items recorded in the PCDS were an estimate of the vehicle's speed at impact, in kilometers/hour (kph), and a classification of the severity of the pedestrian's injury severity as reported on a police crash investigation form, using the KABCN classification system. For our initial analysis the PCDS data set was filtered to identify crashes involving adult (age 15-60) pedestrians, with a police-reported injury severity, and where the impact speed was estimated from crash scene information by NHTSA personnel. This gave a total of 247 relevant cases.

Our second data source was the reported vehicle/pedestrian crashes occurring in the Twin Cities metro area during the years 2008-2015. An original list of almost 4700 crashes was filtered to produce a subset consistent with the cases from the PCDS study. That is, crashes involving multiple vehicles or where the involved vehicle was other than a passenger car, sport-utility vehicle, pickup truck or van were removed. Crashes involving "non-motorized conveyances," such as bicycles, skate boards, strollers, or inline skates were also removed. Finally, in order reliably match the police-reported injury severity to pedestrian age, crashes involving multiple pedestrians were also removed. This left a total 2764 Twin Cities crashes involving pedestrians age 15-60.

For our initial analysis both the PCDS crashes and the Twin Cities crashes were then classified as follows:

N or C injuries were coded as Slight (0),

B, A, or K injuries were coded as Serious (1).

Table 1 shows the distribution across injury class for both our PCDS subset and our Twin Cities subset. The proportion of Serious injuries is noticeably higher (75%) in the PCDS subset than in the Twin Cities subset (44%), indicating that serious injuries are over-represented in the PCDS compared to crashes reported in the Twin Cities. Figure 1 shows a boxplot of impact speed versus injury severity in the PCDS subset. Although there is a clear trend for more severe injuries to be associated with higher impact speeds the impact speed ranges for the two injury groups show considerable overlap.

Table 1. Injury Severity Distributions from PCDS and Twin Cities Subsets

	Slight	Serious	Total
PCDS	62 (25%)	185 (75%)	247
Twin Cities	1560 (56%)	1204 (44%)	2764

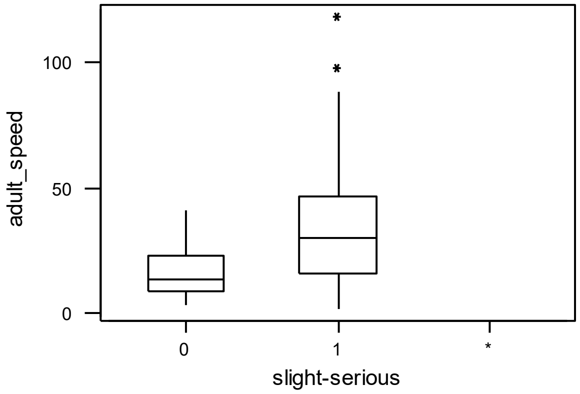

Figure 1. Boxplot showing distributions of PCDS impact speeds for slight (0) and serious (1) injuries. Data are for adults ages 15-60, speeds are in kilometers/hour.

Analysis

The basis of our estimation approach is a special case of the threshold model described in Davis (2001), where the "damage" experienced by a pedestrian is assumed to be proportional to impact speed but also subject to a random component accounting for unobserved, individual, features of the crash. That is

$$\text{Damage} = bv + e \tag{1}$$

where

v = impact speed

b = damage increase rate

e = random effects.

A serious injury then results when damage exceeds a threshold denoted by a.

$$\text{Prob(serious injury} \mid v) = \text{Prob}(bv + e > a) \tag{2}$$

When the random damage e follows a logistic distribution equation (2) leads to a logistic regression model

$$\text{Prob(serious injury} \mid v\,) = \frac{\exp(bv - a)}{1 + \exp(bv - a)} \tag{3}$$

The problem then is to reliably estimate the threshold parameter a and the slope parameter b. It is well known that unbiased estimates of slope parameters such as b can be obtained from an outcome-based sample, such as the PCDS, but that estimates of intercepts, such as the threshold *a*, will depend on the relative proportion of Slight versus Serious cases (e.g. Hosmer and Lemeshow 2000). However, applying a result from Hsieh et al (1985), when the population outcome proportions can be estimated from an exogenous sample, consistent, asymptotically normal estimates of both the slope and intercept parameters can be computed by maximizing the weighted, exogenous sample likelihood function

$$wesl = \frac{s_0}{m_0}\sum_k (1-y_k)\ln\left(\Pr(slight \mid v_k, a, b)\right) + \frac{s_1}{m_1}\sum_k y_k \ln(\Pr(serious \mid v_k, a, b)) \qquad (4)$$

where

s_0 (s_1) = proportion of slight (serious) injuries in exogenous sample

m_0 (m_1) = proportion of slight (serious) injuries in outcome-based sample

y_k = 0, if outcome-based case k has slight injury

1, if outcome-based case k has serious injury

v_k = impact speed from outcome-based case k

ln denotes the natural logarithm function.

Hsieh et al (1985) also provided expressions for estimating the covariance matrix associated with the weighted exogenous sample maximum likelihood (WESML) estimates. This, together with the asymptotic normality of the WESML estimates leads to a practical set of tools for estimation, hypothesis testing, and computing confidence intervals.

If the impact speeds v_k were known with negligible error WESML would solve our estimation and inference problem, at least for suitably large samples. Unfortunately, the state-of-art in crash reconstruction is such that uncertainty almost always remains (Davis 2003), and a reliable prediction methodology should first quantify this uncertainty and then propagate it through to the desired predictions. Accounting for covariate measurement error in logistic regression has historically been difficult (Carroll et al 1995) and a straightforward but computationally intensive solution is multiple imputation (MI) (Rubin 1978). To apply MI to our problem one must first characterize the probability distribution of the true, but unobserved, impact speeds given their measured values. One then uses Monte Carlo simulation to generate, for each PCDS case, a simulated impact speed. Using the simulated speeds and the observed injury severities one then computes the WESML estimates and their covariance matrix. Repeating this process a number of times gives a sample of the estimates, which can be combined, using Rubin's Rules (van Buuren 2012), to give an overall estimate of the parameters along with a covariance matrix that accounts for impact speed measurement error.

To apply MI to our problem a Mathcad 14 document (Maxfield 2009) was constructed which uses Mathcad's Minerr function to compute, for a given set of impact speeds, WESML estimates of the slope and threshold parameters. This routine was then embedded in a Mathcad function that iteratively generates a random set of impact speeds, solves for the associated WESML estimates, computes the associated covariance matrix, and saves these results. After completing the specified set of iterations the document applies Rubin's Rules to produce a final set of parameter estimates and their covariance matrix.

RESULTS

As a first test, standard logistic regression was applied to the PCDS data without the exogenous sample, primarily to see if the linear relationship between impact speed and injury severity was plausible. (Since WESML in essence adjusts the model's intercept so as to reproduce the exogenous sample's distribution, standard logistic regression goodness of fit tests would not be appropriate.) Table 2 summarizes these results. Of interest here are the Somers' D and the Hosmer-Lemeshow test, both of which indicate that the model given in equation (2) provides a reasonable representation of the PCDS data.

Table 2. Results from Standard Logistic Regression Using Only PCDS Data

Parameter	Estimate	Standard Error	Z-statistic	P-value
a	0.531	0.297	1.79	0.074

b	0.071	0.013	5.28	5.28
Somers’ D = 0.53		Hosmer-Lemeshow = 3.98, DF = 8, P = 0.867		

Next, as indicated above, applying MI to this problem requires that we characterize the posterior distribution of a crash’s true impact speed given its reported impact speed. Although work remains to be done on this problem some preliminary results using crash tests with pedestrian dummies has indicated that lognormal measurement error models are not unreasonable for a first approximation (Davis 2011). Applying this, the true (unobserved) impact speeds, given the reported impact speeds, were treated as lognormal random variables with user-specified coefficients of variation (COV). MI was then carried out with 50 imputed speed samples, for coefficients of variation equal to 0.1, 0.2, and 0.3. To see how to interpret the COVs, when the coefficient of variation equals 0.1 and the measured impact speed was 30 kph, the true impact speed would probably be between 24 kph and 36 kph. With a coefficient of variation of 0.3 and a measured impact speed of 30 kph the true speed would probably be between 10 kph and 50 kph. Table 3 summarizes our results.

Table 3. Results from Multiple Imputation Experiment

	Impact Speed Measurement Error							
	None		COV = 0.1		COV = 0.2		COV = 0.3	
Parameter	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Estimate	1.94	0.073	1.89	0.71	1.77	0.065	1.63	0.058
Standard error	0.23	0.011	0.24	0.013	0.26	0.013	0.27	0.014

As expected, as the magnitude of the measurement error increases the standard errors associated with the slope and threshold estimates also increase, illustrating how uncertainty regarding the impact speeds induces uncertainty about the parameter estimates. Even for COV = 0.3, which is probably unreasonably high, it is possible to determine that both the slope and threshold parameters are different from zero. To see how measurement error affects ability to predict injury severity, Figures 2-4 plot probabilities of serious injury as functions of impact speed, along with approximate ± 2 standard error ranges. An appeal to the asymptotic normality for the slope and threshold estimates and to the delta method suggests that the ±2 standard error range is, to a first approximation, a 95% confidence interval for the predicted injury probability.

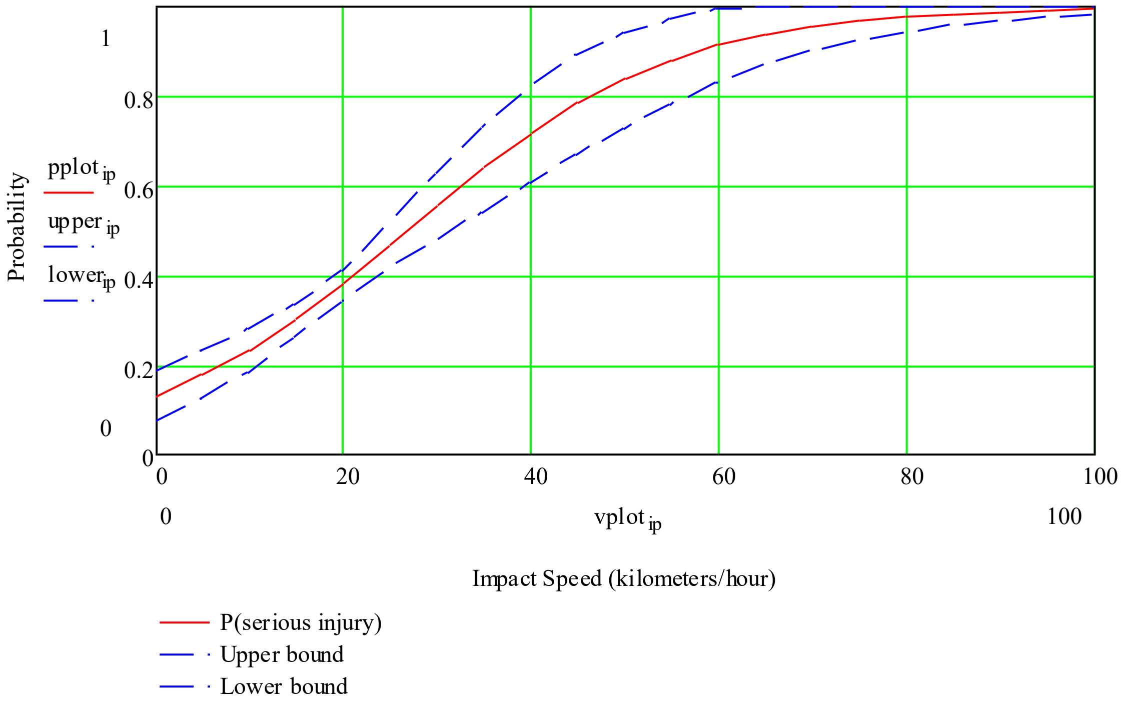

Figure 2. Probability of serious injury vs impact speed when impact speed uncertainty has a coefficient of variation equal to 0.1

Figures 2-4 show the effect of uncertainty regarding the impact speeds more clearly than the estimation summary in Table 3. When COV equal to 0.1, Figure 2 indicates that impact speed uncertainty has only modest effect on the predicted probability of a serious injury, while when COV=0.5, Figure 4 shows that the usefulness of these predictions is noticeably compromised, especially for impact speeds greater than 40 kph.

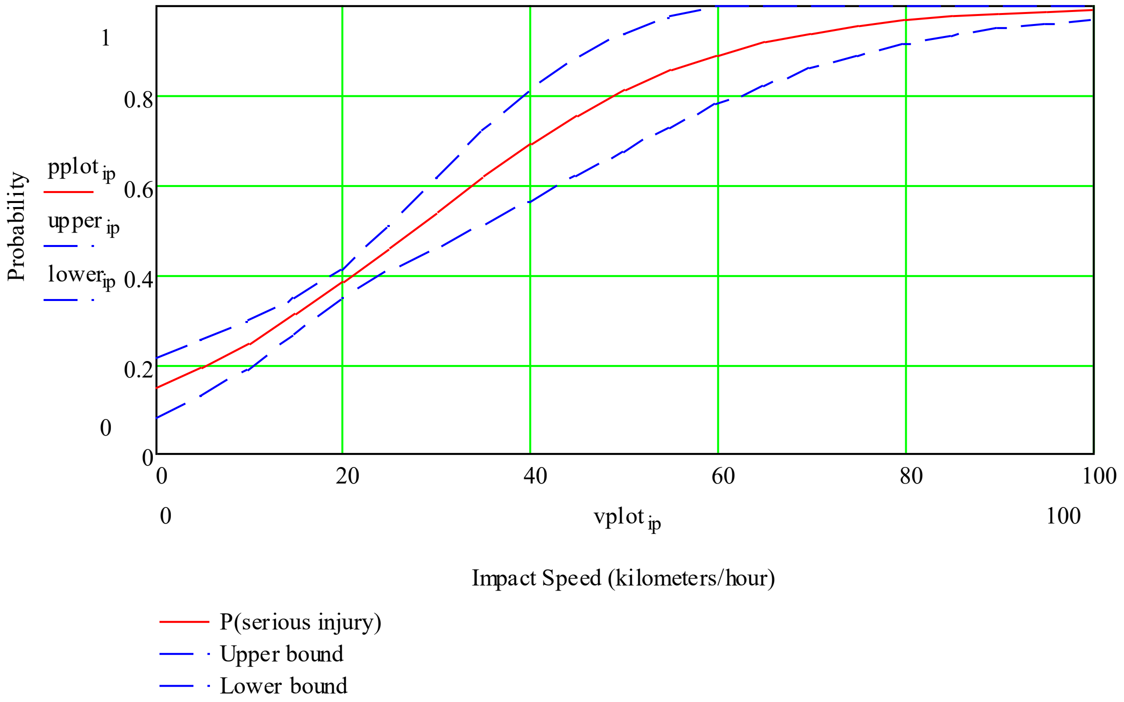

Figure 3. Probability of serious injury vs impact speed when impact speed uncertainty has a coefficient of variation equal to 0.2.

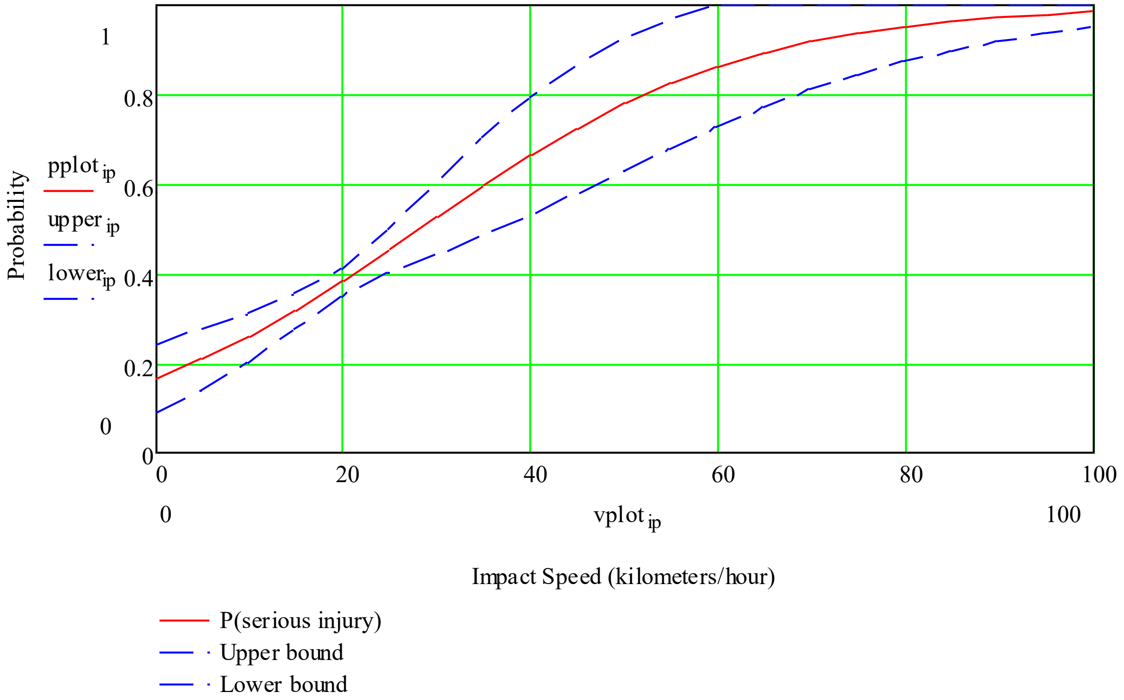

Figure 4. Probability of serious injury vs impact speed when impact speed uncertainty has a coefficient of variation equal to 0.3.

CONCLUSION

This paper described a method for constructing predictive relationships between vehicle impact speed and pedestrian injury severity, where results from a national sample were calibrated to reflect pedestrian injury prevalence in the Twin Cities metro region. Three methodological issues identified in Rosen et al (2011), outcome-based sampling, the need for confidence intervals, and possible uncertainty regarding estimated impact speeds, were addressed by applying multiple imputation to weighted exogenous sample maximum likelihood estimation. Given a reliable characterization of impact speed uncertainty this approach can be applied to any jurisdiction having an exogenous sample of pedestrian crash severities. Characterizing the uncertainty in the impact speed estimates is, however, something of an open question and one which were are currently investigating.

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