Pedestrian Treatments in Phoenix: Guidance on Implementation and Operation

Final Report

Prepared for

City of Phoenix

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DISCLAIMER

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EXECUTIVE SUMMARY

Pedestrian safety is a critical transportation and public health issue, with fatalities increasing substantially over the past decade. Given this trend, it is important to understand where and when to most effectively implement countermeasures that help prevent pedestrian crashes, injuries, and fatalities. To address this issue and with the goal of improving safety for non-motorized users within the City of Phoenix, this project included the following activities:

- Literature review regarding implementation and operation of different pedestrian treatments at signalized intersections, as well as bicycle clearance intervals and confirmation lights for Rectangular Rapid Flashing Beacons (RRFB) and Circular Rapid Flashing Beacons (CRFB),
- Laboratory tests of advanced pushbuttons to determine their suitability for application in low desert environments,
- Before and After safety assessment of the Leading Pedestrian Interval (LPI) and 'No Right Turn on Red' (NRTOR) treatments from field collected conflict, speed, and volume data,
- Development of public facing LPI implementation guidelines, and
- Recommendations for a Standard Operating Procedure (SOP) for a pedestrian scramble.

Literature Review

The literature review provided an overview of implementation guidance and safety effectiveness evaluations of different pedestrian treatments such as LPI, pedestrian scramble, RRFB/CRFB indicator beacons, and advanced push buttons. existing LPI guidelines in California, Florida, Toronto, and Scottsdale were highlighted and found to have varying suitability and duration criteria based on factors such as crash frequency, traffic volume, visibility, and intersection geometry. In contrast, there is a lack of standardized guidelines for implementing pedestrian scrambles in North American jurisdictions. Regarding RRFB/CRFB confirmation lights, no official guideline or documentation was found, however, two distinct types of confirmation lights for RRFB systems installed on overhead and pole-mounted systems that were observed in Nevada and Indiana. With respect to bicycle signal clearance intervals, the guidance in NCHRP Report 969 is the most recent and describes rules and recommendations in the most detailed format.

Pushbutton Laboratory Tests

Laboratory tests of advanced pushbuttons involved performance evaluation experiments on Polara iNS3 and Guardian Wave pushbutton devices, testing their touchless detection, extended press capabilities, and responsiveness under various conditions. Both devices were evaluated for their range, sensitivity, and other settings, with a particular focus on environmental impacts such as dark conditions, gloves, and heated buttons. The Polara's minimum wave time settings and Guardian Wave's sensitivity and delay settings significantly influenced their detection fields. The Polara unit's centroid height was above the button's centerline, whereas the Guardian Wave's was below. Both units' extended press and Polara's rain lockout functionalities worked as intended, with the Polara PedApp also providing effective accessibility features.

LPI Guidelines

To develop implementation guidelines for the LPI treatment, an analysis of field-collected conflict data was conducted. First, Phoenix pedestrian crash data from 2016 to 2022 were analyzed to identify priority intersections. Next, a volume analysis was performed on these intersections to select high-exposure crosswalks, with eight crosswalks from four intersections selected for video data collection. Five-second LPIs were implemented at each selected site, where video was recorded both before and after LPI implementation. Conflict data were manually reduced from field-collected videos, focusing on incidents where the Post Encroachment Time (PET) was 5 seconds or less. Conflicts were categorized into high, medium, and low severity based on PET thresholds, with high severity defined as PET ≤ 1.5 seconds. Factors related to the frequency and severity of the conflicts were analyzed. Notable results from the conflict analysis included:

- A significant reduction was observed in both the frequency and severity of vehicle-pedestrian conflicts after LPI implementation.
- Most conflicts observed involved right turning vehicles and pedestrians, with the pedestrian typically arriving first to the conflict area.
- Conflict frequency models indicated a significant negative relationship between LPI implementation and conflict frequency, predicting a reduction of 10-15% for all vehicle-pedestrian conflicts and 44-50% for more severe conflicts.
- A conflict severity model also found LPIs significantly reduce the likelihood of high and medium severity conflicts.

NRTOR restriction was also evaluated at one crosswalk using field-collected conflict data. While a reduction in conflicts was observed, the treatment's effectiveness may be limited due to significant non-compliance among drivers, with over 50% of right-turning vehicles violating the temporarily-installed restriction.

Building on the crash and conflict analyses conducted in this work as well as other published guidance, a set of public-facing LPI implementation guidelines were developed. Incorporating a flowchart and a worksheet, these guidelines use intersection level factors (e.g., crash history, geometry and the built environment, vehicular level of service) and crosswalk level factors (e.g., pedestrian and conflicting turning vehicle volumes) to develop a score for each analyzed crosswalk. As LPIs should be implemented in pairs, the scores of each crosswalk in a pair are then entered into a suitability matrix to determine if implementation of an LPI at those crosswalks would be expected to have a low, medium, or high safety benefit.

Pedestrian Scramble SOP Recommendations

Finally, SOP recommendations for the pedestrian scramble treatment were developed. While only Los Angeles was found to have robust implementation guidance, a review of the literature allowed for the development of guidance regarding locations that may or may not be suitable for a pedestrian scramble, implementation challenges, and design and operational recommendations.

Looking forward, the SOP recommendations for the pedestrian scramble could be improved through further research on the topic. A practitioner survey to uncover other, unpublished implementation and operational guidance would provide additional insight into how other agencies are using the treatment, while a field calibrated simulation / sensitivity analysis of the treatment based upon local operational characteristics could provide additional guidance on the effectiveness of the treatment, and the impact it has on user behavior (violation, conflicts, etc.).

1 INTRODUCTION

There are a number of pedestrian treatments that are available to reduce pedestrian / motor vehicle conflicts at signalized intersections. While these treatments have been implemented at many locations across the nation and have shown to be beneficial to pedestrian safety, a number of questions remain about their implementation and operation, particularly within the City of Phoenix. Regarding implementation, a number of cities have developed both prescriptive and descriptive guidelines for implementation of some of these treatments. While some inspiration may be gleaned from these and other examples of implementation guidelines, no existing guidelines are likely to be a best fit for the City of Phoenix due to inherent differences in these unique characteristics. In order to take a more proactive approach toward the implementation and operation of Leading Pedestrian Intervals (LPIs) and other non-motorized user-focused treatments in the City of Phoenix, this project had the following objectives:

- Conduct a literature review regarding implementation and operation of pedestrian treatments at signalized intersections, focusing on the LPI, pedestrian scramble, and advanced pedestrian push buttons, as well as RRFB/CRFB indicator beacons at midblock locations to evaluate the suitability of the content contained for application within the City of Phoenix,

- Utilize crash data analysis to identify signalized intersections in the City of Phoenix with a high frequency of turning vehicle-pedestrian crashes and rank these intersections to prioritize locations for field data collection,

- Conduct volume analysis at selected priority intersections to identify high-exposure crosswalks for video data collection, considering pedestrian and vehicle counts during specified time periods,

- Generate quantitative observational data on vehicle-pedestrian interactions at signalized intersections with and without pedestrian treatments from field collected videos,

- Analyze factors related to the frequency and severity of pedestrian-vehicle conflicts observed in the field-collected data to provide insights into the development of evidence-based strategies for pedestrian treatments implementation,

- Perform laboratory tests of advanced pushbuttons to determine their suitability for application in low desert environments, and

- Develop public-facing guidelines for pedestrian treatment implementation for the City of Phoenix based on the review of the existing literature and field and lab-collected data and analysis, and provide recommendations for a Standard Operating Procedure (SOP) for a pedestrian scramble.

2 LITERATURE REVIEW

This chapter documents previous research related to the topic of this project: pedestrian safety at signalized intersections focusing on pedestrian treatments and their implementation guidelines. A review of relevant journal articles, reports, and other publications and guidance documents was conducted. The review is focused on previous research regarding implementation and operation of pedestrian treatments at signalized intersections, focusing on the LPI, pedestrian scramble, and advanced pedestrian push buttons, as well as RRFB/CRFB indicator beacons at midblock locations as well as methods for analyzing pedestrian safety including crash frequency analysis and the use of surrogate measures of safety. Additionally, various guidelines for bicycle clearance signals are discussed.

2.1 Leading Pedestrian Interval

The LPI has been implemented as a low-cost countermeasure to provide pedestrians an advance start before the concurrent green traffic signal to increase pedestrian visibility and safety in crosswalks, as shown in **Figure 1**. Different North American jurisdictions have developed and implemented differing guidelines for LPI implementation, which are covered in the subsequent subsections of this report.

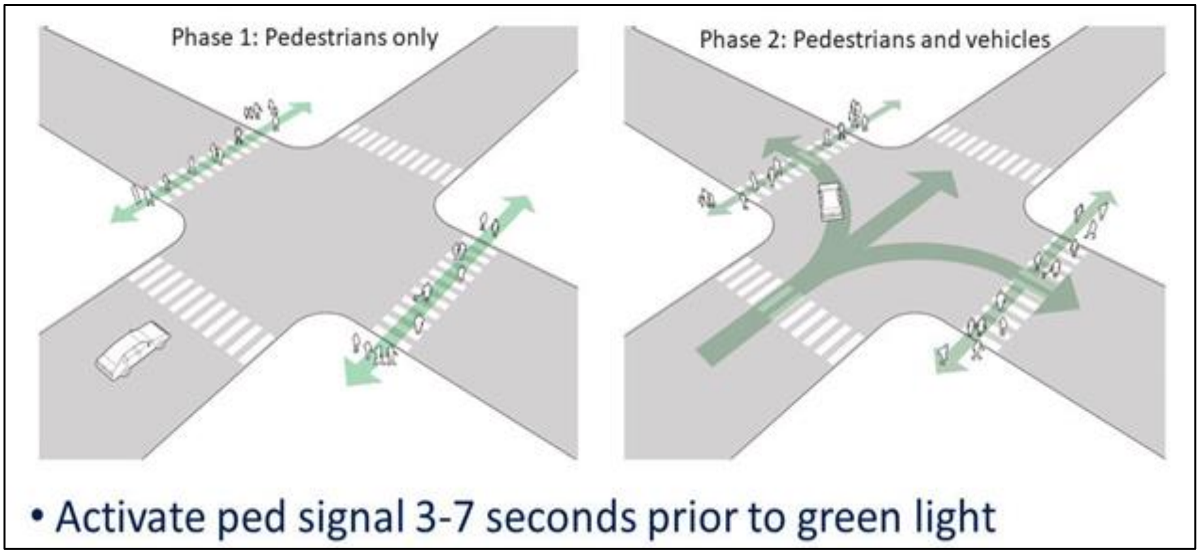


Figure 1: Leading Pedestrian Interval (National Association of City Transportation Official, 2013)

2.1.1 LPI implementation guidelines of Toronto, Canada

The transportation services of the City of Toronto, Canada, developed an implementation and assessment guideline for LPIs in 2015 (City of Toronto, 2015). The suitability of an LPI at a selected location was evaluated using a score-based suitability worksheet based on the following factors: intersection geometry (T-intersection or one-way intersection), visibility issues, pedestrian volume, collision rate, proximity to elementary schools and elderly residents' activity, and impact on vehicular traffic. In addition, the guideline included the formula of LPI duration with a minimum of 5 seconds or the time requiring pedestrians to clear at least half the crosswalk in one direction of moving traffic. **Figure 2** shows the flowchart of steps for Toronto's guidelines.

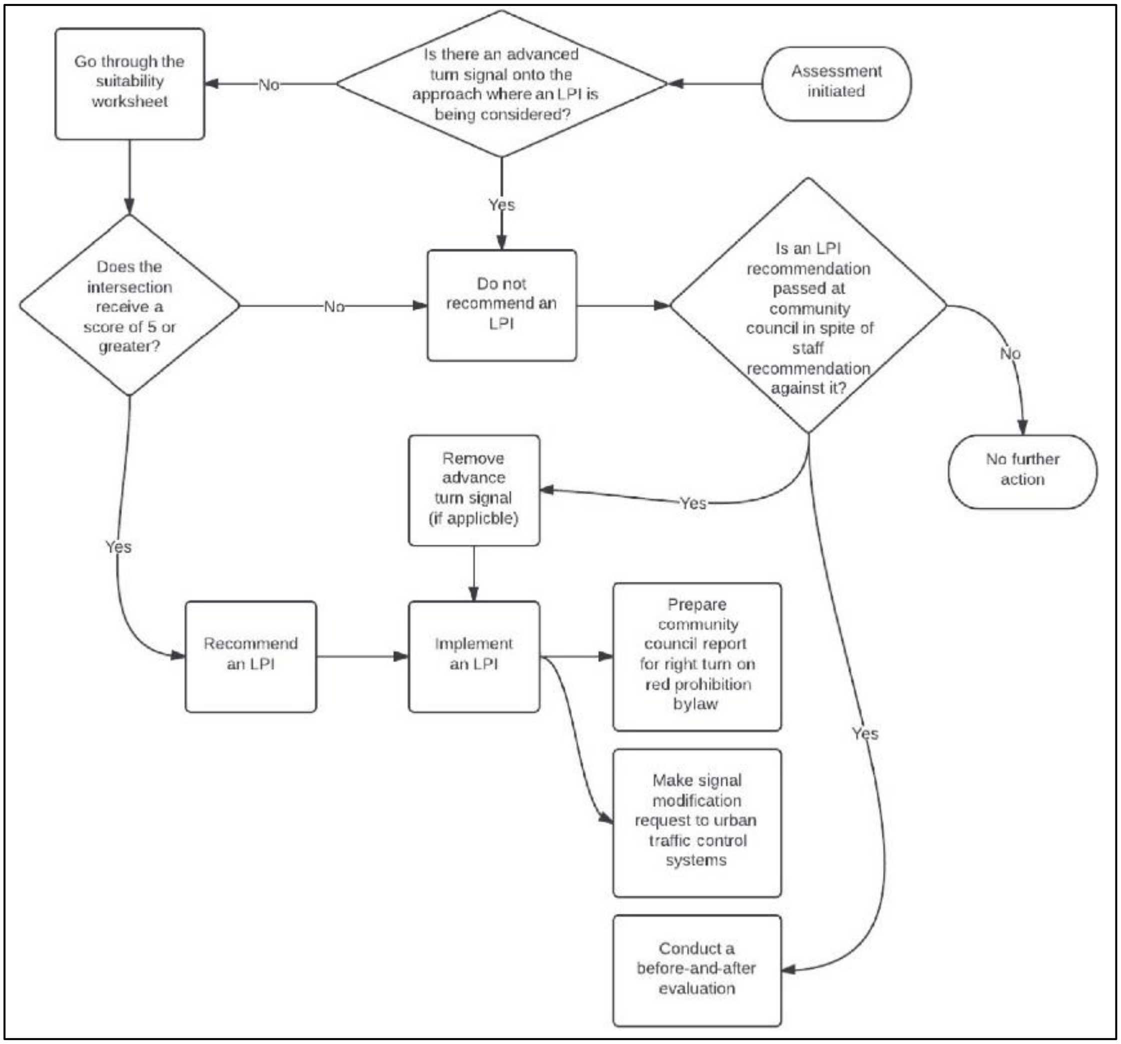


Figure 2: Flowchart on LPI Suitability Assessment and Implementation (Saneinejad & Lo, 2015)

The guidelines proposed right turn-on red (RTOR) provisions with all LPIs unless there is a considerable adverse effect on vehicle capacity. LPI was not recommended at semi-actuated and protected leading left-turn signals. To reduce the negative impact of an LPI on road capacity and vehicular delay, leading through intervals and smaller turning radii were suggested as mitigation alternatives. A before and after safety evaluation was also recommended in their study 6 months after installation to measure the effectiveness of the LPI.

In 2021, the City of Toronto developed additional guidance and proposed a systematic and proactive approach for the implementation of an LPI (City of Toronto, 2021). In this document, the Empirical Bayes (EB) method was used to rank intersections based on the potential for safety improvement to determine the phasing of an LPI implementation. Additionally, LPI was suggested for implementation in conjunction with corridor-level traffic signal studies to mitigate the negative impact of vehicular delay. "New Pedestrian Head Start" information signs were also recommended to install for a few months after an LPI implementation to alert users to changes.

2.1.2 LPI implementation guidelines of Florida

In 2017, researchers from the Florida Department of Transportation (FDOT) conducted a study to develop statewide guidelines for LPI implementation (Lin et al., 2017). At first, the research team developed a preliminary guideline based on knowledge and guidance from literature reviews and experienced traffic engineering professionals. A flow chart of the preliminary guidelines is presented in **Figure 3**. After that, video data were collected from nine geographically diverse intersections that met one or more of their preliminary guidelines' warrants. From the before/after study, LPIs were effective in reducing vehicle-pedestrian conflicts at six intersections. Simulation analyses from two sites indicated that the LPI caused a minor increase or decrease in the average total delay per vehicle on different approaches. Results found that LPIs were effectively utilized at most of the studied intersections, with a percentage of utilization above 85%. Marginally lower utilization was observed on parallel crosswalks where LPI was activated by pressing the pushbutton by either side It should be noted that an LPI was noted as not utilized when pedestrians press a pushbutton to activate it, but they cross the street or otherwise exit the intersection before it starts, resulting in the activation of the LPI but no pedestrian crossing.

Refined guidelines were then proposed based on data analysis results and findings from pilot LPI implementations. In these new guidelines, eight reformed warrants based on crash frequency, visibility issues, vehicle non-yielding behavior, vehicle, and pedestrian peak hour volume, four-hour vehicular and pedestrian volume, eight-hour vehicular and pedestrian volume, and school crossings were included. An LPI was only recommended if one or more warrant requirements were satisfied. The guidelines did not recommend an LPI in cases of high traffic congestion and travel delays. Additionally, an electronic blank-out “NO TURN ON RED” sign and a different background-colored informational sign was suggested to enhance LPI implementation. Finally, an extended LPI was considered at particular locations with a large percentage of slow-moving pedestrians and the absence of a pedestrian detector.

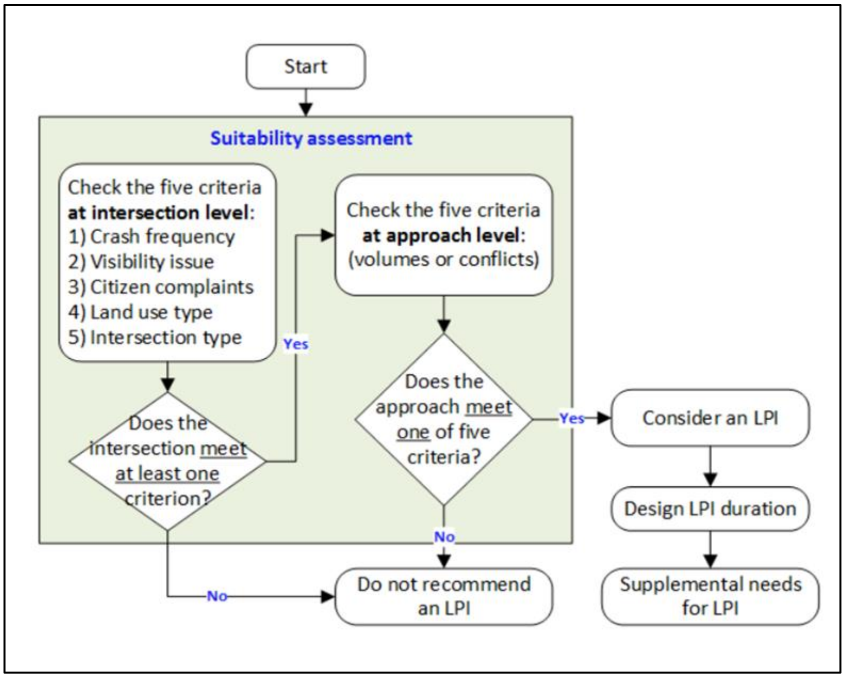


Figure 3: FDOT's Preliminary Suitability Assessment and Design Recommendation Flowchart (Lin et al., 2017)

2.1.3 LPI implementation guidelines of California

California has also published a memorandum for LPI implementation (Carpenter & Bhullar, 2021). The guideline recommended that crossing markings, Accessible Pedestrian Signals (APS), and pedestrian countdown signals might be installed at intersection approaches before LPI implementation. RTOR prohibition was also recommended, however engineering judgment was advised in cases where the RTOR prohibition may severely reduce vehicle capacity. Several factors were considered before selecting a site for LPI implementation. For intersections with multiple crashes or a history of severe injury and fatal crashes, a review of 3-5 years of crash data was suggested for site prioritization; however, conflict analysis data can also be utilized to complement crash data. Another aspect to consider when selecting an intersection for LPI was the estimated exposure (the sum of the volumes of turning traffic and pedestrian traffic). Peak hour exposures in the AM, PM, and midday periods could each be analyzed independently. An LPI was also advised for crossings where a crosswalk's visibility is restricted or limited and one-way streets and T-intersections. Additionally, implementation of an LPI was prioritized in areas with increased school-going children and older people.

Consideration of different signal timing factors was also included in the guidelines. The minimum duration of an LPI was considered as 3 seconds, per the California Manual on Uniform Traffic Control Devices (MUTCD) Section 4E.06 (California Manual on Uniform Traffic Control Devices, 2014). The guideline suggested an increase in cycle length when introducing an LPI at intersections with short cycle lengths to mitigate traffic delay concerns. Additionally, consideration was given to signal phasing and signal coordination prior to recommending an LPI. The signal offset was recommended to be adjusted to ensure that any coordinated platoons of approaching vehicles arrive at the intersection during the green phase rather than the LPI. Implementation of an LPI was not advised on two-way streets with a leading protected-permissive left turn phase. Regarding vehicular delay, the cross-street split reduction was mentioned as a mitigation measure to add green time back to the congested approach.

LPI implementation guidance for several typical intersection types were also included in the California LPI implementation guidelines. For example, an LPI was recommended at the intersection of two major arterial streets as this type of intersection can present challenges to pedestrians due to factors such as long crossing distances across multiple lanes, the high likelihood of turning vehicles, and high vehicle volumes. In the case of an intersection of a major arterial and a minor collector street, an LPI for pedestrians crossing the major street was recommended due to long crossing distances and increased exposure to turning vehicle conflicts. Additionally, because of high-speed vehicles, the LPI was proposed for all four crossings of a typical intersection of an entrance/exit ramp with a major arterial road. An LPI was also effective for one-way and T- intersections. **Figure 4** represents five different typical intersections with an LPI.

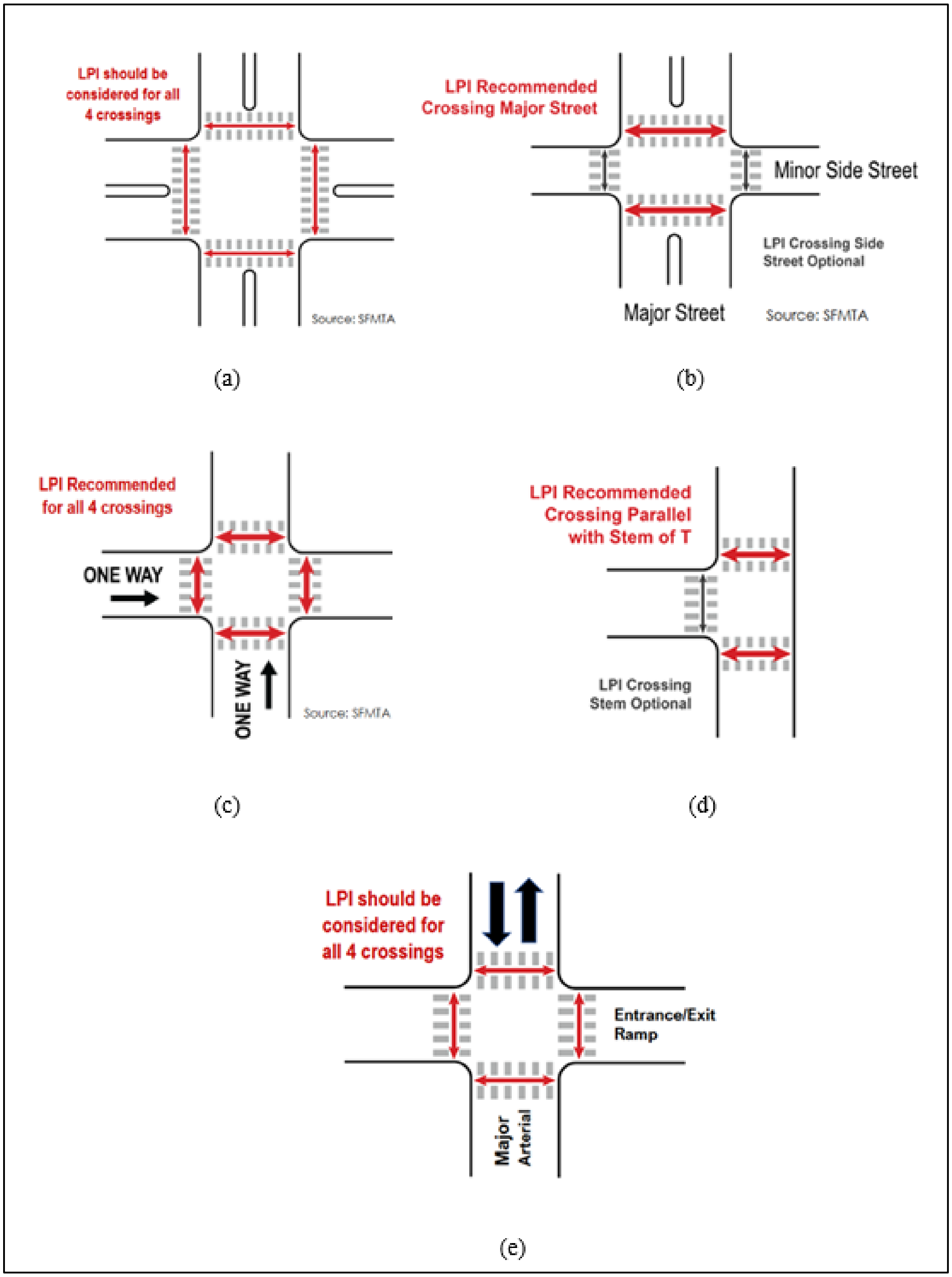


Figure 4: LPIs at Typical Intersections

(a) Two Major Arterial Streets, (b) A Major Arterial and a Minor Collector, (c.) Two One-way Streets (d) A T-intersection (e) An Entrance/Exit Ramp with a Major Arterial (Carpenter & Bhullar, 2021)

2.1.4 LPI implementation guidelines of Scottsdale, Arizona

The City of Scottsdale has also developed a guideline for LPI implementation (City of Scottsdale), recommending 3 seconds or above for the duration of an LPI. Adopting a gradual approach, the city would only install further signs or signals prohibiting turning actions once a necessity is shown following the implementation of LPI. Certain conditions and characteristics are mentioned in the guideline which should be taken into account before LPI implementation, such as the history of collisions between pedestrians and turning vehicles, a high volume of pedestrian crossings, location at a designated signalized school crosswalk, the presence of crosswalks with conflicting left-turn movements that do not need to yield to oncoming traffic, the presence of visibility issues, and a high number of conflicting turns. In addition, the guideline considers a pedestrian volume threshold of 20 pedestrians per hour on one crossing or 10 pedestrians per hour on one crossing over any nonconsecutive four hours for LPI implementation.

2.1.5 Summary of Existing Jurisdiction LPI Guidelines

Table 1 represents a summary table of different factors that are considered in each jurisdiction's LPI guidelines that were covered in this document, which may offer specific guidance on measurements and thresholds.

Table 1: Summary of Factors Considered in Different North American Jurisdiction's LPI Guidelines.

Factors	Jurisdiction	Reference	Thresholds/Considerations
Crash frequency	Toronto	Saneinejad & Lo, 2015	In a score-based suitability worksheet, the rate of annual collisions between pedestrians and left or right turning vehicles per 1,000 8-h pedestrian crossings in the past 5 years. a) 3 or more than 3 would be scored 2 b) less than 3 would be scored 1 The rate of conflicts (conflicts per 1,000 8-h observations) between pedestrians and left or right turning vehicles during 8 h of observation during area specific pedestrian peak and nonpeak periods. a) 3 or more than 3 would be scored 2 b) less than 3 would be scored 1
	Florida	Lin et al., 2017	Average Crash Frequency between turning vehicles on green and pedestrians legally crossing the street with the pedestrian “Walk” signal indication ≥ 1 per year (in last 3 years)

Factors	Jurisdiction	Reference	Thresholds/Considerations
	California	Carpenter & Bhullar, 2021	A review of a minimum of 3 years and up to 5 years of collision data for intersections with multiple crashes or a history of severe injury and fatal crashes.
Visibility issue	Toronto	Saneinejad & Lo, 2015	Irregular intersection geometry, wide-turning radius, crosswalk placement, obstructions such as buildings or base of a bridge, blinding sun angle
	Florida	Lin et al., 2017	Obstructions (e.g., buildings, base of a bridge, trees), blinding sun angle, inferior lighting condition, irregular intersection geometry, etc.
	California	Carpenter & Bhullar, 2021	Street furniture, other obstructions, or geometry, etc.
Vehicle non-yielding behavior	Florida	Lin et al., 2017	a) Average number of conflicts between pedestrians and turning vehicles during the pedestrian "Walk" signal indication ≥ 3 per day, or b) Percentage of compromised pedestrians at onset of the "Walk" signal at the crosswalk ≥ 10%.
Pedestrian Volume	Toronto	Saneinejad & Lo, 2015	In a score-based suitability worksheet, 8-h volume of crossing pedestrians a) more than 1,000 would be scored 2 b) 200 to 1,000 would be scored 1 c) less than 200 would be scored 0
	Florida	Lin et al., 2017	a) For pedestrian volume peak hour of an average day, approach turning vehicle volume ≥100/hour, pedestrian volume at crosswalk ≥50/hour; or b) If either turning vehicle volume ≥100/hour or pedestrian volume at crosswalk ≥50/hour, but not both, is satisfied, and through traffic volume of cross street ≥400/hour/lane is also satisfied.
	California	Carpenter & Bhullar, 2021	a) Intersections with moderate turning traffic and high pedestrian volumes b) Intersections with excessively high turning traffic and moderate pedestrian volumes c) Separate evaluation of AM, Mid-day, and PM peak hour exposures

Factors	Jurisdiction	Reference	Thresholds/Considerations
	Scottsdale	City of Scottsdale	Exceeding 20 pedestrians per hour on one crossing or exceeding 10 pedestrians per hour on one crossing over any nonconsecutive four hours
Vehicular volume	Toronto	Saneinejad & Lo, 2015	In a score-based suitability worksheet, total 8-h vehicular volume at intersection a) less than 16,000 would be scored -1 b) 16,000 to 30,000 would be scored -2 c) more than 30,000 would be scored -3 Through phase volume to capacity ratio of the signal with LPI a) 0.9 or more would be scored -1 b) less than 0.9 would be scored 0
	Florida	Lin et al., 2017	a) For vehicle peak hour of an average day, approach turning vehicle volume ≥130/hour, pedestrian volume at crosswalk ≥25/hour; or b) If either turning vehicle volume ≥130/hour or pedestrian volume at crosswalk ≥25/hour, but not both, is satisfied, and through traffic volume of cross street ≥500/hour/lane
Four-hour and eight-hour vehicular and pedestrian volume	Florida	Lin et al., 2017	Four-hour vehicular and pedestrian volume a) Approach turning vehicle volume ≥105/hour, pedestrian volume ≥30/hour; or b) If either turning vehicle volume ≥105/hour or pedestrian volume ≥30/hour, but not both, and through traffic volume ≥ 400/hour/lane Eight-hour vehicular and pedestrian volume a) Approach turning vehicle volume ≥100/hour, pedestrian volume ≥25/hour; or b) If either turning vehicle volume ≥100/hour or pedestrian volume ≥25/hour, but not both, and through traffic volume ≥ 400/hour/lane
School crossings	Toronto	Saneinejad & Lo, 2015	In a score-based suitability worksheet, the location from the nearest elementary school a) more than 200 m would be scored 2 b) 200 m to 850 m would be scored 1 c) less than 850 m would be scored 0
	Florida	Lin et al., 2017	a) Approach turning vehicle volume ≥50/hour in an intersection with a school crossing,

Factors	Jurisdiction	Reference	Thresholds/Considerations
			b) LPI duration: 1 hour before and 30 minutes after school start time, and the period 30 minutes before and 1 hour after school end time.
	Scottsdale	City of Scottsdale	At a designated signalized school crosswalk
	California	Carpenter & Bhullar, 2021	Intersections where school-aged children are expected to cross.
One-way streets or at T-intersections	Toronto	Saneinejad & Lo, 2015	In a score-based suitability worksheet, presence of one-way streets or at T-intersections would be scored 2
	Florida	Lin et al., 2017	LPI is recommended for T-intersections and intersections with a one-way street
	Scottsdale	City of Scottsdale	LPI is recommended on crosswalks of one-way street and T-intersections with conflicting left-turn movements
LPI duration	Toronto	Saneinejad & Lo, 2015	A minimum of 5 seconds or the time requiring pedestrians to clear at least half the crosswalk in one direction of moving traffic.
	Florida	Lin et al., 2017	A minimum of 3 seconds or the time requiring pedestrians to clear the width of one lane in the direction of moving traffic (and the width of a parking lane, if any)
	California	Carpenter & Bhullar, 2021	A minimum of 3 seconds or the time requiring pedestrians to cross at least one lane of traffic or, in the case of a large corner radius, to travel far enough for pedestrians to establish their position ahead of the turning traffic before the turning traffic is released.
	Scottsdale	City of Scottsdale	A minimum of 3 seconds.
Travel delay	Toronto	Saneinejad & Lo, 2015	In a score-based suitability worksheet, the increase in intersection total or average delay a) less than 10% would be scored 0 b) 10% to 30% would be scored -1 c) more than 30% would be scored -2
	Florida	Lin et al., 2017	LPI is not recommended if it will significantly increase traffic congestion and travel delay based on engineering judgment.

Factors	Jurisdiction	Reference	Thresholds/Considerations
	California	Carpenter & Bhullar, 2021	After the implementation of LPI, reduction of the cross-street split is suggested to add green time back to the congested approach to reduce the effect of vehicular delay.

2.1.6 Safety effectiveness of LPI

There have been many studies to quantify the safety effects of LPI using different approaches. For example, Fayish and Gross (2010) conducted a before-after with comparison group study to evaluate the effectiveness of LPIs with crash data from 2000 to 2008 (except 2002) at 10 signalized intersections (treatment groups) and 14 stop-controlled intersections (comparison groups) in State College, Pennsylvania. All intersections had the same LPI interval of 3 seconds, even though traffic and pedestrian volumes varied between sites and during the day. A pedestrian–vehicle crash rate reduction of between 46.2% and 71.3% was obtained after the LPI implementation with a 95% confidence level. A disaggregate analysis was also conducted to assess the LPI's effectiveness under certain conditions by comparing crashes between two sites. Results from the disaggregate analysis revealed that LPIs might be more effective at locations with higher pedestrian volumes and more crashes. Researchers also found a positive cost-benefit ratio from the economic analysis of LPI implementation in their study. However, the likely increase in vehicle delay was not considered.

Although most existing research considers only pedestrian-vehicle conflicts or crashes to evaluate LPI effectiveness, other studies (Arun et al., 2023; Goughnour et al., 2021) have also examined the effect on vehicle-vehicle collisions. A recent study by Arun et al. (2023) used a new quantile regression technique within the extreme value modeling framework to evaluate crash risks of rear-end and vehicle-pedestrian type conflicts before and after the installation of the LPI treatment. A total of 504 hours of before-after video data was collected from three intersections in Bellevue, Washington. Conflict data was extracted from the video using various software for the analysis. Their proposed before-after evaluation framework applying traffic conflict techniques is presented in **Figure 5**. According to the study, the LPI treatment reduced severe vehicle-pedestrian conflicts at signalized intersections by 42%. A LPI was also found to have no significant effect on the frequency of extreme rear-end conflicts (time-to-collision (TTC) threshold of 0.2 s).

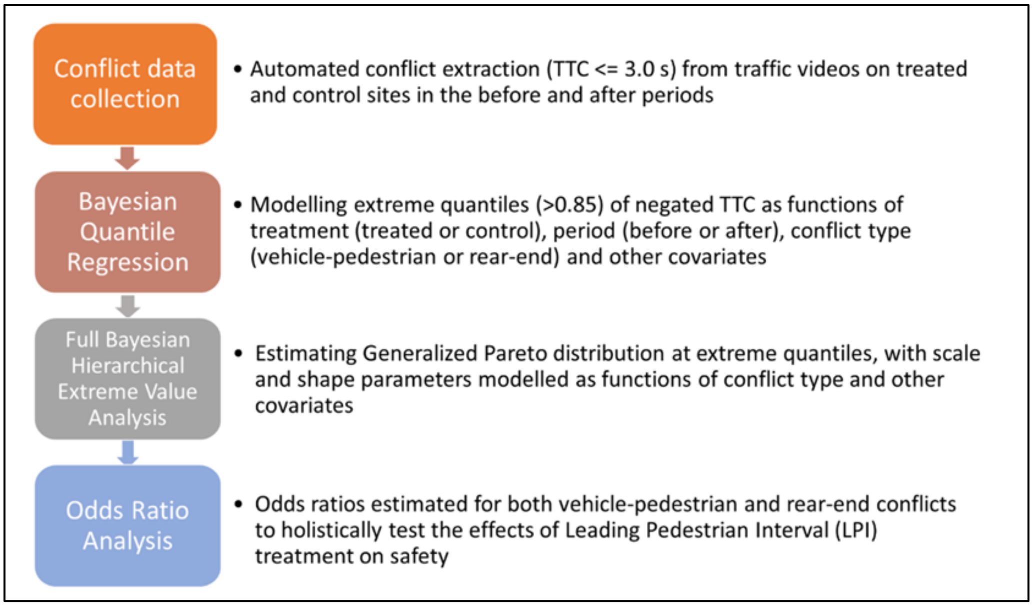


Figure 5: A Before and After Evaluation Framework Applying Traffic Conflict Techniques (Arun et al., 2023)

Goughnour et al. (2021) utilized an empirical-based before-after method with crash data from 2005 to 2014 to develop crash modification factors (CMFs) for LPIs and protected left-turn phasing based on data from four large North American cities: New York, Chicago, Charlotte, and Toronto. The study used 42 treated sites in New York City, 56 treated sites in Chicago, and 7 treated sites in Charlotte, North Carolina. The results showed that the LPI treatment had considerable safety benefits, including a 13% reduction in vehicle-pedestrian crashes and a 13% reduction in vehicle-vehicle crashes. An interesting observation from their study is that they found similar results for both New York and Chicago, while New York prohibits RTOR and Chicago allows RTOR in most cases. This result could be due to the lower pedestrian volume in Chicago compared to New York.

In another safety evaluation study, Guo et al. (2020) utilized a hierarchical Bayesian peak over threshold approach for conflict-based before-after safety evaluation of LPI. Before and after video data were collected for 6 hours and 12 hours from two intersections, respectively, where LPIs were implemented at one crosswalk per intersection in downtown Vancouver. Two control crosswalks were matched to have similar characteristics and geographic proximity to the two treatment crosswalks. Traffic conflict data with post encroachment time (PET) of less than 4s were extracted from the video using an automated computer vision analysis technique. In this study, two cases of pedestrian-vehicle conflicts were considered for the calculation of PET. The first is when pedestrians pass through the crosswalk before vehicles, and the second case is when pedestrians yield to vehicles. **Figure 6** shows an outline of the automated traffic conflict extractions. Graphical methods were used for choosing the PET threshold, in which the mean residual life plot and threshold stability plots were applied to choose an appropriate threshold as demonstrated in Coles (2001). For extreme-serious conflicts, the thresholds from -0.2 to -0.5 with an interval of -0.1 were used in this study. The extreme-serious conflicts were then estimated using the fitted generalized Pareto distribution (GPD) model with the determined PET threshold. The study found a significant reduction (18.1%–20.9%) in severe vehicle-pedestrian conflicts after LPI implementation. However, a concern with LPIs which was mentioned was that the treatment might increase crashes during other phases of the walk cycle. It is noted that the data from only two intersections limit this study. Road conditions, pedestrian volume, the traffic volume of left turn, and different values of LPIs were not considered in the analysis.

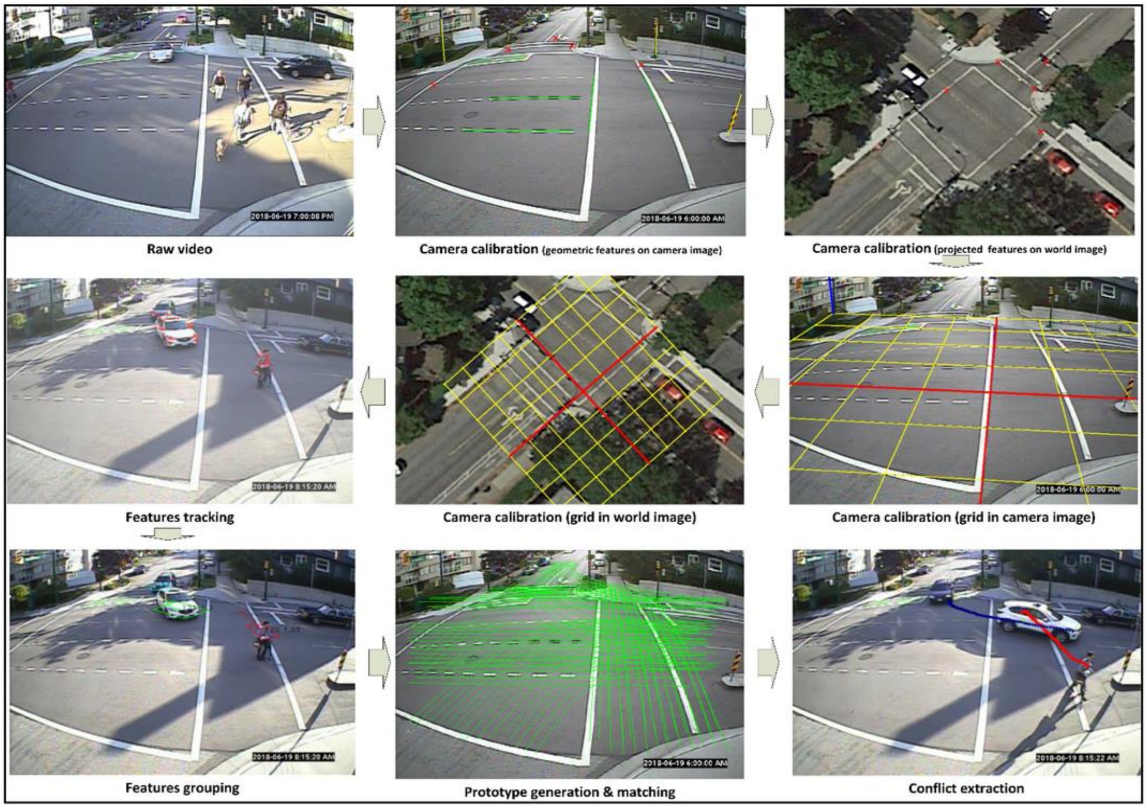


Figure 6: A Diagram of the Process of Traffic Conflict Analysis (Y. Guo et al., 2020)

Few studies have investigated the impact of LPI on congestion and vehicle delays. In one such study, Sharma et al. (2017) established a marginal benefit-cost model with quantitative metrics to assess the implementation of LPIs at a given intersection and estimated costs associated with a traffic conflict. The model used the volume of turning movements, crash data, and geometry to assess the likelihood of a conflict occurring and the direction. The cost-benefit of LPI could be ultimately evaluated by comparing pedestrian crash reduction costs and additional vehicle delay costs. A case-study was performed to evaluate the model using the data from one intersection at SE 122nd and Division Street in Portland, Oregon. **Figure 7** presents the results of the case study using the proposed model. In the north-south route, a benefit-cost ratio of about 7 was discovered, and on both streets, it was found to be about 6.38. Results also suggest that the BC ratio could be increased by providing the LPI only during specific hours of the day.

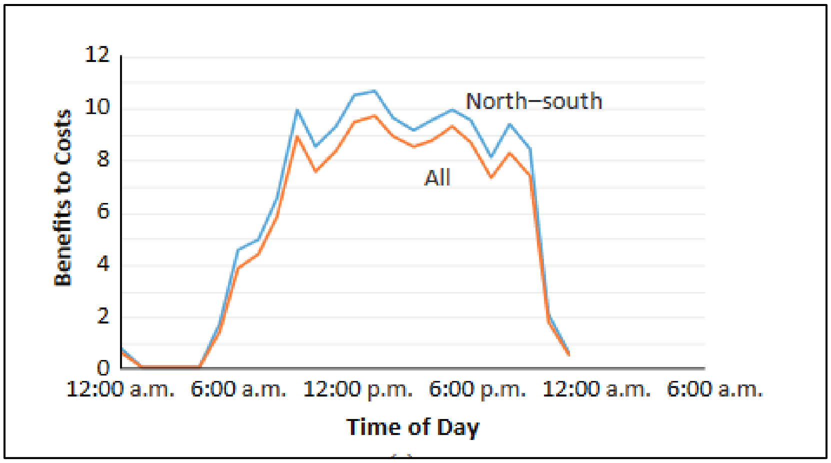


Figure 7: Benefit–Cost Ratio of Providing LPI from the Case Study (Sharma et al., 2017)

Whereas LPI duration is mainly implemented for 3-7 seconds in most states, Dettberner & Vu (2017) suggested using a long LPI in certain situations. A formula for an elongated LPI was developed in their study using conflict distance from the curb, walking speed, "Walk" plus flashing "Don't Walk" duration, and green time for the concurrent vehicular phase. The study suggested using an elongated LPI at certain intersections with the following characteristics: pedestrians' conflict with a permissive left-turn movement, low-volume vehicular through movements parallel to the crosswalk, actuated pedestrian phase, and higher pedestrian crossing time than vehicular demand. At six suburban intersections in Northern Virginia, elongated LPIs have been effectively installed by VDOT using this formula, and none have led to operational issues or customer complaints.

In another study on crash injury outcomes, Sze (2019) analyzed approximately 1.35 million New York City motor vehicle collisions from 2012 to 2018. Fixed effects Difference in Difference linear and Poisson regressions were used to estimate the effect of LPIs on the outcomes of the number of collisions, persons, pedestrians, cyclists, and motorists injured. LPIs were effective in reducing the number of injured pedestrians and motorists from the analysis. Specifically, motorist injuries were primarily reduced in the outer boroughs of New York City, where vehicles can obtain higher speeds. Another interesting observation from the study is the indirect positive impact in neighboring intersections fitted with LPIs. A possible reason might be that drivers might slow down or become more alert to pedestrians before the light changes at the next crossing where there are nearby intersections with LPIs.

2.2 Pedestrian Scramble

The pedestrian scramble, also known as the 'Exclusive pedestrian phase' or the 'Barnes dance,' is an exclusive pedestrian signal phase where traffic in all four directions is stopped, and pedestrians are allowed to make lateral and diagonal crossings, as shown in **Figure 8**. This treatment can reduce pedestrian-vehicle conflicts if properly utilized. The design element and safety effectiveness of this treatment will be discussed in this section.

Figure 8: Pedestrian Scramble (Los Angeles Department of Transportation, 2017)

2.2.1 Pedestrian Scramble Operation in Los Angeles, California

The Los Angeles Department of Transportation (2017) has developed policy and design guidelines for pedestrian scramble operation. According to their guidelines, exclusive pedestrian phases should be considered if all of the following three conditions are met: the pedestrian volumes meet or exceed 30% of the vehicle volume during the peak hour or 300 pedestrians crossing per hour during the peak hour in a single crosswalk, high volumes of turning vehicles occur across more than one crosswalk (at least 200 VPH per crosswalk during the peak hour), and a pattern of crashes involving pedestrians and turning vehicles exists (at least three documented crashes within the last three years of available crash data).

With respect to design guidance,

1. Pedestrian scramble is recommended to be implemented without diagonal crossings if the intersection is very large (diagonal crossing distance would exceed 100 feet).
2. NRTOR restrictions were suggested for implementation for all approaches.
3. The removal of protected-permissive left turn phases was advised, particularly if they were installed due to pedestrian conflicts. The exclusive pedestrian phase might be able to be added without extending the cycle if protected-permissive phasing is removed.
4. Protected-only turning movements or LPI were recommended instead of the pedestrian scramble in case of a few pedestrian-turning vehicle conflicts across one or more legs of the intersection.
5. A Pedestrian scramble is forbidden at or near an at-grade rail crossing or intersection with railroad preemption and at or near a freeway ramp where the stopped queue distance may result in backup onto the freeway mainline.

2.2.2 Pedestrian Scramble Operation in Calgary, Canada

Kattan et al. (2009) evaluated the operational safety effect of a pedestrian scramble using before and after (6 weeks after the implementation) video data from one intersection in the City of Calgary, Alberta, Canada using the number of pedestrian-vehicle conflicts as a surrogate measure of safety. Initially, the intersection operated with a two-phase signal with permitted left turns on green and right turn on red. Following the implementation of the pedestrian scramble, NRTOR was introduced. Pedestrian and vehicle flow, pedestrian-vehicle conflicts, and pedestrian non-compliance information were manually coded from the video and modeled using two Poisson regression models. The findings of this study revealed a reduction in pedestrian-vehicle conflicts but an increase in pedestrian violations after pedestrian scramble implementation. Around 40% of all violations occurred at the beginning of the flashing "Don't Walk" phase, with 13% of all violations occurring at "safe side" crossings (concurrent with vehicle traffic), 2% at "unsafe side" crossings (within 2 to 3 s from the start of the flashing “Don’t Walk”). However, a positive attitude toward this new signal operation was obtained from most respondents (70%) from a survey of 149 pedestrians.

A follow-up study was conducted by Shah et al. (2010) in the following year to determine the longer-term effect of this new operation on pedestrian safety. Four Poisson regression models were developed to model the number of conflicts and violations using one year of data from the post-installation period. The results found from this study differed from the earlier one as they pointed out the operational effects of the scramble operation during different parts of the week. According to the findings, after the implementation of the scramble, the number of pedestrian-vehicle collisions and pedestrian violations was significantly reduced on weekdays. At the same time, both incidents significantly increased on weekends. Around 3.1% of the drivers violated the NRTOR rules on weekends, while only 1.1% were on weekdays.

2.2.3 Pedestrian Scramble Operation in Toronto, Canada

Pedestrian scrambles were implemented at three intersections in Downtown Toronto: Bloor & Bay, Bloor & Yonge, and Yonge & Dundas. An analysis (City of Toronto, 2015) of pedestrian scramble operations at the three sites was performed based on the following performance metrics: utilization of diagonal crossing, intersection safety, corner crowding conditions, pedestrian delay, vehicular delay, traffic diversions, impact on greenhouse gas emissions and fuel consumption, and user feedback. Compared to other intersections, the Bay St and Bloor St intersection observed the lowest number of pedestrians and the lowest ratio of pedestrians to motorized users. Diagonal crossing usage was also lower in this intersection by about 16% on weekdays and 12% on weekends with the reason possibly being its longer crossing distance of 29.1 m compared to the other two intersections. Additionally, the pedestrian scramble caused a significant negative impact on vehicular delay and collision rates. Overall, the intersection delay increased from 40 seconds to approximately one and a half minutes during the morning peak period and about two and a half minutes during the evening peak period. These increased delays increased driver frustration and accelerated the crash rate of the intersection. While rear-end type collisions climbed by 50%, sideswipe crashes more than doubled. Although there was an 8% reduction in pedestrian delays and an 11–13% reduction in corner crowding, that was not as much as was noted at the other two intersections (crowding conditions were estimated based on actual pedestrian volumes measured on site and pre-defined signal timing plans). Based on all these negative results, the city recommended the removal of the pedestrian scramble operation at the Bay St and Bloor St intersection.

2.2.4 Pedestrian Scramble Operation in New York City

The NYC DOT conducted a pedestrian scramble study of five intersections in the summer of 2015 to determine the feasibility of diagonal crossings (New York City Department of Transportation, 2015). Increased waiting time, sidewalk overcrowding, vehicle delays, and reduced crossing time were some of the negative impacts of this treatment found in the study. The NYC DOT recommended some intersection characteristics to consider before pedestrian scramble implementation. Intersections with atypical geometry, mainly where the diagonal crossing is the shortest crossing distance, could be more feasible for the pedestrian scramble. **Figure 9** represents an NYC intersection with a short diagonal distance. "T" intersections and intersections with low vehicular volume and high demand for diagonal crossing could be considered. Several signal timing options such as LPI, split phase LPI, and split phase were recommended with the pedestrian scramble to reduce conflicts at crossings. APS was also suggested to include with the pedestrian scramble, but it was not advised in diagonal crossings because of the risk of user confusion or disorientation caused by nearby APS noise interference.

Figure 9: Intersection with Short Diagonal Distance for Pedestrian Scramble (New York City Department of Transportation, 2015)

2.2.5 Pedestrian Scramble Operation in San Fransisco, California

The pedestrian scramble implementation at four intersections on Stockton Street in San Francisco led to diverse outcomes (SFMTA et al., 2008). The number of pedestrian injury crashes increased from two to four in 5 years; however, there may be other reasons for the increase outside the scramble itself, according to regression to the mean and unrelated instances. Additionally, all post-installation injuries involved elderly pedestrians, possibly due to difficulty adapting to the new system.

Post-installation surveys showed that 69.5% of pedestrians felt safer, and 72% favored the new system, though pedestrian behaviors like running or aborting crossings increased from 5.3% to 11.2%. Vehicle-pedestrian conflicts dropped significantly, from 7.0% to 1.1%. However, transit speeds decreased by 21%, with average travel times increasing by 55 seconds for the five blocks between Broadway and Sacramento, and auto speeds on Stockton Street fell by up to 44%, though side street traffic flow improved due to fewer pedestrian delays. The study concluded that pedestrian scramble can be challenging to use in certain situations (such as large intersections with high through traffic volumes, including transit service), but it has the potential to be very effective in some situations (such as smaller intersections with high volumes of turning vehicles and pedestrians).

2.2.6 Safety effectiveness of Pedestrian Scramble

Several studies have been conducted to estimate the safety effectiveness of a pedestrian scramble. Using a two-stage design method, Chen et al. (2014) evaluated the relative efficacy of a pedestrian scramble along with three other signal-related pedestrian countermeasures including increasing pedestrian walk time, split phase timing, and signal installation in San Fransisco. In the first stage, a comparison group was generated for each treatment group comprising similar intersections but without the countermeasure. Then, a Negative Binomial (NB) model with the generalized estimating equation (GEE) method was developed to account for additional potential confounding factors that were not controlled in the comparison group selection but are potentially associated with crashes. Study results found the pedestrian scramble was the second-best countermeasure for reducing pedestrian crashes among the four tested countermeasures. However, this treatment increased multiple-vehicle crashes, even though the effect was non-significant. Findings also suggested that the pedestrian scramble can be adequate for specific situations (e.g., smaller intersections with heavy volumes of turning vehicles and pedestrians) but can be challenging to apply in others (e.g., wide intersections with heavy through traffic volumes, including transit service). Additionally, downtown areas with a rapid influx of pedestrians were considered suitable for a pedestrian scramble. Because of this treatment's adverse impact on vehicle traffic, a recommendation to reroute traffic away from the installed pedestrian scramble was put forward.

Furthermore, additional research has investigated the relative safety effectiveness of a pedestrian scramble with a conventional concurrent green signal phasing (Ma et al., 2014; Zhang et al., 2015). Zhang et al. (2015) estimated the safety effectiveness of these two different phasing options based on pedestrian crash frequency and vehicle interaction severity. In this study, six hours of pedestrian and vehicle volume data, which were expanded to six years using expansion factors published by the Connecticut Department of Transportation (CTDOT) to get annual average daily traffic (AADT), were collected at forty-two signalized intersections in Connecticut. Pedestrian-vehicle interactions were classified by four interaction definitions: undisturbed crossing, potential conflict, minor conflict, and severe conflict. A Partial Proportional Odds

Model was used to predict interaction and crash severity, whereas an NB log-linear model was utilized as a crash count prediction model. From the analysis, intersections with a pedestrian scramble were found to have fewer crashes compared to concurrent phasing but at higher severity levels. A pedestrian scramble was recommended where pedestrians are more likely to comply because of the greater risk of severe injury in the red phase. Finally, a pedestrian scramble was suggested to be considered only in conditions of high traffic speed, long crossing distances, and low pedestrian volumes, which is contrary to some of the studies (City of Toronto, 2015; New York City Department of Transportation, 2015).

In another similar study of the effectiveness of a pedestrian scramble and concurrent signal phasing by Ma et al. (2014), a multi-objective model was developed to maximize the utilization of the available green time by vehicular traffic and pedestrians for both of these conditions. The Nondominated sorting genetic algorithm-II (NSGA-II) was utilized here to solve the proposed multi-objective model. This model optimizes the use of green light time for both vehicles and pedestrians at intersections by comparing two crossing methods: the pedestrian scramble and concurrent signal phasing. Using the NSGA-II algorithm, it finds the best balance to maximize efficiency for both vehicles and pedestrians. The performance of the model was evaluated with a case study and performing sensitivity analysis. From the designed model, vehicular volume, pedestrian demand, turning volumes, and proportion of diagonal crossing pedestrians were found to significantly impact the operational performance of a pedestrian scramble and two-way crossing. The pedestrian scramble was found to be advantageous at intersections with heavy traffic volumes with high turning movements. Additionally, this treatment performed better at intersections with a higher diagonal crossing proportion, even at relatively low/medium pedestrian volumes.

It should be noted that the pedestrian scramble can have a considerable negative impact on vehicular delay for all users (Kothuri et al., 2017). Kothuri et al. (2017) ranked several efficiency-focused pedestrian treatments, such as actuated-coordination, free operation, short cycle lengths, and safety-focused treatments, including LPI and pedestrian scramble using a software-in-the-loop simulation based on the operational impacts of these treatments. The pedestrian scramble treatment produced the highest delay in both major and minor streets from the simulation results. LPI was also found to increase overall delays due to increased vehicular delays; however, pedestrian delays mainly were unaffected.

2.2.7 ADA Compliance Rules for Pedestrian Scramble

There is not any specific guidance mentioned in the Public Rights-of-Way Accessibility Guidelines (PROWAG) related to Pedestrian Scramble intersections. Pedestrian Scramble intersections, while not specifically addressed in PROWAG guidelines, are subject to Americans with Disabilities Act (ADA) compliance standards for pedestrian facilities (U.S. Access Board, 2023). This includes ensuring the presence of high-visibility crosswalks, refuge islands, pedestrian crossing signs, and curb ramps equipped with detectable warnings. Each crosswalk at these intersections should have separate curb ramps to assist visually impaired pedestrians in navigating safely. Detectable warning surfaces should be installed at the base of each ramp to alert pedestrians to the presence of street crossings.

One of the primary challenges at Pedestrian Scramble intersections is the difficulty faced by individuals who are blind or visually impaired in determining the appropriate time to cross, particularly in areas where right turns on red are permitted. Unlike traditional intersections where vehicle movements provide auditory and tactile cues, Pedestrian Scramble configurations may lack these cues, potentially complicating pedestrian navigation. Efforts to mitigate these challenges have included the installation of Accessible Pedestrian Signals (APS) on all corners. However, these signals, which emit different sounds for various crossing directions during the WALK signal, have proven complex and potentially confusing for pedestrians of all abilities (Harkey et al., 2007).

2.2.8 Summary of Existing Pedestrian Scramble Guidance

Table 2 represents a summary table of suggested locations and other factors that are mentioned in different jurisdiction's pedestrian scramble guidelines and research that were covered in this document.

Table 2: Summary of Factors Considered in Jurisdictional Pedestrian Scramble Guidelines and Research

Factor	Jurisdiction	Reference	Considerations
Suggested locations	Los Angeles	LADOT, 2017	Intersections fulfilling all of the following criteria: a) Pedestrian volumes meet or exceed 30% of the vehicle volume during the peak hour or 300 pedestrians crossing per hour during the peak hour in a single crosswalk, b) High volumes of turning vehicles across more than one crosswalk (at least 200 VPH per crosswalk during the peak hour), c) A pattern of crashes involving pedestrians and turning vehicles (at least 3 documented crashes within the last 3 years)
	New York	NYCDOT, 2015	Intersections with atypical geometry where the diagonal crossing is the shortest crossing distance.
	San Francisco	Chen et al., 2014	a) Smaller intersections with high volumes of turning vehicles and pedestrians. b) Downtown areas with a rapid influx of pedestrians.
	Connecticut	(Zhang et al., 2015)	a) Intersections where pedestrians are more likely to comply due to the greater risk of severe injury in the red phase.

Factor	Jurisdiction	Reference	Considerations
			b) Only in conditions of high traffic speed, long crossing distances, and low pedestrian volumes, which is contrary to some studies.
Not recommended locations	Los Angeles	LADOT, 2017	a) Not recommended at diagonal crossings if the intersection is very large (diagonal crossing distance > 100 feet). b) At or near an at-grade rail crossing or intersection with railroad preemption. c) At or near a freeway ramp where the stopped queue distance may result in backup onto the freeway mainline. d) If there are few pedestrian-turning vehicle conflicts (Use protected-only turning movements or LPI instead)
	San Fransisco	Chen et al., 2014	Challenging to use in large intersections with high through-traffic volumes, including transit service.
NRTOR restrictions	Los Angeles	LADOT, 2017	NRTOR restriction is recommended with pedestrian scramble for all approaches.
Left turn phase	Los Angeles	LADOT, 2017	Removal of protected-permissive left turn phases was advised, particularly if they were installed due to pedestrian conflicts.
APS inclusion	New York	NYCDOT, 2015	APS was suggested to be included with the pedestrian scramble, but not advised in diagonal crossings due to user confusion or disorientation from nearby APS noise interference.
ADA Compliance	Public Right-of-Way Accessibility Guidelines (PROWAG)	U.S. Access Board, 2023	ADA compliance rules for all pedestrian facilities including pedestrian scramble: a) ADA-compliant pedestrian facilities include high-visibility crosswalks, refuge islands, pedestrian crossing signs, and curb ramps with detectable warnings. b) Separate curb ramps for each crosswalk at an intersection should be provided rather than a single ramp at a corner for both crosswalks. The separate curb ramps improve orientation for visually impaired pedestrians

Factor	Jurisdiction	Reference	Considerations
			by directing them toward the correct crosswalk. c) Detectable warning surfaces (truncated domes) must be installed at the bottom of each curb ramp.

2.3 RRFB/CRFB Confirmation Light

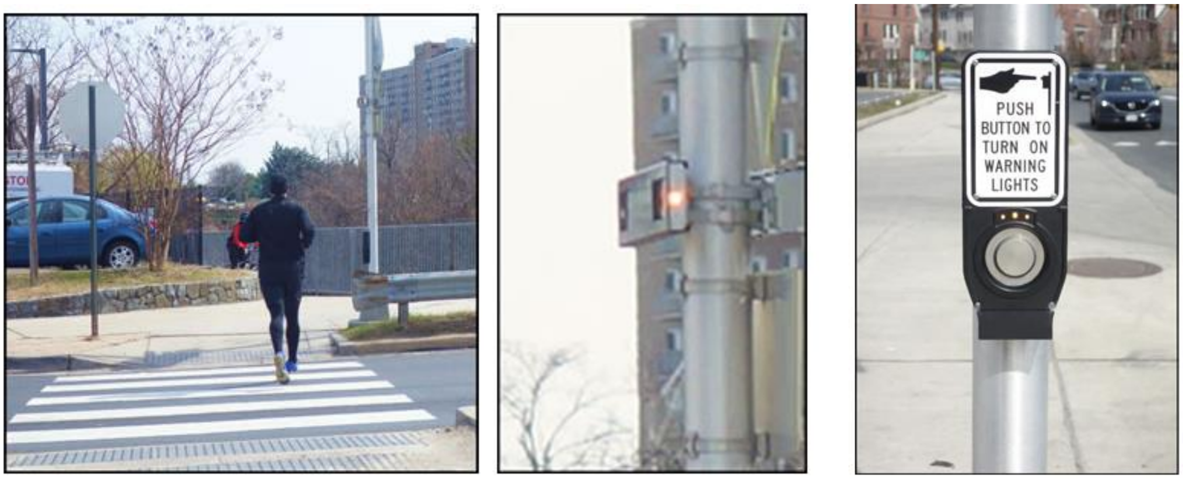
RRFB/CRFB, as shown in **Figure 10**, has been widely used as a safety countermeasure to increase driver awareness and visibility of pedestrians, particularly for midblock crosswalks. This treatment can assist in raising the percentage of vehicles yielding to crosswalk users (Fitzpatrick et al., 2015; H. Guo & Boyle, 2022).

Figure 10: Rectangular Rapid Flashing Beacon

(Source: https://www.kimley-horn.com/rrfb-ia-21/)

However, there can be issues with how the crosswalk user is informed when the beacon is on; given the pedestrian's location with respect to the orientation of the flashing beacons, it is not always apparent that the device is active. This situation can reduce the effectiveness of this treatment. In this case, a confirmation light can assist pedestrians by informing them about the status of the beacon when they push the button.

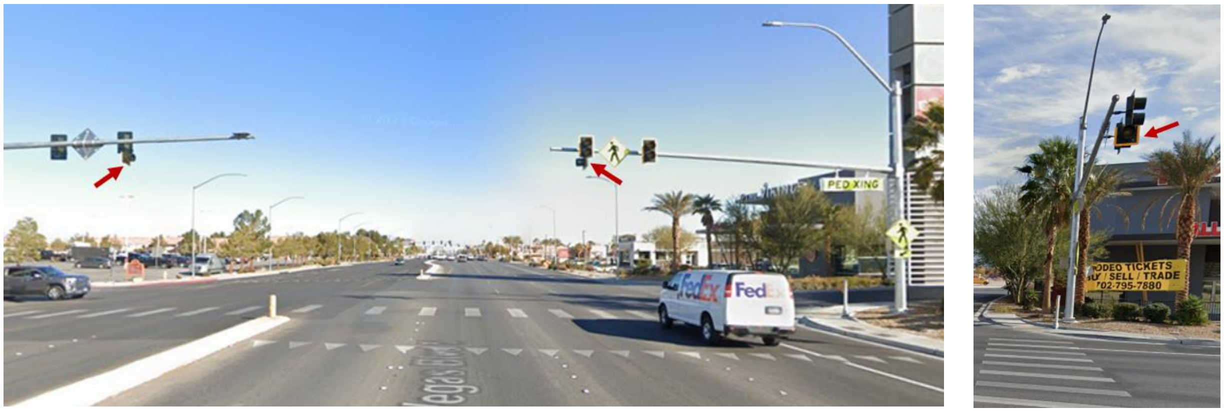
Federal Highway Administration (FHWA) Interim Approval 21 (2018) mentioned installing a small pilot light with the RRFB / CRFB to give confirmation to the pedestrian. **Figure 11** shows images of small pilot light given in FHWA Interim Approval 21. However, any specific guidelines related to the design and operation of this pilot light are not provided in the interim. Apart from that, it does not appear there are any other research papers or official guidance from any state regarding RRFB confirmation lights after searching different online research databases, such as Google Scholar, TRID TRB, ResearchGate, etc. Additionally, several posts in the ITE member forum and LinkedIn platforms to gather information related to the design guidance of the confirmation light yielded no significant information pertaining to pilot light guidelines.



(a) Pilot Light w/ Ped (b) Pilot Light (c) Pushbutton

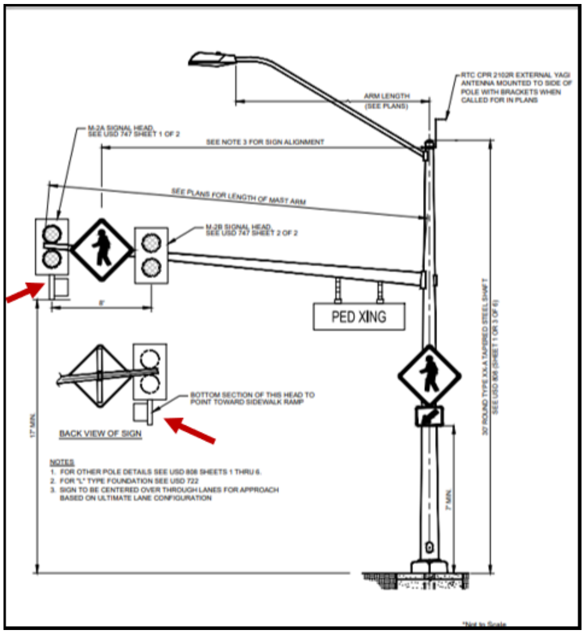
Figure 11: RRFB Crosswalk Equipment (FHWA, 2018)

Though no official guidance on confirmation lights for RRFB / CRFB has been found, several jurisdictions have taken measures to mitigate this problem. In Clark County, Nevada, a unique overhead RRFB system has been noticed at several crosswalks with an additional beacon for pedestrians. This beacon is installed facing the crossing pedestrians in addition to the lights for the through traffic. **Figure 12** represents images of overhead RRFB with confirmation lights at S. Las Vegas Blvd and the South Point Casino exit, with the confirmation lights highlighted by red arrows. Conversations with a traffic engineer of the Transportation Department of Clark County revealed that the department received complaints from residents prior to installing the confirmation lights. One common issue was that the RRFBs were occasionally confusing for pedestrians because they could not see the flashers facing the vehicles. When a vehicle did not stop, the pedestrians used to think that the flashers were not working, when in fact, the vehicle was not adhering to the rule. Hence, the department installed an indication light facing the pedestrians in the crosswalk to inform them that the flasher is active after the pushbutton is pressed. However, this is a local area practice, and they did not have any official documentation related to the confirmation light.



(a) Vehicle View of Installation

(b) Ped Indicator Light



(c) Detail Sheet of Install

Figure 12: Las Vegas RRFB Installation

Confirmation lights are also observed at a pole mounted RRFB system in West Lafayette, Indiana. A small flashing LED light has been installed on the side facing the pedestrians in the crosswalk, along with the LED lights for the vehicles. **Figure 13** represents images of the pole mounted RRFB system with confirmation light (highlighted by a red arrow in the figure) at 1659 Lindberg Road, West Lafayette, Indiana. However, it might be challenging for some pedestrians to see such confirmation lights on a wide street. Within Arizona, the confirmation light has been used at an RRFB crossing on Butler Ave in Flagstaff, among other locations in the state.

(a) Vehicle View (b) Indicator Light

Figure 13: West Lafayette RRFB Installation

2.4 Advanced Pedestrian Pushbutton (APS)

Pedestrian pushbuttons allow pedestrians to activate signals at intersections and other crossings equipped with flashing lights with the press of a button. Since the onset of the COVID-19 pandemic, demand for touchless pedestrian pushbuttons, as shown in **Figure 14**, has increased. As a result, many North American cities have started installing touchless pedestrian pushbuttons for their activated pedestrian signals. This technology can also benefit pedestrians with disabilities. Touchless pushbuttons only require movement between 1-4 inches from the face of the assembly for activation. However, it appears no official guideline related to the sensitivity of touchless pushbuttons has been published yet in any design manual or from any state transportation department.

Figure 14: Touchless Pedestrian Pushbutton

Another advanced pedestrian pushbutton function, extended button press, can actuate additional accessibility features, such as verbal (speech) message capabilities, beaconing, or extended timing to pedestrians. The guidance related to the extended pushbutton function has only been found in MUTCD (2009) Edition Chapter 4E Pedestrian Control Features. The MUTCD recommends that if an extended pushbutton press is used to provide any additional features, the pushbutton should be pushed and held for more than one second to activate those features. A pushbutton press of less than one second should actuate only the pedestrian timing and any associated accessible walk indication. A push for 2 seconds is recommended to activate the feature for additional crossing time. The additional time may be added to either the walk or pedestrian change interval. MUTCD (2009) assumes an average pedestrian walking speed of 4.0 ft/s, which has been maintained in subsequent updates including MUTCD (2023). The effectiveness of pedestrian clearance times may be assessed using a walking speed of 4.0 ft/sec for locations with extended push functions.

The MUTCD (2003) specified a value of 3.5 ft/sec to calculate the pedestrian clearance time. Researcher Li (2015) analyzed the impacts of this reduction in pedestrian walking speed (4 ft/sec) in MUTCD 2009 by simulating various types of intersections under different traffic circumstances yielding a series of datasets. Findings suggest that the reduction in pedestrian walking speed would not substantially influence the intersection traffic delay if the cycle length of an intersection could be optimized. Hence, the extended pushbutton press function would not be necessary to enhance the traffic situation. However, the extended pushbutton press function can be used to alleviate increased intersection delay after the change of pedestrian walking speed in some circumstances if the cycle length of an intersection cannot be changed.

2.5 Pedestrian Crash Frequency Hotspots

The number of pedestrian crashes varies mainly depending on the location and numerous other factors. Researchers have used different methods to identify high crash locations, with one such method being the crash frequency method, which is a basic network screening method. This method counts the number of collisions at a particular location (along a road segment or at an intersection) over a predetermined period, usually three to five years. The results are then ranked from most frequent to least frequent crashes (Federal Highway Administration, 2013). Statistical methods have been used in many variations to analyze pedestrian crash frequency. NB regression and Poisson regression are the default regression methods to use for analyzing factors associated with pedestrian crash frequency (Chimba et al., 2014; Lin et al., 2019; Mahmoudi et al., 2022; Noland et al., 2013; Sener et al., 2021; Singleton et al., 2021). ArcGIS, a geospatial software, has been used to generate heatmaps to visualize the hotspot locations of pedestrian crashes (Codjoe et al., 2021; Sharif & Dessouky, 2021). ArcGIS offers various spatial analysis methods, and they can be categorized as parametric and non-parametric methods. The kernel density method is one of the non-parametric methods that can create a density map of sites displaying relatively low and high expected pedestrian collision counts (Quistberg et al., 2015; Soto et al., 2022). An example of a Kernel density map is presented in **Figure 15**. The map represents higher pedestrian collision risk areas and arterials where many dots indicate high concentrations of values of expected pedestrian collisions and fewer dots indicate lower concentrations of expected pedestrian collisions. Additionally, data-driven analyses such as crash tree analysis, decision tree analysis, and others have also been recently used in some research (Codjoe et al., 2021).

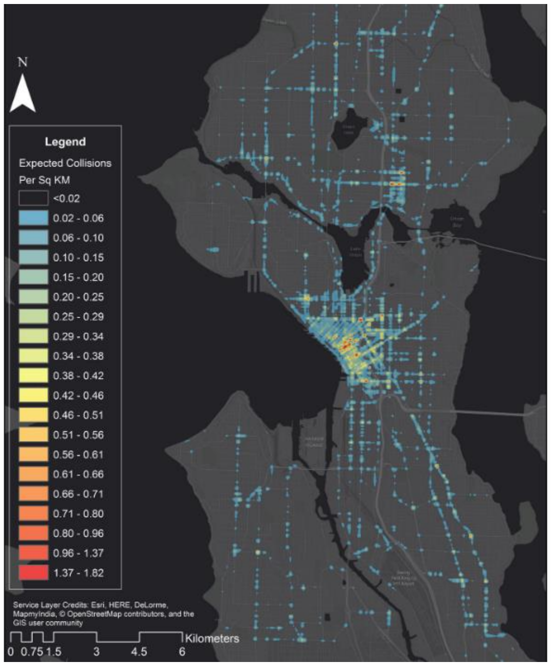


Figure 15: Kernel Density Map of Predicted Counts of Pedestrian Collisions (Quistberg et al., 2015)

Intersections and midblock sections are some areas where a high number of pedestrian crashes were observed (P. Chen & Zhou, 2016; Kimley, 2017; Lin et al., 2019; Nashad et al., 2016). Intersections with more than three lanes (P. Chen & Zhou, 2016; Chimba et al., 2014; Ukkusuri & Aziz, 2011), increased average level of traffic stress (LTS) (Mahmoudi et al., 2022), high pedestrian and motor-vehicle volume (Mahmoudi et al., 2022; Sener et al., 2021; Singleton et al., 2021; Soto et al., 2022), high-speed limit (P. Chen & Zhou, 2016; Chimba et al., 2014; Lin et al., 2019), traffic signals (Lin et al., 2019; Mahmoudi et al., 2022), long crossing distances (Singleton et al., 2021), and absence of shoulders and sidewalks were found to be associated with increased crash risk for pedestrians. Several studies have examined the relationship between built environment factors and pedestrian crash frequency. These studies have shown there are more pedestrian crashes and higher collision risks when there is greater roadway connectivity and more mixed land use (P. Chen & Zhou, 2016). Areas with a greater number of schools (Chimba et al., 2014; Ukkusuri & Aziz, 2011), bus stops (P. Chen & Zhou, 2016; Codjoe et al., 2021; Lin et al., 2019; Singleton et al., 2021; Soto et al., 2022), and a greater number of commercial land uses (Lin et al., 2019; Mahmoudi et al., 2022; Soto et al., 2022) were also more prone to pedestrian crashes. Hotspots were also identified along roadway networks surrounding interstate corridors (Codjoe et al., 2021). Sociodemographic factors are also related to increased crash risk for pedestrians. Neighborhoods with a higher share of African American or Hispanic residents (Chimba et al., 2014; Kimley, 2017; Singleton et al., 2021; Ukkusuri & Aziz, 2011), senior population (Lin et al., 2019; Ukkusuri & Aziz, 2011) households without vehicles (Chimba et al., 2014; Lin et al., 2019; Soto et al., 2022), population with lower socioeconomic status (Chimba et al., 2014; Kimley, 2017; Mahmoudi et al., 2022) and adults with lower levels of educational attainment (Lin et al., 2019; Ukkusuri & Aziz, 2011) were all found to be associated with increased pedestrian crash frequency. Thus, it is evident from previous literature that intersection geometry, land use, sociodemographic composition, and other macro-level factors are associated with pedestrian crash frequency.

2.6 Surrogate Measure of Pedestrian Safety

Traffic safety analyses have traditionally relied heavily on historical crash data reported by law enforcement agencies, despite the limitations inherent in these datasets. The reliability of these datasets may be jeopardized by issues such as inconsistencies in data quality and availability, different crash reporting criteria between jurisdictions or differences in the methods used to collect data (AASHTO, 2010). In addition, crash data is typically not readily accessible and must be compiled over multiple years for effective safety analysis purposes. Furthermore, numerous minor accidents that do not result in injuries might not be reported, leading to the possible exclusion of important data from the assessment (AASHTO, 2010). It can be challenging to evaluate the efficacy of novel safety concepts solely based on crash data because there may not be enough data available if the concepts are not yet extensively implemented. Additionally, it may be difficult to compare results because different locations may test these concepts in different ways. Crash data may occasionally obscure other consequences, such as modifications to traffic patterns.

To address limitations in crash data, surrogate measures of safety, also known as indirect safety measures, have gained popularity in recent years. These measures offer non-crash indicators to evaluate the safety performance of design features. Examples include Encroachment Time (ET), Deceleration Rate (DR), Proportion of Stopping Sight Distance (PSD), Post-Encroachment Time (PET), and Time to Collision (TTC) (AASHTO, 2010). PET and TTC are particularly popular, likely due to their relative ease of calculation and objective assessment of conflict frequency and severity. Numerous previous studies have successfully used surrogate safety measures (TTC and/or PET) to assess pedestrian and bicyclist safety (Beitel et al., 2018; Ghadirzadeh et al., 2022; Jiang et al., 2014; Russo et al., 2023). Typically, these surrogates are gathered through manual transcription of high-resolution field videos. Among these, PET, especially, is favored for its straightforward measurement via defining conflict points and recording timestamps. In this work, PET is utilized to gauge near-miss conflicts between pedestrians and turning vehicles.

2.6.1 Post Encroachment Time (PET)

Post encroachment time was originally introduced by Allen et al. (1978), and represents the duration between the moment when the first road user deviates from the path of the second and the moment when the second road user approaches the path of the first (Johnsson et al., 2018). In simpler terms, PET measures the proximity of two road users occupying the same space at the same time, thus indicating the severity of a potential conflict. A PET value nearing zero seconds indicates a very close call, with the road users narrowly avoiding a collision. Conversely, a higher PET value implies a greater temporal separation, suggesting a lower risk of collision. By setting a threshold (typically between 2 to 5 seconds) to define conflicts, analysts can classify them based on severity. Conflicts with PET values closer to zero are considered more severe. **Figure 16** shows an example of the concept of PET.

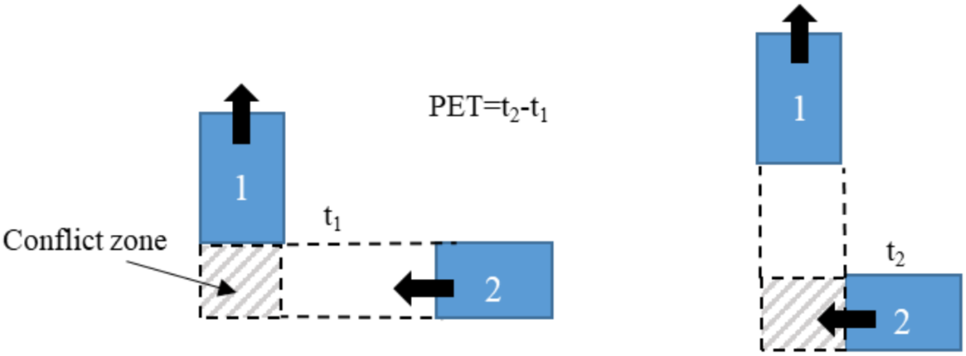


Figure 16: The Concept of PET (Russo, Lemcke, et al., 2020)

2.7 Bicycle Clearance Interval

Clearance intervals required for bicycles are larger than those required for automobiles because of the travel speed difference. Conversely, clearance intervals that are too short for bicycles may result in safety concerns. Hence, accurate estimates of clearance times for bicyclists are essential for the safe and efficient design of traffic signals. Select guidelines related to bicycle clearance interval are mentioned in the American Association of Highway and Transportation Officials (AASHTO) *Guide for the Development of Bicycle Facilities*, National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide*, California MUTCD, and other design manuals discussed in this section.

2.7.1 Bicycle Clearance Interval Guidelines in AASTHO

AASTHO's *Guide for the Development of Bicycle Facilities* (2012) provided new guidelines for signal considerations for bicyclists removing the prior instructions for the duration of the red clearing and yellow change intervals. It was advised to modify the traffic signal parameters (minimum green interval, all-red interval, and extension time), when appropriate, to accommodate bicycles. These parameters are typically designed for the operational characteristics of motor vehicles. The guideline gives two separate formulas for minimum green time for standing and rolling bicyclists. The manual does not provide any specific equations regarding yellow and red intervals. Instead, it advises adjusting the red time or, if this is insufficient, providing for extension time utilizing a dedicated bicycle detection and controller settings to add enough time to clear the intersection. The guidelines do not recommend adjusting the yellow interval to accommodate bicycles.

2.7.2 Bicycle Clearance Interval Guidelines in NACTO

NACTO's *Urban Bikeway Design Guide* (2011) recommends sufficient bicycle clearance intervals to accommodate the 15th percentile biking speed for bicycle specific signals. Therefore, an equation for total clearance interval (C_i) is provided based on bicycle travel speed (V) and intersection width (W) which is given in Equation 1.

$$C_i = 3 + \frac{W}{V} \qquad \textbf{Equation 1}$$

For Equation 1, the travel speed (V) should be measured in the field to establish a clearance interval suitable for the local circumstances. Nonetheless, in the absence of local data, 14 feet per second (9.5 miles per hour) may be used as a default speed at intersections with level approaches. For intersection width (W), distance from the intersection entry (i.e., stop-line or crosswalk in the absence of a stop-line) to halfway across the last lane carrying through traffic is considered. The NACTO guidance indicates that the bicycle minimum green time is calculated using the bicycle crossing time for standing bicyclists, although no precise definition of standing is given.

2.7.3 Bicycle Clearance Interval Guidelines in the California MUTCD

A formula for the total of the three intervals—minimum green, yellow, and red clearance intervals is provided for all signal phases (both all traffic signals and bicycle specific signals) in the California MUTCD (2014) rather than distinct formulas for each period. According to Equation 2, the total time should be sufficient to let a bicyclist riding a 6 feet long bicycle clear the last conflicting lane from the limit line (stop line) at a speed of 14.7 feet/sec with an additional effective start-up time of 6 seconds. A "limit line" is defined in California MUTCD (2014) as a solid white line not less than 12 nor more than 24 inches wide, extending across a roadway or any portion thereof to indicate the point at which traffic is required to stop in compliance with legal requirements.

$$G_{min} + Y + R_{clear} > 6\,sec + \frac{W + 6\,ft}{14.7\,ft/sec} \qquad \textbf{Equation 2}$$

Where,

G_{min} = Length of minimum green interval (sec)
Y = Length of yellow interval (sec)
R_{clear} = Length of red clearance interval (sec)
W = Distance from limit line to far side of last conflicting lane (feet)

2.7.4 Bicycle Clearance Interval Guidelines – Ontario Traffic Council (OTC)

OTC's *Traffic Signal Operation Policies and Strategies* (2015) uses the general formula for the amber (Equation 3) and red interval (Equation 4) for bicyclists. These formulas are for application at signals that serve heterogeneous traffic. However, the additional rule is that the bicycle all-red interval can increase by up to 1.0 second above the vehicle all-red clearance interval.

$$\boldsymbol{Amber\ interval\ =\ PRT\ +\ \frac{v}{2d}} \qquad \textbf{Equation 3}$$

$$\boldsymbol{Red\ interval\ =\ \frac{W+L}{V}} \qquad \textbf{Equation 4}$$

Where,

PRT = reaction time for a cyclist reacting to a signal turning yellow (s)
d = bike deceleration rate at a traffic signal (ft/s2)
v = final bicycle speed (ft/s)
W = intersection width (ft)
L = typical bicycle length = 6 ft
V = bicycle crossing speed at intersection (ft/s)

2.7.5 Bicycle Clearance Interval Guidelines – National Cooperative Highway Research Program (NCHRP)

The most recent and detailed guideline regarding bicycle clearance interval has been obtained from the NCHRP's Report 969 *Traffic Signal Control Strategies for Pedestrians and Bicyclists* (2022). Bicycle red clearance interval was recommended for all signal phases used by bicyclists (at vehicle traffic signals and bicycle-specific signals). Three equations for red clearance interval for different lengths are given in the manual.

$$\boldsymbol{BikeR_{clear}\ =\ \frac{D+L}{V}} \qquad \textbf{Equation 5}$$

$$\boldsymbol{BikeR_{clear}\ =\ \frac{D+L}{V}\ +\ t_{reaction} + \frac{v}{2d} - Y} \qquad \textbf{Equation 6}$$

$$\boldsymbol{BikeR_{clear}\ =\ \frac{D+L}{V}\ +\ t_{reaction} + \frac{v}{2d} - Y\ +\ PET - t_{entry}} \qquad \textbf{Equation 7}$$

Where,

$BikeR_{Clear}$ = bike red clearance time (s)
D = crossing distance (ft) from the queuing position used by bicycles to the end of the most distant travel lane
L = bicycle length (ft), usually taken as 6 ft
v = final bicycle speed (ft/s)
Y = yellow time (s)
R_{Clear} = red clearance time (s)
PET = post-encroachment time (s)
t_{entry} = time needed for the first vehicle released in the next phase to reach the conflict zone
$t_{reaction}$ = reaction time for a cyclist reacting to a signal turning yellow (s)
d = bike deceleration rate at a traffic signal (ft/s^2)

Equation 5 provides the longest red clearance interval, ensuring that a bicycle entering the intersection at the last moment of yellow can clear the most distant travel lane before releasing no conflicting vehicle. This formula is similar to the one given by the previously described OTC design guide in Equation 4. Equation 6 reduces clearance time to some extent by counting some part of the yellow time towards bicycle clearance. In Equation 6, $t_{reaction}$ +v/2d is the time from the start of yellow to the moment the last cyclist who could not stop enters the intersection. Equation 7 further reduces needed clearance by 1.8s by considering a post-encroachment margin. The time it takes for the first car released in the subsequent phase to get to the conflict area is truncated in this equation. In addition to Equation 5, Equation 6, and Equation 7, the guideline mentions the additional method of reducing the clearance time by treating the entry point to the intersection for bicycles to be the curb line of the intersecting street rather than the stop line in certain circumstances.

In summary, the red clearance interval is generally calculated using bicycle travel speed and intersection width or crossing distance in all the guidelines. However, in California MUTCD design guides, the distance from the limit line to the far side of last conflicting lane was considered instead of full intersection width to minimize the time. Another item observed is that NACTO does not include bicycle length (L) in the formula like other guidelines, but it includes an additional 3 seconds in the formula of the total clearance time. A long bike clearance interval can be frustrating for motorists, which can lead to non-compliance. Hence, the most recent NCHRP guidance provides additional formulas and ways of reducing the all red-clearance time.

2.8 Literature Review Summary

This literature review provided an overview of implementation guidance and safety effectiveness evaluations of different pedestrian treatments such as LPI, pedestrian scramble, RRFB/CRFB indicator beacons, and advanced push buttons.

Different jurisdictions have developed guidelines for LPI implementation, with varying suitability and length criteria based on factors such as crash frequency, traffic volume, visibility, and intersection geometry. Guidelines from California, Florida, Toronto, and Scottsdale are highlighted.

In contrast, there is a lack of standardized guidelines for implementing pedestrian scrambles in North American jurisdictions. However, the LADOT has developed specific criteria and design guidance for pedestrian scrambles. Several research studies have evaluated safety factors before and after the implementation of pedestrian scrambles in different areas, analyzing compliance with traffic rules and the number of crashes at those intersections. Typically, intersections with high traffic volumes, especially with a high number of turning vehicles, short diagonal crossing distances, and high pedestrian volumes, are recommended for the implementation of pedestrian scrambles.

No official guideline or documentation regarding RRFB/CRFB confirmation lights was found, however, two distinct types of confirmation lights for RRFB systems installed on overhead and pole-mounted systems that were observed in Nevada and Indiana, respectively, have been discussed in this report.

Pedestrian crash frequency analysis and locating crash hotspots can provide an informative overview of an area, which can be done using different network screening methods. Intersection geometry and characteristics, land use, sociodemographic attributes, and other contextual factors were found to be associated with pedestrian crash frequency. The literature also covered surrogate measures of pedestrian safety, such as PET. It is a critical metric used to evaluate the safety performance of intersections by measuring the proximity of two road users to occupying the same space at the same time, thus indicating the severity of a potential conflict. This measure provides an indirect yet valuable assessment of pedestrian safety improvements.

Finally, various guidelines for bicycle clearance signals were discussed. Among them, the NCHRP guideline is the most recent and describes the rules and recommendations in the most detailed format.

3 ADVANCED PUSHBUTTON OPERATION

This chapter delves into the details of the performance evaluation experiments conducted on Polara and Guardian Wave pushbutton devices to test their functionality and detection fields under laboratory conditions. The objective of the evaluation is to assess the pushbuttons' touchless detection, extended press capabilities, and responsiveness across different settings and environmental scenarios.

3.1 Pushbutton Selection

The two pushbuttons used for the experimentation with this task were the Polara iNS3 made by Polara and the Guardian Wave made by PedSafety, a Campbell Company. These pushbuttons are shown below in **Figure 17**, with Polara on the left and the Guardian Wave on the right.

(a): Polara iNS3 **(b): Guardian Wave**

Figure 17: Tested Pushbuttons

Both products have touchless and extended press capabilities, but the Polara unit also includes additional features, including the ability to work with an accessibility app made by Polara called

PedApp to aid those who are hearing or visually impaired to receive audible crossing information and to activate the pedestrian signals from a smartphone remotely.

3.1.1 Pushbutton Settings

The two pushbuttons are customizable, with many settings that can be adjusted. The settings applicable to touchless detection and extended press for these two pushbuttons are provided in **Table 3**, and are the ones tested in this work.

Table 3: Pushbutton Settings

Polara Settings	Guardian Wave Settings
1. Range a. According to the manual, a lower number is ~ 2 inches, and a higher number is ~ 6 inches. b. Settable slider between 0 and 24 2. Extended Push a. Changes how long someone needs to wave for extended press detection. b. Options: Off, Override Short Push, 1 Sec, 1.5 Sec, 2 Sec, 2.5 Sec, and 3 Sec. 3. Minimum Wave Time a. Changes how long someone needs to wave to activate the pushbutton. b. Options: 0ms, 50ms, 250ms, 500ms. 4. Rain Lockout a. This setting disables iDetect if a “touchless” activation is detected during the walk phase. b. Low (15-minute lockout), Medium 30-minute lockout), and High (1-hour lockout). c. Lockout is disabled after 1-3 minutes, depending on the selected setting level.	1. Range a. Three available presets: 3 inches, 6 inches, and 9 inches. 2. Sensitivity a. Changes the unit reaction time to hand waves. b. Settable slider between 1 (Fast) and 12 (Slow). 3. Delay a. Changes the delay between each wave actuation. b. Options: Range between 5ms and 1,000ms. 4. Extended Press Time a. Changes how long you need to wave or press the button for it to activate an extended press. b. This setting controls both the physical pushbutton and the “touchless” detection. c. Options: range between 0 (off) and 10,000ms.

3.2 Testing Procedure and Setup for Lab Tests

3.2.1 Testing Apparatus Setup

To test the pushbuttons, a local traffic signal technician connected them to the NAU traffic lab cabinet and attached them to a pole following MUTCD mounting height guidelines (Section 4E.08.04.F) of between 3.5 and 4 feet. The pushbuttons were connected in parallel to the cabinet on the same phase to an Econolite ASC/3-2100 controller. **Figure 18** shows the testing apparatus with the pushbutton setup.

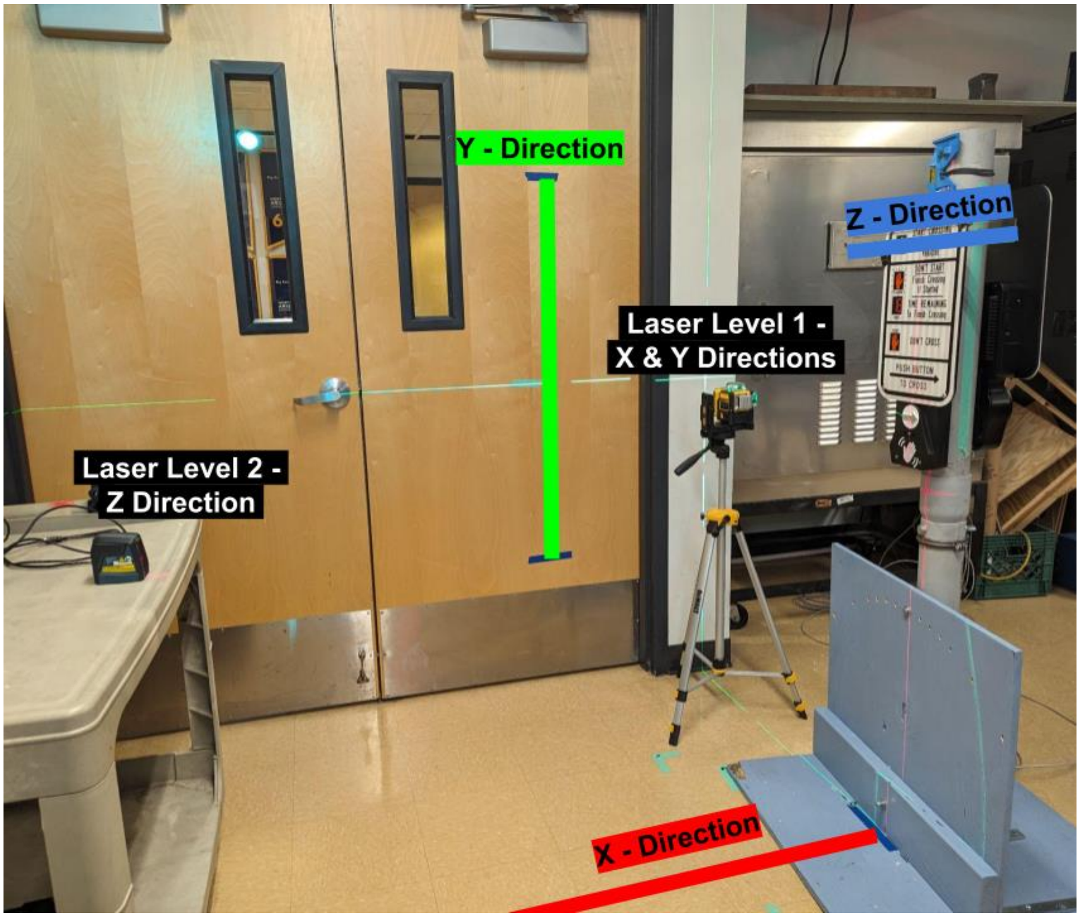


Figure 18: Testing Apparatus

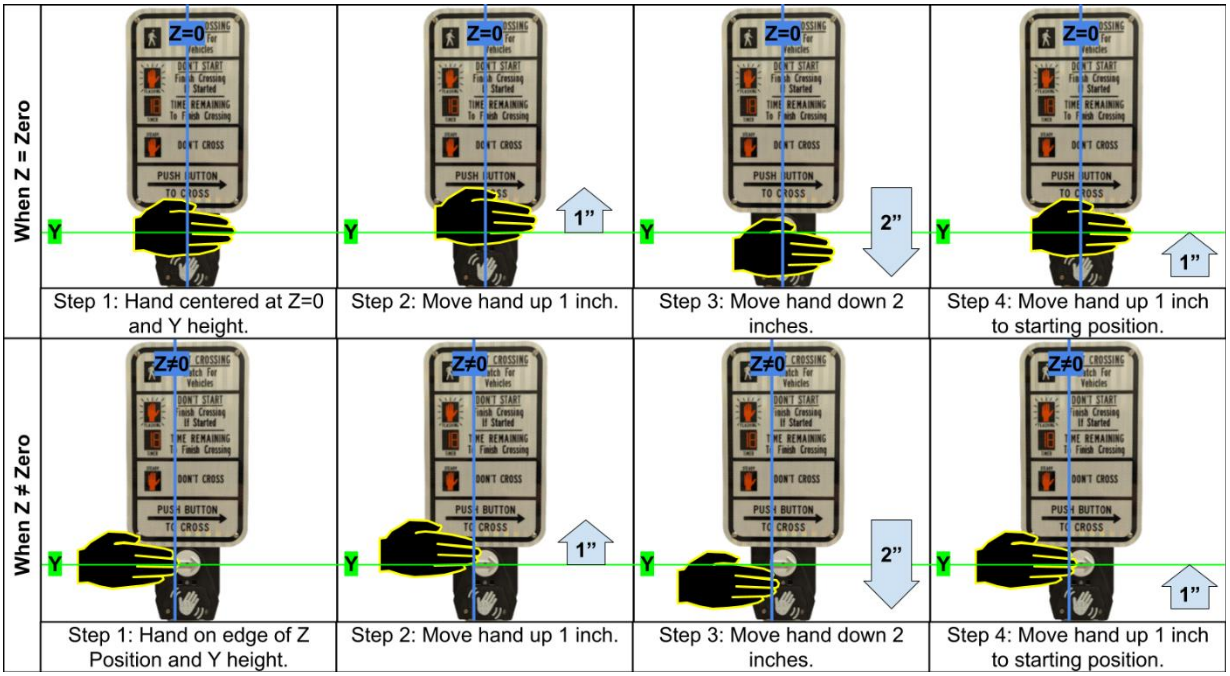
3.2.2 Testing Procedure

Testing of the pushbuttons used the following steps to determine the detection field, with the waving procedure shown in **Figure 19**:

1. Set the desired settings (e.g., range, sensitivity, delay) for the APS unit.
2. Set the first laser level to the desired X and Y positions (as shown in **Figure 18**).
3. Set the second laser level to the desired Z Position (as shown in **Figure 18**).
4. Wave hand ten times following hand positioning (as shown in **Figure 19**). The wave was identified as successful when the push/wave confirmation sound was emitted. If a sound was not emitted, then the wave was considered unsuccessful. Each wave was conducted roughly two seconds apart. If multiple waves were not successful, a second set of ten hand waves would occur to confirm the results.
5. Test zone moves by one-inch increments for the Y and Z directions. Waves repeated at each Y,Z coordinate until there are no successful activations out of ten attempts.
6. Test zone moves by three-inch increments for the X direction until less than ten activations are detected at the zero Y and Z positions. When less than ten activations are detected, move forward at 1-inch increments from the last ten detected activations in the

X position. An example of this is starting at X position zero and having ten detected activations. After this, move X position three inches outward, and if less than ten activations were detected at the X=3 position, move X position one inch and move at one-inch increments (X=1, then X=2).

7. Continue testing until no activations are detected.



Step 1: Hand centered at Z=0 and Y height.
Step 2: Move hand up 1 inch.
Step 3: Move hand down 2 inches.
Step 4: Move hand up 1 inch to starting position.
Step 1: Hand on edge of Z Position and Y height.
Step 2: Move hand up 1 inch.
Step 3: Move hand down 2 inches.
Step 4: Move hand up 1 inch to starting position.

Figure 19: Waving Procedure

3.2.3 Pushbutton Experiments

A total of 12 experiments were conducted on the pushbutton by Polara, with a total of 11 experiments performed on the Guardian Wave. **Table 4** shows the tests that were conducted for each pushbutton.

Table 4: Conducted Experiments

Polara Experiments	Guardian Wave Experiments
• Ranges (0, 3, 6, 9) • *Wave Time (0ms, 500ms)* • *Dark Environment* • *Gloves* • *Heated Pushbutton* • *Rain Lockout* • Extended Press • PedApp	• Ranges (3-inch, 6-inch, 9-inch) • *Sensitivity (1 [Fast], 12 [Slow])* • *Delay (5ms, 1000ms)* • *Dark Environment* • *Gloves* • *Heated Pushbutton* • Extended Press

Based upon manufacturer documentation, a set of default settings were determined for each pushbutton. These are detailed in **Table 5**, along with the typical lab lighting and temperature conditions**.** Tests in *italics* in **Table 4** were conducted at these default settings, with only the item under investigation changed.

Table 5: Default Settings

Polara Default Settings	**Guardian Wave Default Settings**
Range: 3 Minimum Wave Time: 50ms Rain Lockout: Off Extended Press: 1 Second Room Temperature: 77°F Light: 92 – 144 Lux	Range: 6” Delay: 100ms Sensitivity: 3 Extended Press Time: 1000ms Room Temperature: 77°F Light: 92 – 144 Lux

3.2.3.1 Dark Environment

Regarding the ‘dark environment’ test, the light level at the button was measured at 92 lux or 144 lux, depending on what direction the pushbutton was facing when the experiment occurred, and what signal head colors were lit in the lab. While it would be ideal for this light level to be identical for all tests, these values are indicative of a lighting environment that is much darker than the daytime brightness of approximately 1000 lux of an overcast day, but still brighter than a full moon at night which is about 0.1 lux, so the authors are confident that this test did a reasonable job determining whether or not the ambient light conditions had a significant effect on the size of the detection field.

3.2.3.2 Temperature Differentials

Regarding the use of gloves, the gloves used were made of 100% acrylic fiber, which had an outside temperature of between 85.7°F and 90.3°F. Testing followed the same procedure described earlier. Regarding the test of the heated pushbutton, the pushbuttons were heated by placing a space heater three feet away from the pushbutton and waiting for it to heat the pushbutton as high as it could reach, at which time the pushbutton was tested using the same procedures as described before, keeping the space heater on to keep the pushbutton at the high temperature during the test. For the Guardian Wave it reached an average maximum temperature of 102.5°F and for the Polara it reached an average maximum temperature of 110°F. These two testing procedures were conducted to simulate temperature differences between the common temperature of a human hand and the temperature of the button, both with a negative temperature differential (hand colder than the button), as default conditions had a positive differential (roughly 91°F for the tester’s hand and 77°F for the laboratory).

3.3 Results of Lab Tests

Experiment results were summarized as three-dimensional positions with the number of detected activations measured as a success rate. An example dataset is provided in **Table 6**.

Table 6: Example Dataset

Hand Position			Hand Detection		
X	Y	Z	Successful	Total Waves	Success Rate
0	0	0	10	10	100
0	0	2	0	10	0
0	0	1	1	10	10
0	0	-1	1	10	10
0	0	-2	0	10	0
0	1	0	10	10	100
0	1	2	0	10	0
0	1	1	5	10	50
0	1	-1	4	10	40
0	1	-2	0	10	0
0	2	0	10	10	100

The data shown in **Table 6** were used to create a figure that visually shows the results of the detection field, an example of which is shown in **Figure 20.** In **Figure 20,** the results of two testing procedures are shown (at X= 0", and X=3"), with the results plotted for X distances between these two tests (X=1", X=2", identified by the gray highlight) determined through interpolation. Additionally, the result plots include a color scale with a 0% detection success rate shown in red, 100% detection success rate in green, and lighter shades of green, yellow, and orange to show values between 0% and 100%.

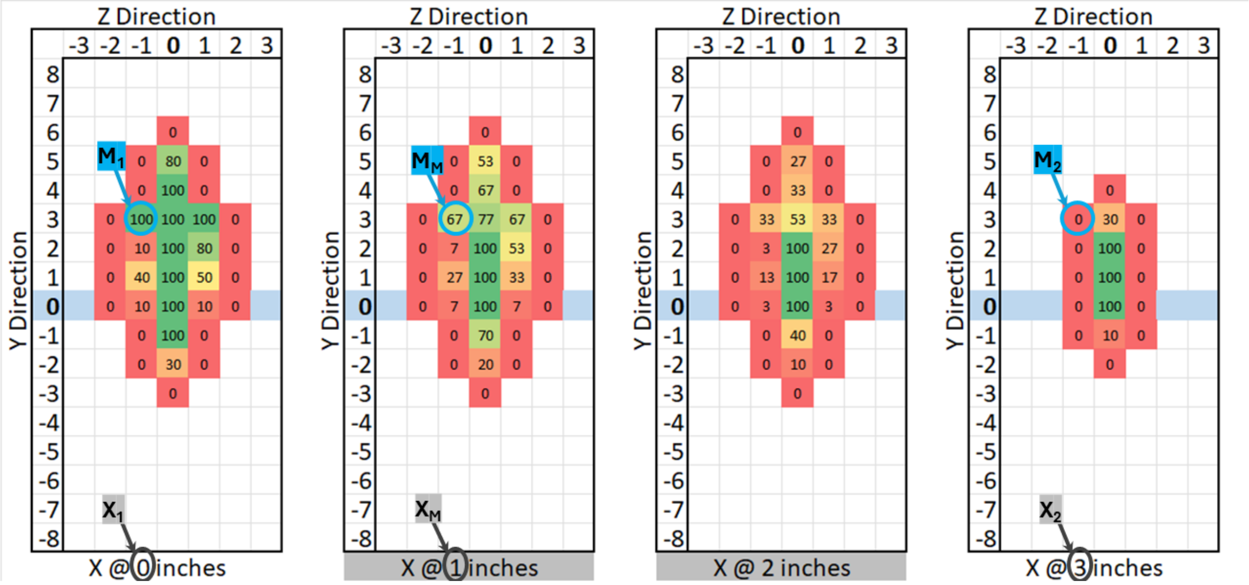


Figure 20: Example Experimental Graphic with Annotations

Regarding the interpolation, this was calculated using **Equation 8** where M_M is the missing measurement, M_1 and M_2 are the results of the measured results that come before and after the missing measurement, X_M is the X distance of the missing measurement, X_1 and X_2 are the X distances that correspond to the measurements that come before and after the missing measurement. These variables are annotated in Figure 20.

$$M_M = M_1 + \frac{(M_2 - M_1)}{(X_2 - X_1)} * (X_M - X_1) \qquad \textbf{Equation 8}$$

Equation 9 shows an example calculation using the values annotated in **Figure 20.** With a success rate of 100% at X =0, Y = 3, and Z = -1 and a success rate of 0% at X = 3, Y = 3, Z = -1, the interpolated values for X = 1 and X =2 (at the same Y and Z positions) are 67% and 33%, respectively. Calculations for the former are shown in **Equation 9**.

$$M_M = 100 + \frac{(0 - 100)}{(3 - 0)} * (1 - 0) = 67 \qquad \textbf{Equation 9}$$

An additional item that was used for comparison was the 100% detection field volume (DFV). This value is calculated by determining the overall volume of the of the detection field measured at 100% (green '100' squares in **Figure 20)**. This can be visualized by thinking of the shape of the detection field like a traffic cone, as shown in **Figure 21**, with X at 0 being the base of the cone and the end of the detection field being the end of the cone. The 100% DFV would be the volume of the traffic cone.

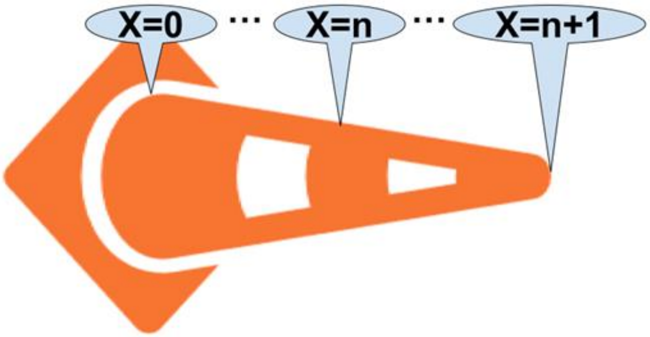


Figure 21: Detection Field Shape

DFV was calculated using **Equation 10** for X =0 and **Equation 11** for all other X positions, where DFV is detection field volume, W is the width of the 100% detection field in inches, and H is the height of the 100% detection field in inches. For depth, 0.5 inches is used at X = 0 and 1.0 inch for all other X positions (**Equation 10** and **Equation 11**, respectively).

$$\boldsymbol{DFV = W * H * 0.5} \qquad \textbf{Equation 10}$$

$$\boldsymbol{DFV = W * H * 1.0} \qquad \textbf{Equation 11}$$

A helpful way to visualize the data is by thinking of the detection field like a traffic cone shown in Figure 21, with X at 0 being the base of the cone and the end of the detection field being the end of the cone.

A set of experiment results is show in **Table 7** and **Figure 22**, which were performed on the Polara button with default settings. **Table 7** shows the 100% field volume, the settings for the experiment, and the environmental conditions during experimentation. The results are shown in **Figure 22**. Interpolated results have a gray highlight over the x-axis label.

Table 7: Polara Default Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 46in^3	**Centroid (Y, Z):** 2, 0

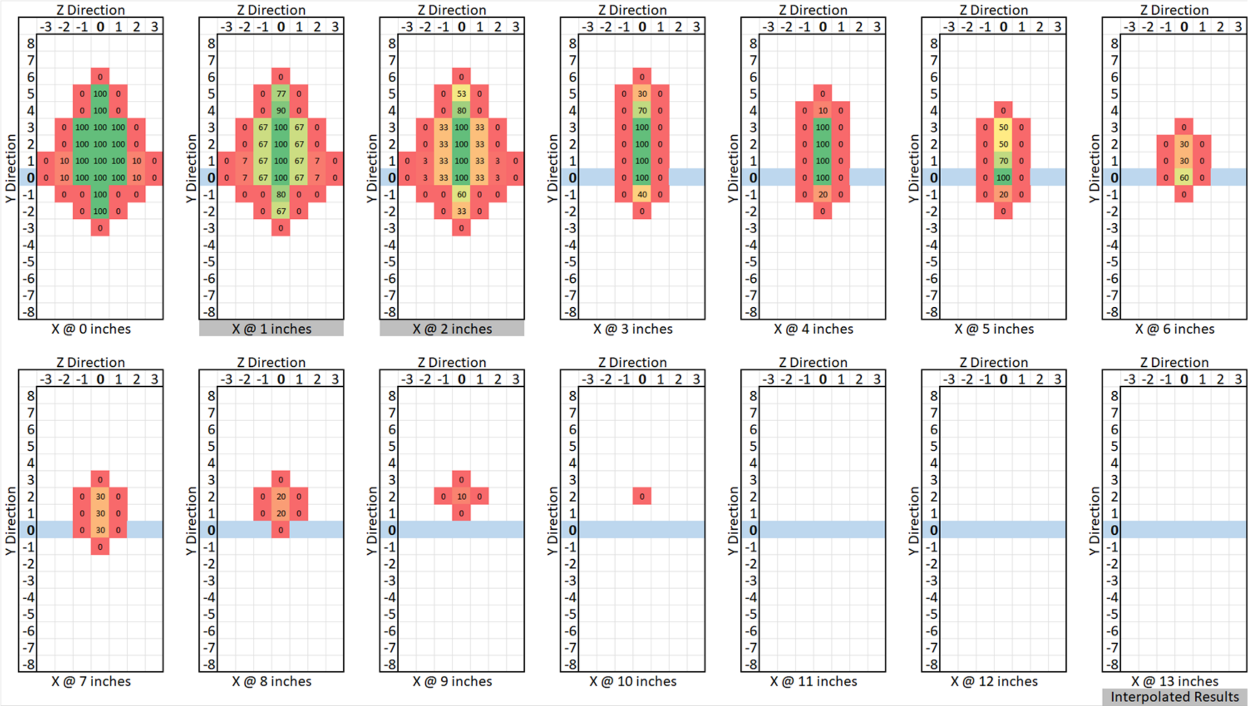


Figure 22: Polara Experimental Results, Default Settings

Table 8 and **Figure 23** show the results from the Guardian Wave at default settings. As can be seen when comparing the shape and 100% DFV of the two devices at their default settings, there are distinct differences to the shape, volume, and centroid of the field.

Table 8: Gaurdian Wave Default Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 64in^3	**Centroid (Y, Z):** -1.5, 0

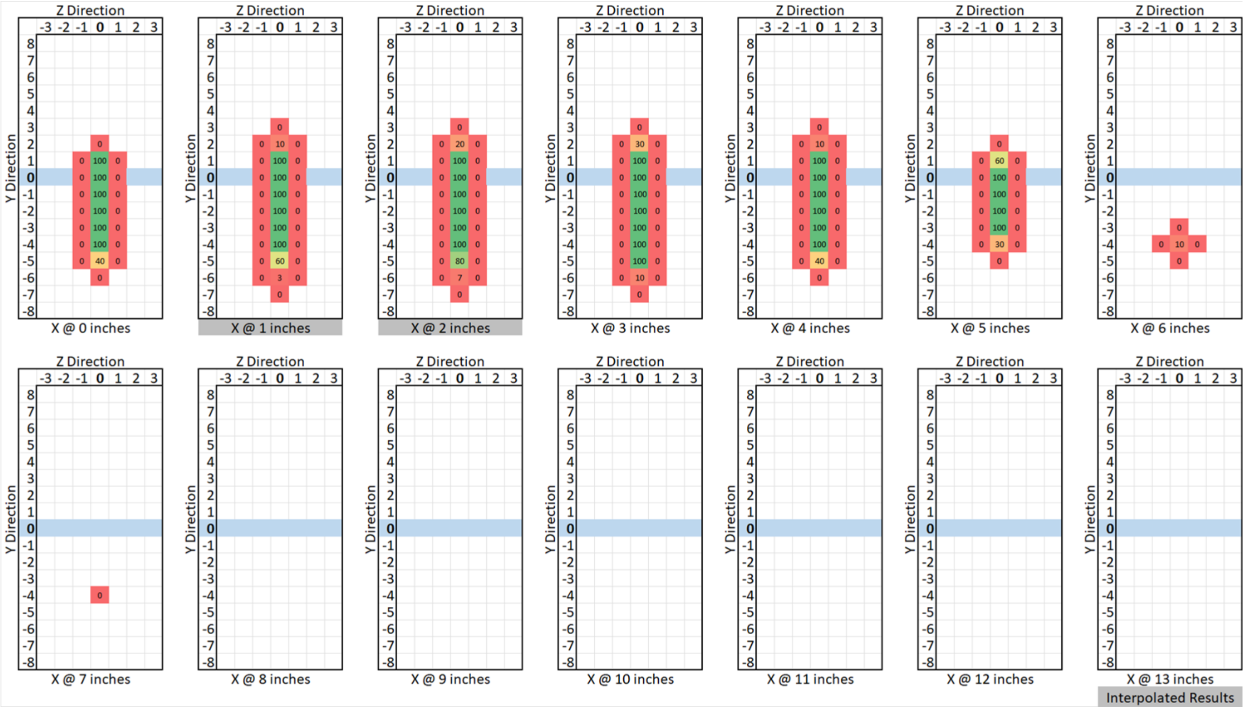


Figure 23: Gaurdian Wave Experimental Results, Default Settings

3.3.1 Summarized Results

The detailed results of each test are shown Appendix A: Polara Wave Detection Experiment Results and Appendix B: Guardian Wave Detection Experiment Results for Guardian Wave.

All the detection range experiment results are summarized below in **Table 9**. This table shows the unit of the experiment, the experiment, the settings used for that experiment, the 100% detection field volume in cubic inches, how far the 100% detection field was observed to reach from the unit, and the centroid of the base of the 100% detection field cone.

Table 9: Results Summary Table

		Settings				Results		
Vendor	**Test**	**Range**	**Wave Time (ms)**	**Sensitivity**	**Delay (ms)**	**100% DFV (in^3)**	**100% Max Cone X Distance (in)**	**Centroid of 100% Cone Base (y,z)**
Polara	Range 0	0	50	-	-	25	3	(2,0)
Polara	**Range 3**	**3**	**50**	**-**	**-**	**46**	**5**	**(2,0)**
Polara	Range 6	6	50	-	-	97	8	(2,0)
Polara	Range 9	9	50	-	-	156	10	(2,0)
Polara	Gloves	3	50	-	-	43	5	(2,0)
Polara	Heated Pushbutton	3	50	-	-	53	6	(2,0)
Polara	Dark Environment	3	50	-	-	42	4	(2,0)
Polara	Wave Time 0ms	3	0	-	-	100	9	(2,0)
Polara	Wave Time 500ms	3	500	-	-	33	4	(2,0)
Guardian	Range 3 in	3	-	3	100	34	3	(-1.5,0)
Guardian	**Range 6 in**	**6**	**-**	**3**	**100**	**64**	**5**	**(-1.5,0)**
Guardian	Range 9 in	9	-	3	100	97	7	(-1.5,0)
Guardian	Gloves	6	-	3	100	60	5	(-1.5,0)
Guardian	Heated Pushbutton	6	-	3	100	64	5	(-1.5,0)
Guardian	Dark Environment	6	-	3	100	60	5	(-1.5,0)
Guardian	Fast Sensitivity	6	-	1	100	79	7	(-1,0)
Guardian	Slow Sensitivity	6	-	12	100	45	4	(-2,0)
Guardian	Delay 5ms	6	-	3	5	71	5	(-2,0)
Guardian	Delay 1000ms	6	-	3	1000	56	4	(-1.5,0)
Note: Bolded Results are the default setting for the pushbutton								

Looking at the range experiment results, the size of the detection field for the Guardian Wave 3-inch range setting is between the Polara range 0 and 3 settings, the Guardian Wave range setting of 6 inches is between Polara's range of 3 or 6, and the Guardian Wave 9-inch range is similar to Polara's range of 6. The Guardian Wave did not have a preset range setting that resulted in a similar detection field cone distance to Polara's range 9 detection field.

Turning to environmental conditions, there was a slight change in detection field range compared to the baseline setting of range 3 on the Polara unit when gloves, a dark environment, and heated pushbutton were used during experimentation. The use of gloves or in the dark environment slights reduced the 100% DFV, with the 100% DFV increased slightly when the button was heated. Similarly, gloves or a dark environment slightly reduced the 100% DFV of the Gaurdian Wave from default, though there was no change to the 100% DFV when the button was heated. Reducing the Wave Time on the Polara had a similar effect to setting the Gaurdian at Fast Sensitivity; both saw a marked increase in the 100% DFV from default. The reverse of this was also consistent; increasing the wave time on the Polara or setting the sensitivity to slow on the Gaurdian Wave greatly decreased the 100% DFV. With regards to the centroid, the Polara Unit had a centroid height of two inches above the centerline of the button, which is higher than the Guardian Wave unit, which had a centroid height of one to two inches below the centerline of the button.

3.3.1.1 Other Experiment Results

Other experiments that were conducted were experimentation with the touchless extended press functionality for both of the units and the rain lockout feature of the Polara unit. These were only experimented with to confirm that they work. As such, a detection field for these settings was not determined.

3.3.1.1.1 Extended Press Functionality

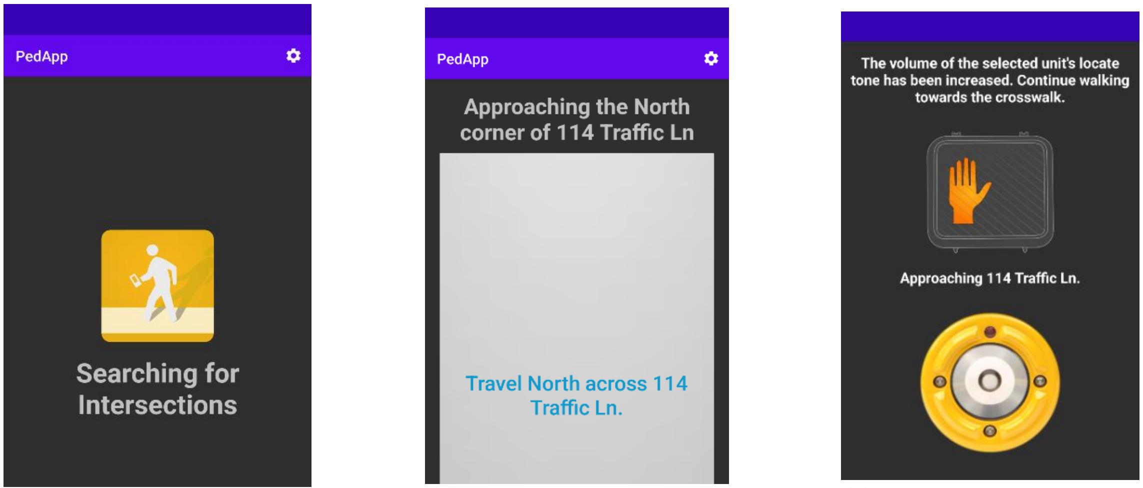
One of the additional functionalities of the Polara and Gaurdian Wave APS units is the extended press functionality, and the experimentation conducted on this setting confirmed that this function of the devices works. This functionality was tested on each pushbuttons' default setting and was confirmed to function when the extended press sound was emitted multiple times at different distances.

3.3.1.1.2 Rain Lockout

This setting of the Polara unit will temporarily disable the touchless sensor for a selected period of time if the sensor detects activation during the walk cycle. The Rain Lockout feature was tested by waving during the walk cycle to activate the lockout of the touchless sensor, and then during the don't walk cycle a second wave was attempted to confirm that the lockout was still active during the stated lockout time. Then, when the lockout had lapsed another wave was attempted to confirm that the lockout was disabled and the touchless functionality was restored. The functionality of this setting was experimented under multiple of the available Rain Lockout settings, and setting was confirmed to work as expected.

3.3.1.1.3 PedApp Functionality

The PedApp is a unique feature of the Polara Accessible Pedestrian System. **Figure 24** illustrates the functionality of the system. The application utilizes Bluetooth to identify adjacent pushbuttons (a) and alerts the user when they are approaching a pushbutton (b). The volume is automatically increased when close to the pushbutton (c). The app allows the user to place a call to the unit using their phone (d) and will let the user know when the walk sign is on and is safe to cross (e). When the walk cycle changes to a flashing don't walk sign, the app will let the user know in the app (f). Finally, it will let the user know that the don't walk sign is on and will then search for pushbuttons again (g).



Searching for Intersections

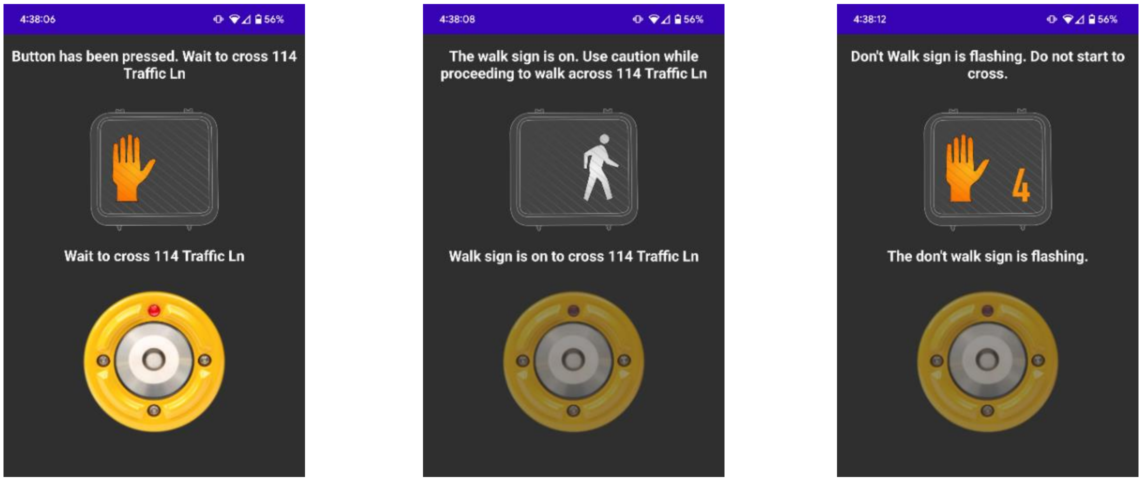
Approaching the North corner of 114 Traffic Ln

Travel North across 114 Traffic Ln.

The volume of the selected unit's locate tone has been increased. Continue walking towards the crosswalk.

Approaching 114 Traffic Ln.

(a): Searching (b): Approaching (c): Increased Volume



Button has been pressed. Wait to cross 114 Traffic Ln

Wait to cross 114 Traffic Ln

The walk sign is on. Use caution while proceeding to walk across 114 Traffic Ln

Walk sign is on to cross 114 Traffic Ln

Don't Walk sign is flashing. Do not start to cross.

The don't walk sign is flashing.

(d): Button Pressed (e): Walk Sign On (f): Don't Walk Sign Flashing

The Don't Walk sign is on.

Don't Walk

(g): Don't Walk Sign On

Figure 24: Functionality of the PedApp

3.3.2 Items Noted During Experimentation

During experimentation, some anomalies were noticed with the pushbuttons. The first was that with the Polara unit, at different ranges, the tester's body would activate the unit at a further distance than what the unit could detect with the hand of the tester. This was noticed if the tester's body passed close enough to set the unit off but far enough that the tester's hand did not. An example of this was when the Polara unit had range set to 6; the unit would detect hand waves until X distance of 11 inches from the unit but would still register activations until the X distance of 16 inches if the tester's body walked by, at approximately 30% of the time from the X distance of 16 inches.

The second was that the Guardian Wave would occasionally activate with no discernible stimulus. This would occur when the unit was powered on, but experimentation was not occurring while data was being recorded. The unit was typically five or more feet away from any wall or object and would not happen during every experimentation session. This anomaly would occur between zero and three times during an 8-hour experimentation session and did not happen in most experimentation sessions.

3.4 Recommended Pushbutton Settings

For each of the pushbuttons that were tested, different settings can be changed to achieve a desired detection range. In the following subsections, settings will be explained to achieve ranges of 3-inches and 6-inches for the two different pushbuttons.

3.4.1 Polara Settings

For a Polara unit, the default settings of Detection Profile 1 should be used as a starting point. To achieve a range of approximately 3-inches, set the Range to 3 and the Minimum Wave Time to the maximum of 500ms. For an approximate range of 6-inches, set the Range to 6 and the Minimum Wave Time to the maximum of 500ms.

If a different range is desired, it should be understood that with the Polara pushbutton the range slider is not in inches, so as an example a Range of 9 does not definitively indicate that the detection field would be 9-inches.

3.4.2 Guardian Wave Settings

With the Guardian Wave unit, there are 3 preset ranges that are available by default. Using the default settings, selecting one of the 3 default range options is all that is required to achieve a desired range if the desired range is approximately 3-inches, 6-inches, or 9-inches.

If a range that is not available by default, it is required that a phone number provided in the software is contacted to receive input on what settings would need to be adjusted to get the desired detection range.

3.5 Field Test

For the Advanced Pushbutton field test, two signalized intersections were identified for data collection, as described in Appendix A: Polara Wave Detection Experiment Results. However, due to network communication issues at the selected intersections, event-based data was unavailable. As a result, efforts were redirected to other tasks, and the Advanced Pushbutton field test was not conducted as part of this work.

4 PEDESTRIAN VEHICLE CONFLICT ANALYSIS

This chapter presents information pertaining to the examination of pedestrian-turning vehicle conflicts at signalized intersections in the City of Phoenix identified and measured using PET. It outlines the steps involved in conducting crash and volume analysis to identify appropriate sites for video data collection. Additionally, it discusses the process of reducing and analyzing conflict data from field-collected videos. The primary objective of the field data analysis was to conduct a Before and After safety assessment of two pedestrian treatments: LPI and NRTOR restriction. The evaluation for LPI treatment aimed to examine and compare factors associated with the frequency or severity of conflicts between pedestrians and turning vehicles.

4.1 Site Identification for Data Collection

4.1.1 Crash Analysis for Priority Intersections Identification

Pedestrian crash data from 2016 through 2022 for the City of Phoenix were obtained from City staff, and this initial dataset contained 4,685 crash records. Since this project is primarily focused on development of guidance for the implementation of LPIs, pedestrian crashes that would be most impacted by an LPI were identified. This was accomplished by filtering the dataset to include crashes at signalized intersections that involved a turning vehicle (left or right) and a crossing pedestrian using the unit action variables in the crash data. Note that a GIS file with data for each signalized intersection in Phoenix was also provided by City staff, and this dataset was used in this process by assigning crashes to each signalized intersection using a 150 ft buffer. After this filtering process, a total of 1,117 crashes remained for inclusion in this analysis.

After turning vehicle-pedestrian crashes was assigned to signalized intersections using the previously mentioned 150 ft buffer, all 1,170 signalized intersections (this was the total in the dataset provided by City staff) were ranked from highest to lowest turning vehicle-pedestrian crash frequency. Ultimately, this ranked list is provided for use in subsequent tasks in determining which locations would be most appropriate for field video data collection.

The top 85 intersections, all which experienced 3 or more turning vehicle-pedestrian crashes were separated into different tiers for future data collection consideration based on the frequency of turning vehicle-pedestrian crashes. It is deemed less desirable to collect field data at sites with fewer of this crash type in developing LPI guidelines. In determining the location of future data collection sites, priority was given to Tier 1 sites with the highest crash rates, followed by Tier 2 sites if an adequate number of Tier 1 sites couldn't be identified, and then to Tier 3 sites if needed. Along with the crash data, additional characteristics such as relative expected pedestrian volumes, ability to collect video, expected number of pedestrian / motor vehicle conflicts, and the ability to make signal timing / signing changes to a site was considered by City Staff in consultation with the research team in identifying these. **Figure 25** shows a map of Phoenix with both Tier 1 and Tier 2 intersections. Appendix D shows a list of Tier 1,2 and 3 intersections along with the frequency of turning vehicle-pedestrian crashes and the overall intersection rank.

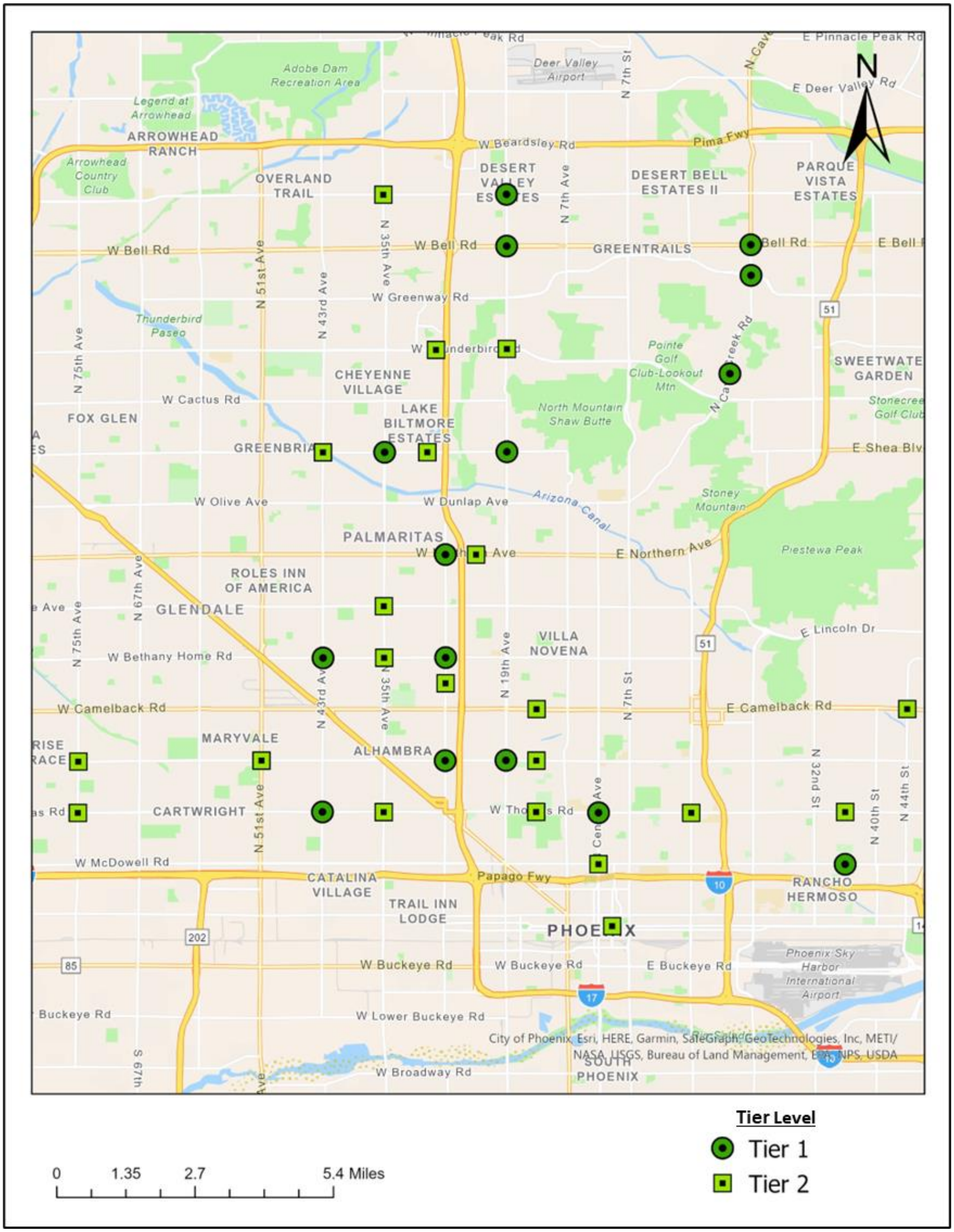


Figure 25: Map of Phoenix Showing Tier 1 and Tier 2 Intersections

In addition to crash data, a number of intersection characteristics and factors were collected from each Phoenix signalized intersection. Evaluation of these factors is necessary when deciding whether to implement LPIs at specific intersections. These characteristics and factors were considered in reviewed LPI implementation guidelines which are discussed in **Table 1**; however, to the authors' knowledge, no previous research has analyzed the quantitative effects of these variables on turning vehicle-pedestrian crash frequency using empirical data in the context LPI implementation guidelines. The evaluation of these variables will be utilized in creating more robust and data driven LPI guidelines for Phoenix. Crash frequency models were developed to examine the impacts of factors commonly considered in different LPI guidelines on pedestrian crashes with turning vehicles.

Intersection characteristics were identified using Google Aerial View and Street View imagery, including types like T-intersections, one-way streets, skewed intersections, site obstruction, crosswalk details (number and length), presence of NRTOR signs, exclusive right turn lanes, and pedestrian pushbuttons. Traffic-related data, such as Average Annual Daily Traffic (AADT), were sourced from the Arizona Department of Transportation. The study also collected population density, employment density, proximity to schools, and transit stops to gauge pedestrian activity levels around intersections. Several existing LPI guidelines mention priority in areas with a high number of school-aged children, though specific thresholds for intersection distance from school were only included in Toronto LPI implementation guidelines. The categories of intersection distance from school were created using similar thresholds and a geocoded school database: within 200m, 200m to 850m, and 850m+. In addition, intersections that are within 300ft of a transit stop were identified by using GIS. Due to the unavailability of direct pedestrian volume data, gross activity density (combining population and employment densities) served as a surrogate indicator. Appendix D: shows the details of variables collected for analysis.

A Negative Binomial (NB) regression model was developed to analyze factors associated with turning vehicle-pedestrian crash frequency. Numerous variables were found to be significantly associated with this frequency, many of which were referenced in existing LPI implementation guidelines. Using the NB model results, the expected percent change in pedestrian crash frequency was calculated for each variable and those values are presented in **Table 10** with underlined values representing statistically significant (≥90% confidence) and a color scale with red/orange/yellow indicating higher predicted percent increases. The highest predicted percent increases were for the presence of 4 crosswalk legs, different ranges of gross activity density, higher ranges of minor road AADTs, transit stop presence, presence of a school within 850m, and the T-intersection indicator. These relative expected increases may be useful in providing data-driven evidence to help establish difference weighting schemes for future iterations of LPI implementation guidelines.

Table 10: Expected Percent Change in Crash Frequency based on NB Model Results

Variable	Turning Vehicle-Pedestrian Crashes Expected % Change
T intersection Indicator	51.59%
One way street (1 or more approaches)	-71.58%
Intersection skewed ≥ ~15 deg.	25.22%
Site Obstruction Present on 1 or More Corners	43.36%
Crosswalk on 1 and 2 legs (ref.)	
Crosswalk on 3 legs	146.47%
Crosswalk on 4 legs	410.83%
Average Crosswalk Length (ft)	0.61%
No Ped Push-buttons Present (ref.)	
Ped Push-button on 1 or More Legs	-22.46%
Exclusive RT Lanes Not Present (ref.)	
Exclusive RT Lanes Present on 1+ Approaches	16.28%
NRTOR Not Present (ref.)	
NRTOR Restriction Present on 1+ Approaches	2.00%
Major Rd AADT 0-15,000 vpd (ref.)	
Major Rd AADT 15,001-30,000 vpd	19.98%
Major Rd AADT 30,001-45,000 vpd	32.62%
Major Rd AADT 45,001+ vpd	29.46%
Minor Rd AADT 0-5,000 (ref.)	
Minor Rd AADT 5,001-15,000 vpd	41.55%
Minor Rd AADT 15,001-30,000 vpd	95.24%
Minor Rd AADT 30,001+ vpd	131.31%
Intersection Distance from School 851m+ (ref.)	
Intersection Distance from School 201-850m	50.63%
Intersection Distance from School ≤200m	49.22%
Intersection Distance from Transit Stop 301+ ft (ref.)	
Intersection Distance from Transit Stop 0-300 ft	76.38%
Gross Activity Density 0-5 persons+jobs/acre (ref.)	
Gross Activity Density 5.1-15 persons+jobs/acre	189.07%
Gross Activity Density 15.1-30 persons+jobs/acre	346.76%
Gross Activity Density 30+ persons+jobs/acre	205.75%

Notes: 1) Darker Red/Orange/Yellow colors indicate larger expected percent increases in crash frequency
2) Underlined numbers indicate variable was statistically significant at a ≥90% confidence level in model

4.1.2 Volume Analysis for High Exposure Crosswalks Selection

The 85 priority intersections identified from crash analysis were provided to the City of Phoenix. Following discussions with the research team, the City of Phoenix staffs selected seven intersections from the three-tier list for volume analysis, based on criteria including the feasibility of video collection, expected number of pedestrian/motor vehicle conflicts, and potential for signal timing/signing changes. Volume analysis aimed to identify high-exposure crosswalks for video data collection from these seven intersections. The intersections selected for volume analysis are outlined in **Table 11**.

Table 11: Intersection Locations Selected for Volume Analysis

Tier#	Intersection#	Name
1	2	Indian School & 19th Ave
	10	Bell & 19th Ave
	15	Camelback & 15th Ave
2	23	Indian School & 51st Ave
	34	Washington & 3rd St
3	60	Southern & 19th Ave
	65	Baseline & 51st Ave

For volume analysis, the data that the City of Phoenix provided included vehicle counts for each left turn, through, right turn movements, and the count of the number of pedestrians crossing at the crosswalks for each leg from 12:00 PM to 1:00 PM and 5:00 PM to 6:00 PM for 7 intersections for a single day. Timing plans were also provided so that research staff could determine phasing at each intersection, particularly left turn treatments (FYA, protected only, protected-permitted, or permitted).

A review of the provided data was undertaken to gain an understanding of which crosswalks at each intersection would be expected to have the most vehicle-pedestrian interactions. For each intersection, the data was reviewed to identify which crosswalk had the highest pedestrian volume, the highest number of conflicting vehicles crossing that crosswalk (those turning across it when executing a permitted movement), and the cross-product between the pedestrian volume and the number of conflicting vehicles. **Figure 26** shows the possible conflicting movements across each crosswalk.

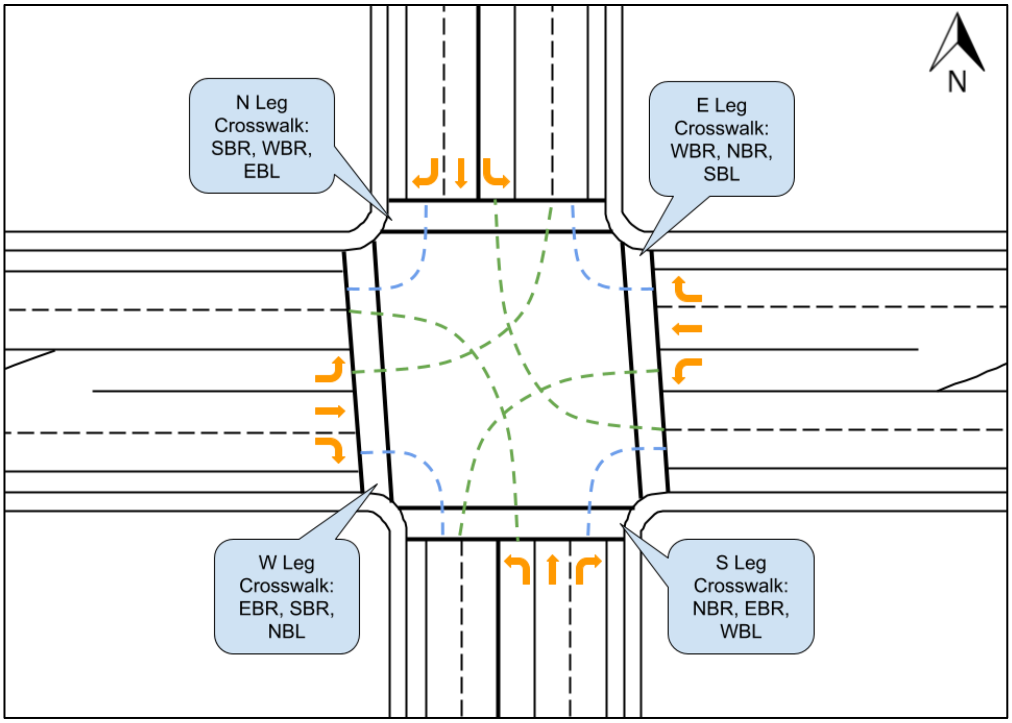


Figure 26: Possible Conflicting Movements

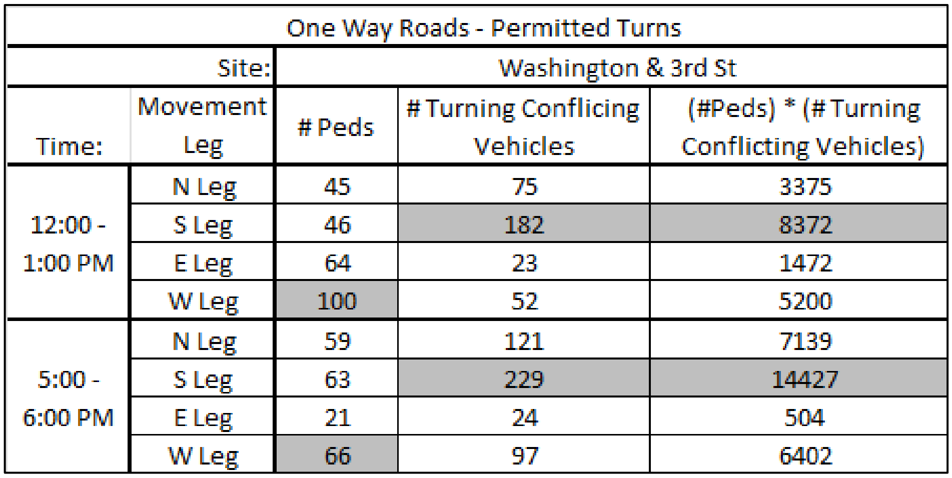
Calculation results were compiled into tables for each intersection for each time period, separated by intersection leg and time of day. An example calculation for calculating the cross product is provided as Equation 13, where PedCrossing is the total number of pedestrians to cross that legs crosswalk for the time period, and ConflictingVehicles is the total number of conflicting vehicles for the time period.

$$\boldsymbol{CrossProduct = PedCrossing * ConflictingVehicles = 45 * 75 = 3,375}$$

Equation 12

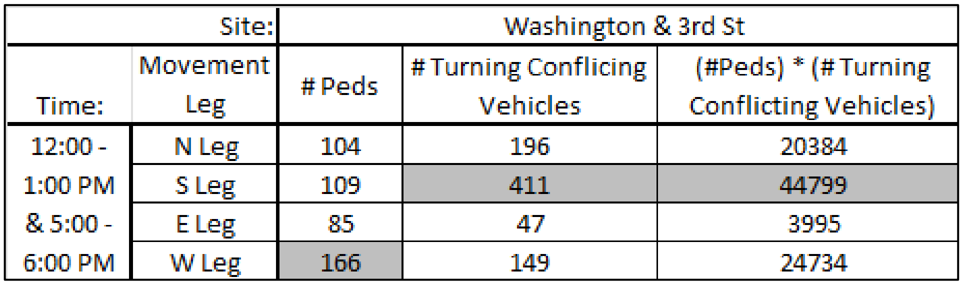
The highest value in each column was highlighted in grey for each time period. An example table is shown as **Table 12**, while **Table 13** is an example table that shows the results of this analysis with both time periods combined (results for all locations can be found in Appendix F: Crosswalk Rank Detailed Results for LPI Site Selection). Reviewing the data in this manner provided the research staff with an opportunity to gain an understanding of which crosswalks at each intersection could be expected to have the highest number of pedestrian / vehicle interactions, which would be beneficial for subsequent data analysis.

Table 12: Example of Initial Results Table



One Way Roads - Permitted Turns				
	Site:	Washington & 3rd St		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	45	75	3375
	S Leg	46	182	8372
	E Leg	64	23	1472
	W Leg	100	52	5200
5:00 - 6:00 PM	N Leg	59	121	7139
	S Leg	63	229	14427
	E Leg	21	24	504
	W Leg	66	97	6402

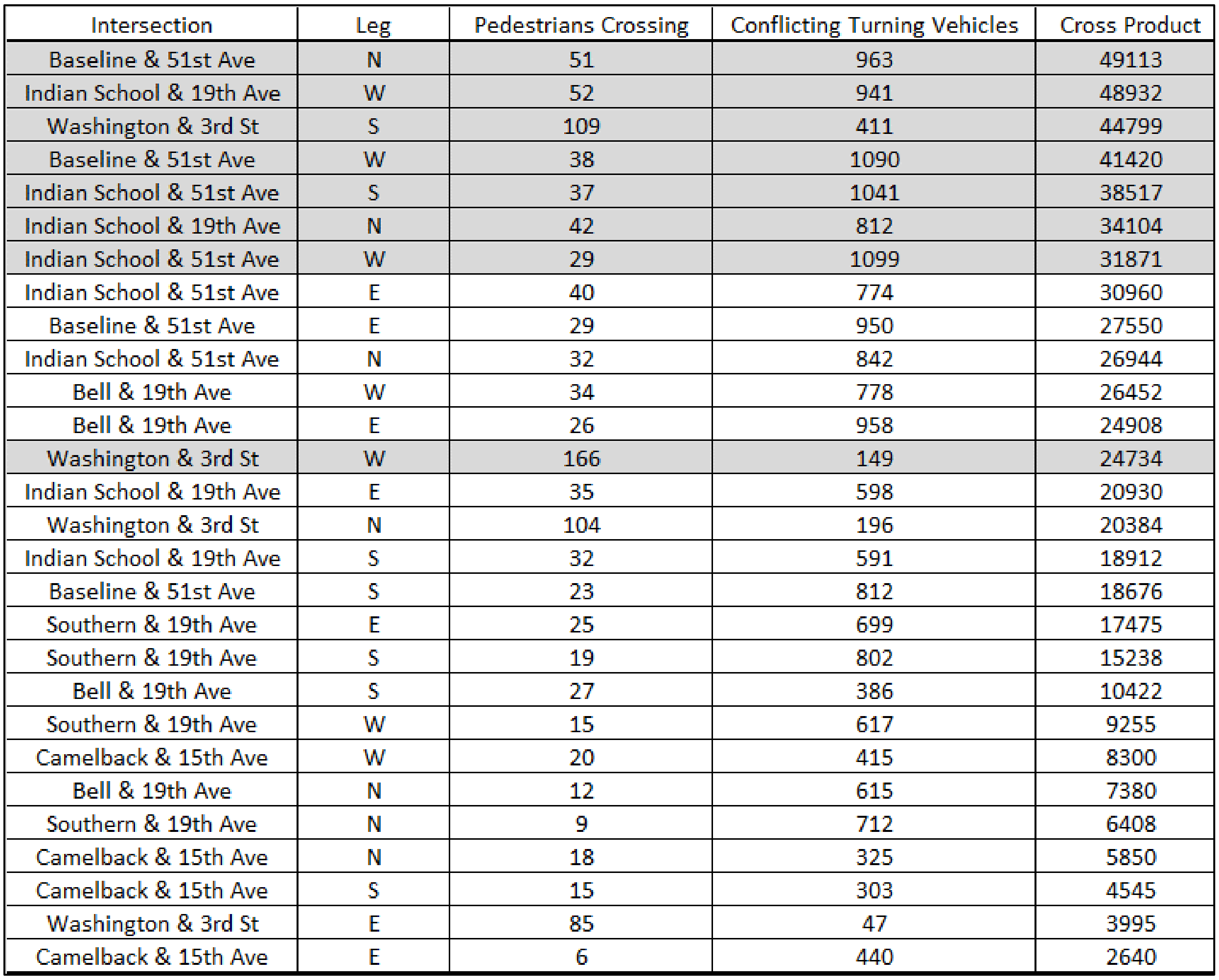
Table 13: Example of Combined Results Table



	Site:	Washington & 3rd St		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	104	196	20384
	S Leg	109	411	44799
	E Leg	85	47	3995
	W Leg	166	149	24734

From this, the results were aggregated in an overall summary table shown in **Table 14**, which presents the data in a similar manner as **Table 13**, with suggested crosswalks for data collection highlighted in grey. The research team used the value of the cross product to prioritize crosswalk legs for data collection, with the stipulation of recommending no more than two crosswalks from any one intersection to ensure a diverse set of sites. Additionally, two legs at Washington and 3rd St. were selected due to their high pedestrian volumes and agency preference.

Table 14: Summary of LPI Crosswalk Ranking Analysis



Intersection	Leg	Pedestrians Crossing	Conflicting Turning Vehicles	Cross Product
Baseline & 51st Ave	N	51	963	49113
Indian School & 19th Ave	W	52	941	48932
Washington & 3rd St	S	109	411	44799
Baseline & 51st Ave	W	38	1090	41420
Indian School & 51st Ave	S	37	1041	38517
Indian School & 19th Ave	N	42	812	34104
Indian School & 51st Ave	W	29	1099	31871
Indian School & 51st Ave	E	40	774	30960
Baseline & 51st Ave	E	29	950	27550
Indian School & 51st Ave	N	32	842	26944
Bell & 19th Ave	W	34	778	26452
Bell & 19th Ave	E	26	958	24908
Washington & 3rd St	W	166	149	24734
Indian School & 19th Ave	E	35	598	20930
Washington & 3rd St	N	104	196	20384
Indian School & 19th Ave	S	32	591	18912
Baseline & 51st Ave	S	23	812	18676
Southern & 19th Ave	E	25	699	17475
Southern & 19th Ave	S	19	802	15238
Bell & 19th Ave	S	27	386	10422
Southern & 19th Ave	W	15	617	9255
Camelback & 15th Ave	W	20	415	8300
Bell & 19th Ave	N	12	615	7380
Southern & 19th Ave	N	9	712	6408
Camelback & 15th Ave	N	18	325	5850
Camelback & 15th Ave	S	15	303	4545
Washington & 3rd St	E	85	47	3995
Camelback & 15th Ave	E	6	440	2640

4.2 Video Data Collection

For the field data collection, eight study crosswalks from four intersections were identified through crash and volume analysis. These crosswalks are referred to as ‘Site’ in this study. Aerial views of the eight studied sites in the four intersections are presented in **Figure 27**. The pedestrian treatments to be evaluated at each crosswalk were chosen in consultation with the City of Phoenix Street Transportation Department. The evaluation included LPI assessment at each crosswalk and NRTOR restriction assessments at the Baseline and 51st Avenue West crosswalk (EB right turn had the NTOR restriction at Site 8). LPIs were implemented with 5-second durations at each selected site.

Figure 27: Aerial Views of Studied Intersections

The research team provided annotated figures with possible camera installation points to the Phoenix technician team. Example annotated figures for camera installation positions are presented in **Figure 28**. Additionally, the research team provided a presentation of the project to the technician team to enhance their understanding of traffic control and traffic control device changes for video collection. The Phoenix technician team collected 10 hours of video (7 am-5 pm) at each of the eight study sites for both the Before and After phases, except for 20 hours of video collected at Site 8 during After phase (10 hours for each treatment). In total, 170 hours of video were collected.

Video collection started in November to avoid the hot summer weather of Phoenix and to coincide with the period of high pedestrian activity on the roads. Before phase videos were collected between November 8, 2023, and November 28, 2023. Prior to After phase data collection, LPI and NRTOR restriction were implemented at each studied crosswalk, and 'New Traffic Pattern Ahead' signs were installed before approaches to warn drivers about the new traffic rules associated with the treatments. At Site 8, LPI and NRTOR restriction were assessed individually. After phase videos were collected between February 23, 2024, and April 10, 2024. Video files were directly provided to the research team by being uploaded to a shared OneDrive folder. **Table 15** provides a summary of the video data collection, including the site ID, intersection crossroads, crosswalks, date of video collection, and studied pedestrian treatments.

Table 15: Summary of Video Data Collection

Site ID	Road 1	Road 2	Crosswalk	Before Data Collection Date	After Data Collection Date	Treatment
1	Washington St	3rd St	South	11/17/2023	03/07/2024	LPI
2	Washington St	3rd St	West	11/17/2023	03/07/2024	LPI
3	Indian School Rd	51st Ave	South	11/28/2023	02/29/2024	LPI
4	Indian School Rd	51st Ave	West	11/28/2023	02/29/2024	LPI
5	Indian School Rd	19th Ave	North	11/14/2023	02/23/2024	LPI
6	Indian School Rd	19th Ave	West	11/14/2023	02/23/2024	LPI
7	W Baseline Rd	51st Ave	North	11/08/2023	03/05/2024	LPI
8	W Baseline Rd	51st Ave	West	11/08/2023	03/05/2024	LPI
8*					04/10/2024	NRTOR

Camera installation pole for south and west crosswalks

Figure 28: Example Annotated Figure of Camera Installation Positions for Washington and 3rd Intersection.

4.3 Video Data Reduction

This section discusses the video data reduction methods used to obtain pedestrian-turning vehicle conflict and volume data from field collected videos.

4.3.1 Pedestrian-Turning Vehicle Conflict Data Reduction

Pedestrian-turning vehicle conflicts on the study approach for each site were manually reduced from the field-collected videos. The conflicts were measured using PET, and only conflicts with a PET of 5 sec or less were included in this study based on previous research in this area (Russo et al., 2020; Zangenehpour et al., 2016). It should be noted that details regarding the use of PET to assess conflicts was provided previously in **Section 2.6.1** of this report. In addition to PET, the speed of conflict involved units was measured near the conflict area using measured distances between landmarks and time differences, and the unit which occupied the conflict area first (e.g., pedestrian or vehicle) was noted. To assist research team members in reducing conflict data uniformly, a set of instructions was created along with a conflict data collection template spreadsheet. Appendix G: Pedestrian-Turning Vehicle Conflict Data Reduction shows the instructions and an example template spreadsheet for speed and conflict data reduction.

This data reduction effort involves transcribing a series of timestamps documenting interactions between pedestrians and vehicles. These timestamps are then utilized to calculate conflict PET and speed at specified locations. It should be noted that research team members could advance (or reverse) the video frame by frame, and time stamps are recorded to a hundredth of a second precision. Pedestrian speed is determined by considering the length of the crosswalk and the timestamps of pedestrian entry and exit from the edges of the crosswalk. Similarly, the speed of turning vehicles was determined by considering the width of the crosswalk and the timestamps representing the entry and exit of the vehicle's front wheel/bumper within this width. Prior to official data reduction, research team members first reduced data from video as trial, and results were compared to ensure consistency. The results of trial video data reduction were consistent after clarifications and iterations to the method were made.

Figure 29 shows an example of an observed pedestrian-vehicle conflict at Indian School Rd and 51st Avenue South Crosswalk in the Before Phase of LPI implementation. A conflict block is a common area on the surface that both parties of a conflict pass through. In **Figure 29**, the conflict block is highlighted with a red rectangle with white and red stripes. A right-turning vehicle was seen to approach the conflict block soon after a pedestrian left it. The interval between the pedestrian's departure and the vehicle's arrival at the conflict block is defined as the PET value of the conflict, which in this example was 1.2 seconds. Additionally, this is an example of a conflict where the pedestrian arrived at the conflict area first (as opposed to the vehicle arriving first). The other party of a possible conflict for this pedestrian could also be a left turning vehicle or a right turning vehicle from the other side of the road Because of that, the conflict block may be located at a different location on the crosswalk for each conflict as the pedestrian walks through it.

Figure 29: Example annotated figure for conflict reduction.

4.3.2 Pedestrian-Turning Vehicle Volume Data Reduction

Pedestrian and turning vehicle volumes were extracted for the study approach at each intersection along with conflict data. These volumes were used to explore correlations with conflict frequency. Volumes were extracted manually from the videos and the following information was recorded in 15-minute bins over the full 10-hour periods (7am-5pm) at each study site:

- Pedestrian: Pedestrian volume data included counts of individuals moving away and towards the camera, engaging in activities such as walking, bicycling, non-powered scootering, and using visible mobility devices within the crosswalk.

- Protected and Permitted Left-Turning Vehicles: Counts were conducted for left-turning vehicles entering the crosswalk. Left-turning vehicle counts were conducted separately for protected and permitted phases. Except for the Washington and 3rd intersection, which featured permitted left turns, the other three intersections employed a combination of protected and permitted signal phasing.

- Adjacent and Crossing Right-Turning Vehicles: This category involved counting vehicles making right turns, both adjacent to the study approach and crossing the crosswalk perpendicular to it, in red and green signal phases. Examples of these movements are shown in **Figure 30**.

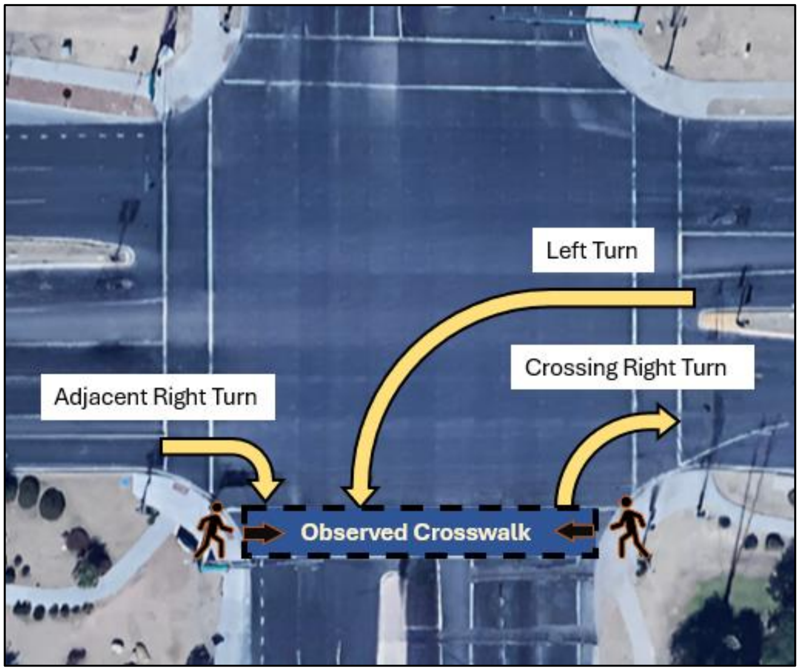


Figure 30: Annotated Figure Specifying the Crossing Right Turn, Adjacent Right Turn, and Left Turn Reduced for a Specific Crosswalk.

Separate counts were conducted for passenger vehicles and heavy vehicles. Passenger vehicles included cars, pickup trucks, vans, and SUVs, while heavy vehicles comprised buses, semi-trucks, package trucks, firetrucks, and RVs. Research team members also provided notes for any atypical behavior observed during data collection. Appendix H: Pedestrian-Turning Vehicle Volume Data Reduction shows the instructions and an example template spreadsheet for volume data reduction.

4.4 Before and After Evaluation of LPI Treatment

This section provides a summary and analysis of the impact of LPI treatment based on reduced data from eight implementation sites. It examines factors related to conflicts between pedestrians and turning vehicles to assess the effectiveness of the treatment.

4.4.1 Summary of Field Observed Conflict and Volume Data

Table 16 provides a summary of the observed pedestrian-vehicle conflicts over the full 10 hours of video at each study approach including total conflicts, conflicts summarized by different PET severity ranges (lower PET indicates more severe conflict severity) and conflicts within first 5 seconds of WALK time. A comparison of Before and After data shows a general reduction in the total number of conflicts and severe conflicts in most sites after LPI treatment. The number of conflicts within the first 5 seconds of walking time is of special interest, as the LPI treatment aims to reduce those conflicts by allowing pedestrians to get on the crosswalk before vehicles and making them more easily noticeable by drivers. Interestingly, there were no conflicts found within 5 seconds of walking time at Site 1 and Site 2, the south and west crosswalks of the Washington St & 3rd St intersection. The reason could be that, unlike the other intersections in **Table 16**, this intersection is located in the Downtown Phoenix area with one-way streets, lower speed limits, and higher pedestrian volumes.

It should be noted that the PET thresholds defining high/medium/low severity conflicts are based on existing published research (Russo et al., 2020; Zangenehpour et al., 2016), and PET values ≤ 1.5 sec are generally considered potentially the most severe interactions. The use of PET provides a quantitative measure to evaluate the proximity and temporal overlap of pedestrian and vehicle paths, with lower PET values indicating more severe interactions. **Figure 31** represents the percentage of conflicts in each severity category. The percentage graph indicates a reduction in high-severity categories and an increase in low-severity categories following LPI implementation. This suggests that the intervention was especially effective in reducing the more severe conflicts.

Table 16: Summary of Observed Pedestrian-Vehicle Conflicts

Site ID	Total Conflicts (PET ≤ 5 sec)		High Severity Conflicts (PET ≤ 1.5 sec)		Medium Severity Conflicts (PET >1.5-3.5 sec)		Low Severity Conflicts (PET >3.5-5 sec)		No. of Conflicts Within 5 sec of Walk Time	
	Before	After	Before	After	Before	After	Before	After	Before	After
1	152	82	7	3	71	44	74	35	0	0
2	318	90	14	1	162	35	142	54	0	0
3	274	336	55	34	121	149	98	153	23	36
4	189	210	27	4	93	106	69	100	23	30
5	171	158	18	6	91	82	62	69	23	13
6	239	185	9	6	112	67	118	112	14	7
7	159	135	15	9	92	81	52	45	11	4
8	192	138	13	17	105	68	74	43	14	11
Total	1694	1334	158	80	847	632	689	611	108	101

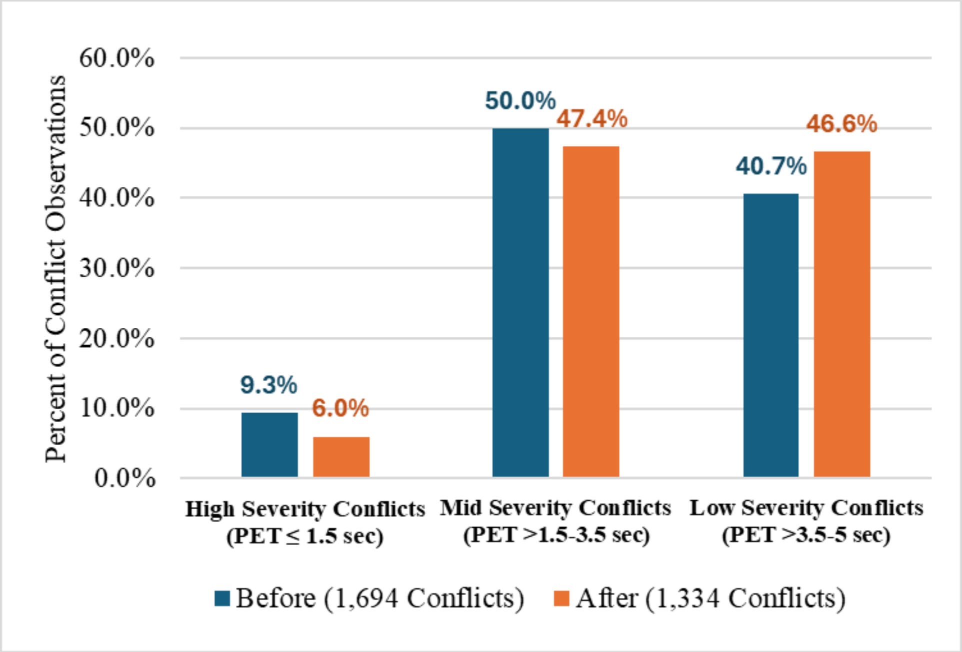


Figure 31: Distribution of Conflicts by Severity Categories

Another way to assess the severity of a conflict is by considering both PET and vehicle speed (Russo et al., 2023). In this context, a conflict with both a (≤ 1.5 sec) and a high vehicle speed would be considered less severe, while a conflict with a higher PET (> 3.5-5 sec) and a low vehicle speed would be considered least severe. To make this determination, the distribution of vehicle speeds in all observed conflicts (across all sites) was analyzed and the mean of this distribution was found to be 11.48 mph (11.6 mph for Before phase conflicts and 11.3 for After phase conflicts). Based on this information, any conflict in which the vehicle speed was less than 11.5 mph was coded as 'low vehicle speed' while any conflict in which the vehicle speed was 11.5 mph or greater was coded as 'high vehicle speed'. These speed categories were combined with the previously described severity categories based on PET. **Table 17** shows the number of conflicts in each category for each site during the Before and After phases.

Figure 32 illustrates the distribution of high and low-speed conflicts across high, medium, and low severity categories. The graph shows a reduction in high-speed conflicts for all severity categories following LPI implementation. This suggests that the LPI treatment was effective in reducing both high-speed and high-severity conflicts.

Table 17: Summary of Conflict Observations by PET-Vehicle Speed Severity

Site ID	PET-Veh Speed Severity Category (1=most severe)											
	1		2		3		4		5		6	
	PET ≤ 1.5 sec, High Vehicle Speed		PET ≤ 1.5 sec, Low Vehicle Speed		PET > 1.5-3.5 sec, High Vehicle Speed		PET > 1.5-3.5 sec, Low Vehicle Speed		PET > 3.5-5 sec, High Vehicle Speed		PET > 3.5-5 sec, Low Vehicle Speed	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
1	5	1	2	2	47	12	24	32	44	13	30	22
2	6	1	8	0	74	14	88	21	82	32	60	22
3	23	12	32	22	57	60	64	89	61	84	37	69
4	6	3	21	1	43	40	50	66	38	49	31	51
5	9	3	9	3	47	30	44	52	40	27	22	43
6	4	2	5	4	29	23	83	44	54	38	64	74
7	3	4	12	5	33	22	59	59	21	11	31	34
8	4	3	9	14	48	22	57	46	31	20	43	33
Total	60	29	98	51	378	223	469	409	371	274	318	348

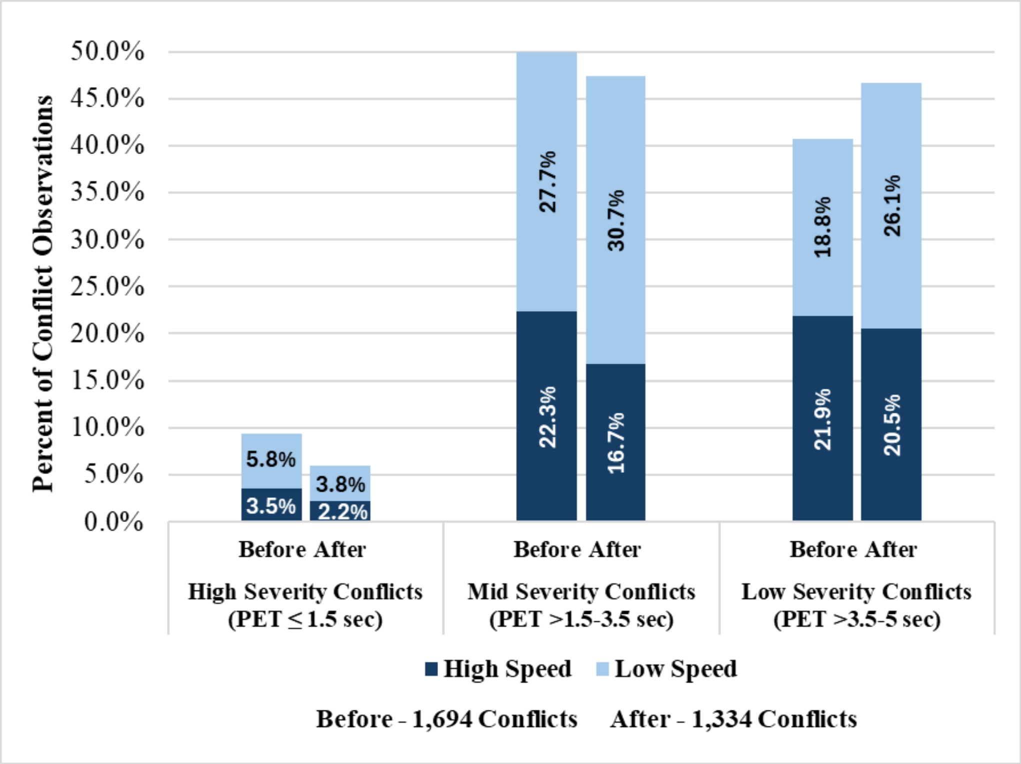


Figure 32: Conflicts distribution considering PET-vehicle speed severity Before and After LPI implementation.

Additionally, since these conflicts involve pedestrian and turning vehicles, the average hourly volume of pedestrian and turning vehicles is provided for reference in **Table 18,** which provides a high-level summary of average hourly vehicle volumes by turning movement at each study approach, along with average hourly pedestrian volumes. Note that the values represent averages across all 10 hours (7am-5pm) at each site.

Table 18: Summary of Average Hourly Volumes at Study Approaches

Site ID	Avg. Hourly Protected Left Turn Veh Volume		Avg. Hourly Permitted Left Turn Veh Volume		Avg. Hourly Right Turn Veh Volume		Avg. Hourly Pedestrian Volume	
	Before	After	Before	After	Before	After	Before	After
1	0	0	54.3	89.3	0	0	64.8	43.3
2	0	0	0	0	73.5	49.2	85.8	46.1
3	94.3	134	52.8	20	341.2	367.2	26.3	35.6
4	135.4	148.4	54.8	45.9	297.1	306.9	19.5	27.6
5	60	67.8	46.8	41.2	223.6	226.2	22.9	27.4
6	98.3	102.5	50.5	44.5	257.3	270.9	32.5	34
7	141.8	144.4	56.5	38.2	270.8	247.3	25.4	20.3
8	147.8	167.3	81.8	61.5	258.3	238.1	28.3	23.2

Table 19 provides a summary of pedestrian and vehicle characteristics during interactions. At most of the sites, the intervention resulted in an overall decrease in mean vehicle speeds; only site 2 showed a slight increase. There are more conflicts associated with right-turning vehicles compared to left-turning vehicles. The reason is the presence of protected and permitted left turning phases in the traffic signal operations across most sites, except for sites 1 and 2.

Table 19: Summary of pedestrian and vehicle speed, vehicle direction and pedestrian location during interactions

Site ID	Mean vehicle speed (mph)		Mean Pedestrian Speed (ft/sec)		No. of Conflicts with Left Turning Vehicle		No. of Conflict with Right Turning Vehicle		No. of Conflict when Pedestrians in Near Side		No. of Conflict when Pedestrians in Far Side	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
1	12.3	10.5	5.09	6.17	152	84	0	0	68	33	84	49
2	11.5	14.4	5.06	5.116	0	0	318	90	179	42	139	48
3	12.2	11.05	6.23	5.81	33	61	241	275	144	184	130	152
4	11.5	12.48	6.18	5.66	42	32	147	178	116	121	73	89
5	11.4	11.49	5.09	5.37	24	34	147	124	103	94	68	64
6	10.5	10.67	5.39	5.76	43	36	195	149	88	64	151	121
7	10.8	9.66	5.11	5.37	40	28	119	107	54	46	105	89
8	12.7	10.51	5.292	5.62	34	7	158	131	82	80	110	58

Table 20 provides insights into the behaviors of drivers and pedestrians involved in conflicts at all sites, focusing on first unit to arrive, compliance with traffic rules, and evasive actions taken. In a traffic conflict, identifying the first unit to arrive helps in determining who had the right of way or who should have yielded. The data indicated that most conflicts involved pedestrians arriving at the conflict area first which emphasize the importance of giving pedestrians a head start to increase their visibility to drivers. The traffic signals were visually identified by the research team from the video recordings. For some intersections, the traffic lights and signs of our interest were not covered by the video camera of that intersection. In some cases, direct sunlight on or near the traffic lights made it difficult to see them properly. It was easy to identify the status of those traffic lights in the morning and evening but not in the afternoon. In the afternoon, assumptions regarding the status of a traffic light based on the lights or movement of traffic on the crossroad or overall traffic direction were made. Indistinguishable cases were labeled as unknown. As such, there may be a margin of error in the results of **Table 20**.

Table 20: Summary of conflict-involved pedestrian and vehicle behavior by first unit arrival, compliance with traffic rules, and evasive actions.

Variable	Before		After LPI	
	Count	%	Count	%
First Unit				
Pedestrian	1167	68.9%	865	64.8%
Bicyclist	93	5.5%	75	5.6%
Passenger Vehicle	405	23.9%	379	28.4%
Heavy Vehicle	11	0.6%	4	0.3%
Scooter	18	1.1%	11	0.8%
Driver Violation				
No Violation	1562	92.2%	1198	89.8%
Rolling Stop	27	1.6%	68	5.1%
Stopping Inside Crosswalk	75	4.4%	47	3.5%
Red Light Running	14	0.8%	17	1.3%
Others	16	0.9%	4	0.3%
Driver Evasive Action				
None	1633	96.4%	1321	99.0%
Hard Braking	24	1.4%	13	1.0%
Other	37	2.2%	0	0%
Pedestrian Starts Crossing at				
WALK	1309	77.3%	772	57.9%
FDW	144	8.5%	149	11.2%
SDW	190	11.2%	182	13.6%
Unknown	51	3.0%	232	17.4%
Pedestrian Evasive Action				
None	1640	96.8%	1282	96.1%
Hard Stopping	17	1.0%	8	0.6%
Hard Swerving	6	0.4%	19	1.4%
Others	31	1.8%	25	1.9%
Pedestrian Distraction				
No Distraction	1600	94.5%	1295	97.1%
Talking on cell	11	0.6%	17	1.3%
Texting on cell	42	2.5%	11	0.8%
Headphones	20	1.2%	6	0.4%
Others	22	1.3%	5	0.4%
Pedestrian Crosswalk Violation	426	25.1%	369	27.7%
Total Conflicts	1694	100%	1334	100%

Table 21 presents demographic details of pedestrians involved in conflicts across all sites, including group size, age, gender, and use of mobility devices. Gender and age group of a

pedestrian were assumed based on their appearance by the research team. The research team used their best judgment to accomplish this. In cases where demographic detail could not be observed, the variable was coded by the research team as ‘Unknown.’ Furthermore, it's important to note that these are assumed genders and ages, subject to a margin of error, and the actual gender or age of some individuals may differ. Note that making assumptions based on appearance is not uncommon in safety research (Stipancic et al., 2016) when precise demographic information is not available. Site-specific statistics for the variables are presented in Appendix I: Summary of Variables in Before and After Phases for Each Site.

Table 21: Demographic and Mobility Characteristics of Conflict-Involved Pedestrians

Variable	**Before**		**After LPI**	
	Mean	**SD**	**Mean**	**SD**
Pedestrian Group Size	1.7	1.2	1.7	1.2
	Count	**%**	**Count**	**%**
Pedestrian Age				
Child	55	3.2%	26	1.9%
Adult	1540	90.9%	1255	94.1%
Older Adult	72	4.3%	47	3.5%
Unknown	27	1.6%	6	0.4%
Pedestrian Gender				
Male	1038	61.3%	853	63.9%
Female	547	32.3%	394	29.5%
Unknown	109	6.4%	87	6.5%
Pedestrian with Additional Mobility Device				
None	1463	86.4%	1149	86.1%
Device Ridden	118	7.0%	85	6.4%
Device Walked	46	2.7%	53	4.0%
Walking Aid	21	1.2%	16	1.2%
Stroller	27	1.6%	21	1.6%
Others	19	1.1%	10	0.7%

4.4.2 Analysis of Field Observed Conflict and Volume Data

This subsection provides an analysis of factors related to the frequency and severity of pedestrian-vehicle conflicts reduced from the field-collected videos to assess LPI treatment.

4.4.2.1 Analysis of Pedestrian-Vehicle Conflict Frequencies

Understanding the impact of various factors, such as pedestrian and turning vehicle volumes, is crucial when assessing the effectiveness of specific treatments on the frequency of conflicts between pedestrians and vehicles. To quantitatively explore this impact, a series of regression models were developed using data from field observations.

Given the discrete, non-negative nature of the conflict frequency data (i.e., count data), Negative Binomial (NB) regression was considered for this analysis. This modeling framework is appropriate for this type of data and has been employed in previous studies analyzing conflict frequency (Russo et al., 2023; Sacchi & Sayed, 2016). The NB regression model equation is derived from the general form of the Poisson regression model, with the Poisson parameter being the number of predicted pedestrian crashes for an intersection. The NB model is derived from the Poisson with the following Equation 13 (Washington et al., 2011):

$$\boldsymbol{\lambda_i = EXP(\beta X_i + \varepsilon_i)} \qquad \text{Equation 13}$$

where:
λ_i: Poisson parameter for intersection i (predicted number of pedestrian conflicts per intersection)
β: vector of estimable parameters
Xi: vector of explanatory variables (i.e., intersection/roadway characteristics, AADT, etc.)
EXP(ε_i): gamma-distributed error term

To prepare the data for this analysis, conflict frequency, turning vehicle volumes, and pedestrian volumes were summarized by the hour for each site. An LPI indicator variable was included in the model to assess the impact of this treatment. The LPI indicator variable was set to 0 for all conflicts occurring before the LPI implementation and 1 for all conflicts occurring after the LPI implementation. Hourly conflict frequency was then modeled as a function of hourly turning vehicle volumes, hourly pedestrian volumes, and the LPI indicator variable.

4.4.2.1.1 <u>Pedestrian-Vehicle Conflict (PET ≤ 5sec) Frequencies</u>

The analysis presented earlier evaluates the effectiveness of LPI in reducing pedestrian-vehicle conflicts with PET of 5 seconds or less. Several regression models were estimated to determine the impact of different combinations of turning vehicles on conflict frequencies. The first model includes all turning vehicles, including right turns, protected left turns, and permitted left turns. To understand the specific impacts of turning movements that are more likely to conflict with pedestrians, the second and third model focuses on right turns and permitted left turns, excluding protected left turns.

Across all models, LPI indicator is found significantly associated with hourly conflict frequency at greater than a 99.9% confidence level (p-values < 0.001) with a negative parameter estimate indicating a decrease in conflicts after LPI implementation. The expected percent change in pedestrian crash frequency was calculated for LPI indicator variable using the model results. LPI is found to reduce almost 10 to 15% hourly pedestrian-turning vehicle conflicts. Additionally, hourly pedestrian volume and turning vehicle volume are also found significantly associated with hourly conflict frequency.

Table 22: Results of NB Models for Pedestrian-Vehicle Conflict (PET ≤ 5sec) Frequencies

Variable	**Estimate**	**Std. Error**	**P-Value**	**Predicted % Change in Conflicts after LPI**
All Turning Vehicles including Right Turns and Protected and Permitted Left Turns				
Intercept	1.174	0.1222	<0.001***	
LPI presence	**-0.157**	0.0599	<0.001***	**-14.53%**
Total turning vehicle	0.0027	0.0002	<0.001***	
Pedestrian volume	0.022	0.0015	<0.001***	
Conflicting Turning Vehicles including Right Turns and Permitted Left Turns				
Intercept	1.0298	0.1214	<0.001***	
LPI presence	**-0.1122**	0.0566	0.05**	**-10.62%**
Permitted left and right turning vehicle	0.0041	0.0003	<0.001***	
Pedestrian Volume	0.0222	0.0014	<0.001***	
Permitted left and right turning vehicles separately				
Intercept	1.1548	0.136	<0.001***	
LPI presence	**-0.1324**	0.0569	0.02**	**-12.40%**
Permitted left turning vehicle	0.0021	0.0011	0.06*	
Right turning vehicle	0.0041	0.0003	<0.001***	
Pedestrian volume	0.0213	0.0015	<0.001***	

Note: *, **, and *** denotes variable is significant at 90%, 95%, and 99% confidence level, respectively

4.4.2.1.2 High Severity Pedestrian-Vehicle Conflict Frequencies

In this subsection, the impact of LPI on severe conflicts are analyzed, as these conflicts are closer to a collision occurring between two users. Considering that conflicts with PET values ≤ 1.5 seconds are considered the most critical interactions, models were developed to estimate the frequency of these incidents. Across all three models, the LPI indicator consistently demonstrates a significant negative association with conflict frequency, leading to a substantial predicted reduction in severe conflicts ranging from approximately 44.29% to 49.82% after LPI implementation.

Table 23 :Results of NB Models for low PET Pedestrian-Vehicle Conflict (PET ≤ 1.5sec) Frequencies

Variable	Estimate	Std. Error	P-value	Predicted % Change in Conflicts after LPI
All Turning Vehicles including Right Turns and Protected and Permitted Left Turns				
Intercept	-1.357	0.364	<0.001***	
LPI presence	**-0.673**	0.171	<0.001***	**-48.97%**
Total turning vehicle	0.004	0.001	<0.001***	
Pedestrian volume	0.012	0.005	<0.001***	
Conflicting Turning Vehicles including Right Turns and Permitted Left Turns				
Intercept	-1.626	0.371	<0.001***	
LPI presence	**-0.585**	0.165	<0.001***	**-44.29%**
Permitted left and right turning vehicle	0.006	0.001	<0.001***	
Pedestrian Volume	0.013	0.004	<0.001***	
Permitted left and right turning vehicles separately				
Intercept	-1.129	0.421	<0.001***	
LPI presence	**-0.690**	0.170	<0.001***	**-49.82%**
Permitted left turning vehicle	-0.002	0.004	0.69	
Right turning vehicle	0.006	0.001	<0.001***	
Pedestrian volume	0.009	0.005	0.05**	

Note: *, **, and *** denotes variable is significant at 90%, 95%, and 99% confidence level, respectively

It is also possible to assess the severity of a conflict considering both PET and vehicle speed, as presented in **Table 17** and **Figure 32**. In this context, a conflict with both a low PET (≤ 1.5 sec) and a high vehicle speed would be considered most severe, while a conflict with a higher PET (> 3.5-5 sec) and a low vehicle speed would be considered least severe. The model results for low PET high-speed pedestrian-vehicle conflict frequencies are presented in **Table 24**. Estimates of LPI indicator remain consistently negative and highly significant coefficients across all scenarios. The presence of LPI is associated with a notable reduction in severe conflicts, approximately 50%, consistent with previous model results. These consistent findings reinforce the effectiveness of LPI in reducing severe conflicts.

Table 24: Results of NB Models for Low PET High-Speed Pedestrian-Vehicle Conflict Frequencies

Variable	Estimate	Std. Error	P-value	Predicted % Change in Conflicts after LPI
All Turning Vehicles including Right Turns and Protected and Permitted Left Turns				
Intercept	-2.341	0.525	<0.001***	
LPI presence	**-0.690**	0.250	0.006***	**-49.86%**
Total turning vehicle	0.004	0.001	<0.001***	
Pedestrian volume	0.018	0.006	0.003***	
Conflicting Turning Vehicles including Right Turns and Permitted Left Turns				
Intercept	-2.673	0.541	<0.001***	
LPI presence	**-0.632**	0.244	<0.001***	**-46.83%**
Permitted left and right turning vehicle	0.006	0.001	<0.001***	
Pedestrian Volume	0.020	0.006	0.001***	
Permitted left and right turning vehicles separately				
Intercept	-2.308	0.630	<0.001***	
LPI presence	**-0.712**	0.256	0.005***	**-50.92%**
Permitted left turning vehicle	0.00004	0.006	0.99	
Right turning vehicle	0.006	0.001	<0.001***	
Pedestrian volume	0.017	0.006	0.008***	

Note: *, **, and *** denotes variable is significant at 90%, 95%, and 99% confidence level, respectively

4.4.2.1.3 Model Predicted Conflicts

The model results presented in **Table 22**, **Table 23**, and **Table 24** can be used to predict hourly conflict frequency across different ranges of pedestrian and turning vehicle volumes using **Equation 14**. **Figure 33** illustrates the NB model predicted hourly conflicts for various combinations of hourly turning vehicle volumes (including right turns and protected and permitted left turns) and hourly pedestrian volumes, with and without LPI treatment.

$$N_{predicted\_crashes} = exp[\beta_0 + (\beta_1 * X_1) + (\beta_i * X_i)] \quad \textbf{Equation 14}$$

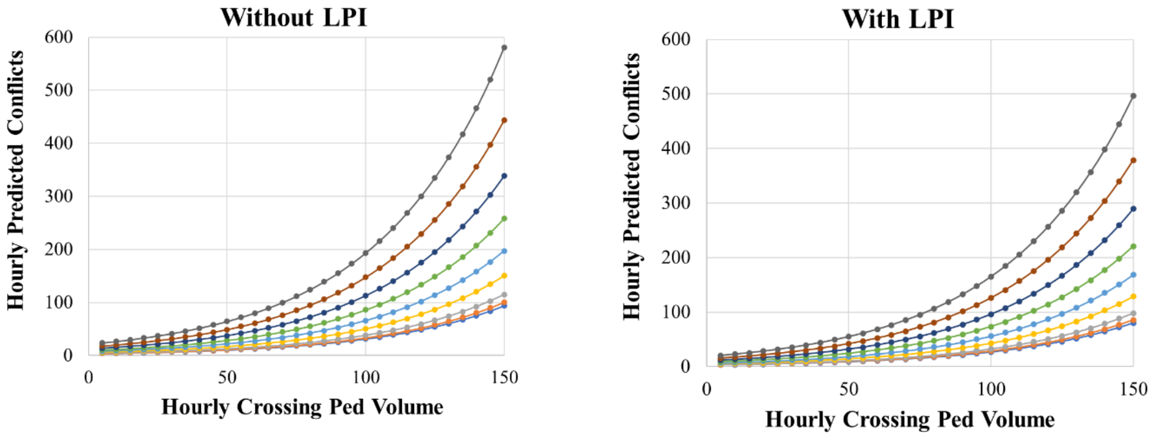
Where:

$N_{predicted\_crashes}$ = Predicted pedestrian crash frequency per intersection
β_0 = Model-estimated intercept term
β_1 = Model-estimated coefficient for explanatory variable X_1
β_i = Model-estimated coefficient for explanatory variable X_i

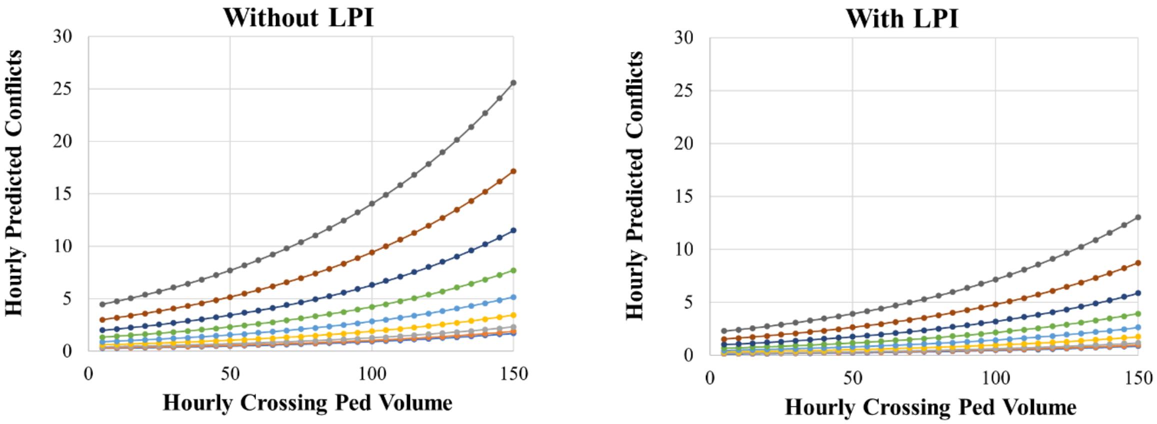
For the graph without LPI, the LPI indicator value is set to 0, while for the graph with LPI, it is set to 1. The predicted hourly conflict frequencies are plotted across ranges of 5 to 150 pedestrians crossing per hour and 25 to 700 turning vehicles per hour (vph). These ranges were chosen because the hourly pedestrian volumes across all sites ranged from a minimum of 6 to a maximum of 122, and the hourly turning vehicle volumes ranged from a minimum of 36 to a maximum of 655.

From this figure, it is evident that lower predicted conflict counts are observed with LPI treatment across all volume ranges. Specially, LPI has a more substantial impact on reducing severe conflicts. Predicted conflicts increase markedly when hourly turning vehicles exceed 200 vph and pedestrian volume exceed 100 per hour. These volume ranges from the graphs will be used to establish threshold values for turning vehicle and pedestrian volume in Phoenix LPI implementation guidelines.

Predicted Counts of Conflicts of PET ≤ 5sec



Predicted Counts of Low PET Conflicts



Predicted Count of Low PET High Speed Conflicts

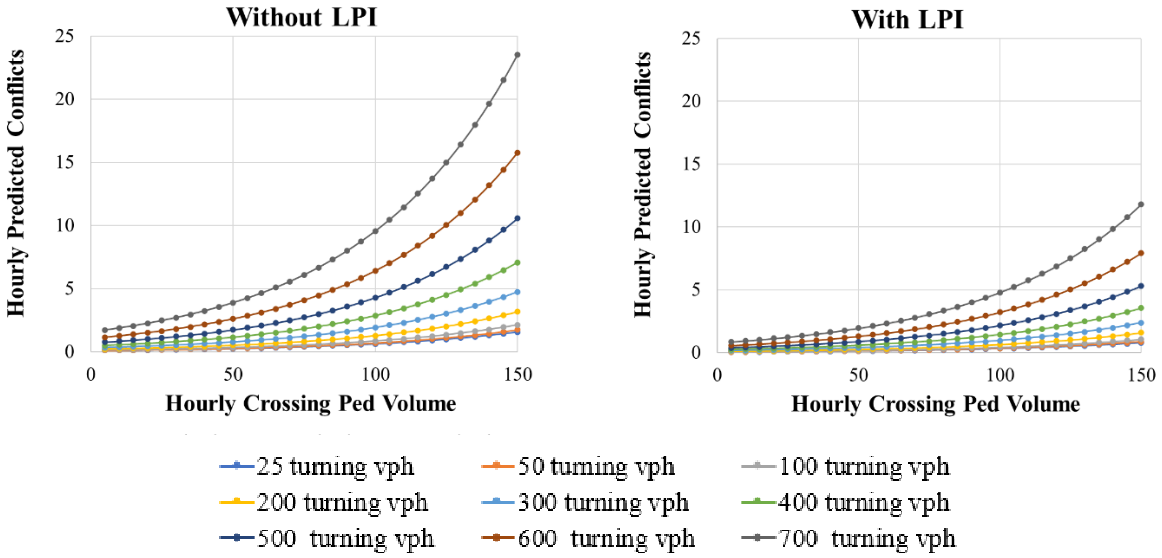


Figure 33: Predicted hourly conflict frequency with and without LPI treatment.

4.4.2.2 Analysis of Pedestrian-Vehicle Conflict Severities

The section will analyze factors potentially associated with conflict severity including PET values, vehicle speeds, and other factors mentioned in **Section 4.4.1**. The severity of each observed conflict (with PET ≤ 5 sec) was categorized into one of three discrete categories as shown in **Table 16**:

- High severity conflict: PET ≤ 1.5 sec
- Medium severity conflict: PET > 1.5 to 3.5 sec
- Low severity conflict: PET > 3.5 to 5 sec

As discussed previously, the thresholds for these severity categories are based on previous research (Russo et al., 2023; Zangenehpour et al., 2016), and high severity conflicts are considered potentially dangerous interactions while low severity conflicts are considered mild interactions. As such, it is important to assess the effectiveness of pedestrian treatments in reducing severe conflicts.

To statistically explore whether LPI treatment is significantly associated with reducing conflict severity, an ordered logit model was estimated. In this context, if a conflict occurs, the ordered logit model will analyze the predicted probability that the conflict is high, medium, or low severity as a function of independent variables. This modeling framework is appropriate given the discrete ordered nature of the conflict severity data (low severity, medium severity, high severity). In estimating an ordered logit model, a latent variable z is specified for modeling the ordered ranking of the conflict severity data such that (Washington et al., 2011):

$$\boldsymbol{Z = \beta X + \varepsilon} \qquad \textbf{Equation 15}$$

where:

X: vector of variables determining the discrete ordering for each conflict severity observation
β: vector of estimable parameters (e.g., treatment type)
ε: disturbance term

The observed ordered data, y, for each conflict observation is then defined as:

$$\boldsymbol{y = 1\,(PET > 3.5 - 5\,sec)\ if\ z \leq \mu 1,} \qquad \textbf{Equation 16}$$

$$\boldsymbol{y = 2\,(PET > 1.5 - 3.5\,sec)\ if\ \mu 1 < z \leq \mu 2,} \qquad \textbf{Equation 17}$$

$$\boldsymbol{y = 3\,(PET \leq 1.5\,sec)\ if\ z > \mu 2,} \qquad \textbf{Equation 18}$$

where:

μ_i: estimable threshold parameters that define *y*, which corresponds to the ordered conflict severity categories.

The μ thresholds are parameters that are estimated jointly with the model parameters β. Ultimately, of most interest are the signs of the β parameters for each independent variable; a positive β indicates that variable tends to increase the probability of a severe conflict, while the opposite is true for a negative β estimate. **Table 25** shows the results of the ordered logit model.

Table 25: Results of Ordered Logit Conflict Severity Model (N=3018)

Variables	Estimate	Std. Error	P-Value
LPI Indicator	-0.33	0.08	<0.001***
Vehicle Direction - Left (Ref.)			
Vehicle Direction - Right	0.29	0.09	0.002***
Pedestrian Temporal Location - Far Side (Ref.)			
Pedestrian Temporal Location - Near Side	0.35	0.07	<0.001***
Pedestrian Starts Walking at WALK (Ref.)			
Pedestrian Starts Walking at FDW	0.13	0.12	0.304
Pedestrian Starts Walking at SDW	0.52	0.12	<0.001***
Pedestrian Starts Walking at Unknown	-0.05	0.13	0.672
Pedestrian Speed	0.10	0.02	<0.001***
Driver Violation - None (Ref.)			
Driver Violation - Red Light Running	0.23	0.37	0.540
Driver Violation - Rolling Stop	0.55	0.21	0.010**
Driver Violation - Stopping inside Crosswalk	0.42	0.19	0.026**
Driver Violation - Other	1.87	0.46	<0.001***
Driver Evasive Action - None (Ref.)			
Driver Evasive Action - Hard Braking	0.92	0.33	0.005***
Driver Evasive Action - Hard Swerving	2.15	1.50	0.152
Driver Evasive Action - Other	0.93	0.34	0.007***
Pedestrian Evasive Action - None			
Pedestrian Evasive Action - Hard Stopping	0.79	0.43	0.067*
Pedestrian Evasive Action - Hard Swerving	0.93	0.41	0.022**
Pedestrian Evasive Action - Other	0.64	0.28	0.019**
Pedestrian Group Size	-0.21	0.03	<0.001***
Pedestrian Gender Female			
Pedestrian Gender Male	0.16	0.08	0.034**
Low Severity | Mid Severity	0.41	0.15	
Mid Severity | High Severity	3.32	0.17	
Restricted Log-Likelihood (LL)		-2657.273	
LL at convergence		-2636.273	

Note: *, **, and *** denotes variable is significant at 90%, 95%, and 99% confidence level, respectively

Table 26 presents the marginal effect of each variable in three severity level from model results. Marginal effects show how each variable influences the likelihood of observing different severity levels of conflicts. Interpreting results of marginal effects for positive coefficients in **Table 25** is done as follows: one unit increase of X variable would shift the threshold to the left, thereby increasing the probability of a high severity conflict, and the opposite effect (i.e., right shifting of the probability density) for variables with negative coefficients. For example, if a pedestrian was crossing in Solid Don't Walk (SDW), the probability of a high severity pedestrian- vehicle conflict increased by 4%, all else being equal.

Table 26: Marginal Effects of Variables in Ordered Logit Model

	High Severity	**Medium Severity**	**Low Severity**
LPI Indicator***	**-0.021**	**-0.06**	**0.082**
Vehicle Direction - Left (Ref.)			
Vehicle Direction - Right***	0.017	0.054	-0.072
Pedestrian Temporal Location - Far Side (Ref.)			
Pedestrian Temporal Location - Near Side***	0.023	0.064	-0.086
Pedestrian Starts Walking at WALK (Ref.)			
Pedestrian Starts Walking at FDW	0.009	0.022	-0.031
Pedestrian Starts Walking at SDW***	0.04	0.082	-0.122
Pedestrian Starts Walking at Unknown	-0.003	-0.01	0.013
Pedestrian Speed***	0.006	0.018	-0.024
Driver Violation - None (Ref.)			
Driver Violation - Rolling Stop**	0.044	0.082	-0.125
Driver Violation - Stopping inside Crosswalk**	0.031	0.066	-0.097
Driver Violation - Other***		0.071	-0.324
Driver Evasive Action - None (Ref.)			
Driver Evasive Action - Hard Braking***	0.087	0.111	-0.198
Driver Evasive Action - Other***	0.088	0.112	-0.2
Pedestrian Evasive Action – None (Ref.)			
Pedestrian Evasive Action - Hard Stopping*	0.07	0.103	-0.173
Pedestrian Evasive Action - Hard Swerving**	0.089	0.111	-0.2
Pedestrian Evasive Action - Other**	0.054	0.092	-0.146
Pedestrian Group Size***	-0.013	-0.038	0.051
Pedestrian Gender Female (Ref.)			
Pedestrian Gender Male**	0.01	0.029	-0.039

The ordered logit model results, which examine the severity of conflicts (low, medium, and high), further support the efficacy of LPIs in reducing conflict severity. LPI indicator demonstrated a significant reduction in the likelihood of high-severity conflicts ($p < 0.001$). The marginal effects indicate that LPIs decrease the probability of high and medium severity conflicts by 2.1% and 6%, respectively. This aligns with previous studies that show LPIs' effectiveness in reducing severe conflict incidents (Arun et al., 2023; Y. Guo et al., 2020).

Several other variables were also analyzed and found to be significantly associated with severe turning vehicle-pedestrian conflicts. Compared to left-turning vehicles, right-turning vehicles were found to increase the probability of high and medium severity conflicts, likely due to the presence of protected and permitted left-turn phases at most sites. Pedestrians crossing from the near side were associated with a 2.3% increase in high severity conflicts compared to those crossing from the far side. This increased risk could be a result of reduced time available for both the pedestrian and driver to react when crossing near the approaching vehicle.

Understandably, pedestrians initiating crossings during SDW signals were found associated with increased severity of conflicts. Pedestrians who begin walking during these prohibited phases significantly increase the chance of severe conflicts probably because their movements are unexpected to drivers. Rolling Stops were associated with a 4.4% increase in high severity conflicts and Stopping inside the Crosswalk increased high severity conflicts by 3.1%. The category "Other" driver violations also had a pronounced effect; however, this value could be exaggerated because of the small sample size (1.2%). These results indicate that driver non-compliance with traffic rules, especially unexpected or aggressive behaviors, significantly elevates the chance of severe pedestrian conflicts.

Driver and pedestrian evasive actions were associated with an increase in high severity conflicts. These evasive actions likely occur in response to imminent danger, which inherently correlates with higher severity conflicts. In contrast, larger pedestrian group sizes significantly decreased conflict severity. This result may be due to the increased visibility and predictability of larger groups, making it easier for drivers to notice and yield to them. Lastly, pedestrian gender was another significant predictor in high severity conflicts. Male pedestrians had a higher probability of high severity conflicts compared to female pedestrians. This difference could reflect variations in risk-taking behaviors or exposure patterns between genders.

4.5 Before and After Evaluation of NRTOR Restriction

The NRTOR treatment was evaluated at Baseline and at the 51st West crosswalk (Site 8) for East Bound Right Turn (EBRT) traffic or crossing right turn traffic. Adjacent right turns on red were permitted. The LPI treatment was also assessed for this crosswalk separately. Both treatments aimed to reduce pedestrian-vehicle conflicts, with similar variables collected for each treatment.

Table 27 provides an overview of observed turning vehicle-pedestrian conflict for NRTOR evaluation. Initially, there were 192 total conflicts (with PET ≤ 5 seconds) before any treatments were applied. After implementing NRTOR, this number dropped significantly to 139, indicating a 28% reduction in overall conflicts. Similarly, the LPI treatment resulted in a reduction, bringing the total conflicts down to 138, which is a 28.1% reduction. Low and medium severity conflicts reduced following the NRTOR restriction, but the reduction in high-severity conflicts (PET ≤ 1.5 seconds) was not substantial. Conflict severity is also categorized considering PET and vehicle speed, as mentioned in **Section 4.4.1**, with results provided in **Table 27**. The data shows that the most significant reductions occurred in high vehicle speed scenarios for both medium and low severity conflicts.

Table 27: Summary of Observed Pedestrian-Vehicle Conflicts at Site 8

Variables	Before	After NRTOR	After LPI
Total Conflicts (PET ≤ 5 sec)	192	139	138
High Severity Conflicts (PET ≤ 1.5 sec)	13	12	17
Medium Severity Conflicts (PET >1.5-3.5 sec)	105	84	78
Low Severity Conflicts (PET >3.5-5 sec)	74	43	43

Table 28: Summary of Conflict Observations at Site 8 by PET-Vehicle Speed Severity

PET-Veh Speed Severity Category (1=most severe)		Before	After NRTOR	After LPI
1	PET ≤ 1.5 sec, High Vehicle Speed	4	3	3
2	PET ≤ 1.5 sec, Low Vehicle Speed	9	9	14
3	PET > 1.5-3.5 sec, High Vehicle Speed	48	25	22
4	PET > 1.5-3.5 sec, Low Vehicle Speed	57	59	46
5	PET > 3.5-5 sec, High Vehicle Speed	31	12	20
6	PET > 3.5-5 sec, Low Vehicle Speed	43	31	33

It is also essential to consider pedestrian and traffic volumes in assessing any treatment's effectiveness. **Table 29** provides the average hourly volume of pedestrians and turning vehicles. It was observed that there were fewer pedestrians and less turning vehicle volume on the day of the NRTOR evaluation compared to the baseline phase. These decreases in traffic volumes suggest that the observed reduction in conflicts could be partly due to fewer vehicles on the road, potentially lowering interactions between vehicles and pedestrians. Therefore, to accurately evaluate the efficacy of the NRTOR treatment in reducing conflicts, volume data must be carefully analyzed. Crash frequency models can be developed to quantify the impact of volume on conflict frequency, as demonstrated for the LPI treatment in **Section 4.4.2.1**. However, the dataset is restricted to observations from a single day at one site for NRTOR evaluation. More comprehensive data from various sites is necessary for a complete evaluation.

Another important consideration in assessing this treatment is compliance, as NRTOR is a restrictive measure. The effectiveness of NRTOR largely depends on driver adherence to the restriction. Despite the prohibition on crossing right turns under NRTOR, violations still occurred, with an average of 14.7 vehicles turning on red per hour—a number even higher than the 12.9 crossing right turning vehicles on green. It suggests that among the 27.6 hourly crossing right-turning vehicles, more than 50% of those violated the NRTOR restriction. This suggests that the effectiveness of NRTOR is compromised by driver non-compliance.

Table 29: Summary of Hourly Pedestrian and Vehicle Volume at Site 8

Variables	Before	After NRTOR	After LPI
Average Hourly Pedestrian Volume	28.3	6.5	23.2
Average Hourly Turning Vehicle Volume	258.3	126.6	238.1
Average Hourly Crossing Right Turning Vehicle in Red (Restricted for NRTOR)	47.2	14.7	60.0
Average Hourly Crossing Right Turning Vehicle in Green	62.6	12.9	47.6
Average Hourly Adjacent Right Turning Vehicle	148.5	42	129.7
Average Hourly Permitted Left Turning Vehicle	81.8	15.3	61.5

In addition to traffic and pedestrian volumes, other conflict characteristics were collected and are presented in **Table 30**. Following the implementation of NRTOR, vehicle speed decreased while pedestrian speed remained constant. Despite the restriction on right turns for EBRT, there were still a considerable number of conflicts involving right-turning vehicles, while conflicts with left-turning vehicles were notably fewer.

Table 30: Summary of pedestrian and vehicle speed, vehicle direction and pedestrian location during interactions at Site 8

	Before	After NRTOR	After LPI
Mean vehicle speed (mph)	12.7	9.7	10.51
Mean Pedestrian Speed (ft/sec)	5.3	5.3	5.6
No. of Conflicts with Left Turning Veh	34	24	7
No. of Conflict with Right Turning Veh	158	115	131
No. of Conflict when Pedestrians in Near Side	82	60	80
No. of Conflict when Pedestrians in Far Side	110	79	58

Conflict involved driver and pedestrian's behavior, compliance with traffic rules were collected and present in **Table 31**. **Table 32** represents the demographic distribution of the conflict-involved pedestrians. Driver violation increased after NRTOR implementation. 16.5% of drivers involved in conflicts were found to have violated the restriction. If drivers were fully compliant to the restrictive measure, possibly these 16.5% conflicts on that crosswalk could have been avoided.

Table 31: Summary of conflict-involved pedestrian and vehicle behavior by first unit arrival, compliance with traffic rules, and evasive actions.

Variable	Before		After NRTOR		After LPI	
	Count	%	Count	%	Count	%
Driver Violation						
No Violation	191	99.5%	116	83.5%	134	97.1%
NRTOR violation	**-**	**-**	**23**	**16.5%**	**-**	**-**
Stopping Inside Crosswalk	1	0.5%	0	0%	4	2.9%
Rolling Stop	0	0%	6	4.3%	0	0%
Others	0	0%	0	0%	0	0%
First Unit						
Pedestrian	138	71.9%	95	68.3%	94	68.1%
Bicyclist	7	3.6%	5	3.6%	8	5.8%
Passenger Vehicle	45	23.4%	34	24.5%	34	24.6%
Heavy Vehicle	0	0%	2	1.4%	0	0%
Scooter	2	1.0%	3	2.2%	2	1.4%
Driver Evasive Action						
None	191	99.5%	139	100.0%	138	100.0%
Hard Braking	0	0%	0	0%	0	0%
Other	1	0.5%	0	0%	0	0%
Pedestrian Start Crossing at						
WALK	170	88.5%	78	56.1%	94	68.1%
FDW	8	4.2%	22	15.8%	23	16.7%
SDW	14	7.3%	39	28.1%	21	15.2%
Unknown	0	0%	0	0%	0	0%
Pedestrian Evasive Action						
None	192	100.0%	133	95.7%	138	100.0%
Hard Stopping	0	0%	0	0%	0	0%
Hard Swerving	0	0%	0	0%	0	0%
Others	0	0%	6	4.3%	0	0%
Pedestrian Distraction						
No Distraction	186	96.9%	131	94.2%	137	99.3%
Talking on cell	1	0.5%	1	0.7%	0	0%
Texting on cell	0	0%	2	1.4%	1	0.7%
Headphones	4	2.1%	0	0%	0	0%
Others	2	1.0%	5	3.6%	0	0%
Pedestrian Crosswalk Violation	35	18.2%	35	25.2%	8	5.8%
Total Conflicts	**192**	**100.00%**	**139**	**100%**	**138**	**100%**

Table 32: Demographic and Mobility Characteristics of Conflict-Involved Pedestrians at Site 8

Variable	Before		After NRTOR		After LPI	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Pedestrian Group Size	1.6	0.8	1.7	0.8	1.8	1.1
	Count	**%**	**Count**	**%**	**Count**	**%**
<u>Pedestrian Age</u>						
Child	5	3%	7	5%	3	2%
Adult	186	97%	124	89%	133	96%
Older Adult	1	1%	8	6%	2	1%
Unknown	0	0%	0	0%	0	0%
<u>Pedestrian Sex</u>				0%		
Male	139	72%	84	60%	87	63%
Female	53	28%	50	36%	49	36%
Unknown	0	0%	5	4%	2	1%
<u>Pedestrian with Additional Mobility Device</u>						
None	172	90%	114	82%	128	93%
Device Ridden	10	5%	4	3%	0	0%
Device Walked	4	2%	11	8%	10	7%
Walking Aid	3	2%	3	2%	0	0%
Stroller	3	2%	7	5%	0	0%
Others	0	0%	0	0%	0	0%

4.6 Summary and Discussion

This chapter described the site identification, video data collection and analysis of conflict data reduced from field-collected videos to perform a Before and After safety evaluation of LPI and NRTOR treatment. Eight study crosswalks from four intersections were identified through crash and volume analysis for video data collection. The evaluation included LPI assessment at each crosswalk and NRTOR restriction assessments at one crosswalk. LPIs were implemented for 5 seconds at each selected site. A total of 170 hours of video was collected for both the Before and After phases, 10 hours each day. Conflict data were manually reduced from field-collected videos, focusing on incidents where the PET was 5 seconds or less. Conflicts were categorized into high, medium, and low severity based on PET thresholds, with high severity defined as PET $\leq$ 1.5 seconds.

LPI Evaluation: A significant reduction in both the total number of conflicts and their severity was observed after implementing the LPI treatments. Additionally, a new method to categorize conflict severity was used considering both PET and vehicle speed. Six severity categories were defined with the most severe being 'low PET-high vehicle speed' and least severe being 'high PET-low vehicle speed'. There was a marked decrease in high-severity conflicts, particularly those involving high vehicle speed conflicts following LPI implementation. Additionally, the data showed that right-turning vehicles were more frequently involved in conflicts compared to left-turning ones, likely due to the presence of protected and permitted left-turn phases at most sites. Furthermore, the average vehicle speeds generally decreased after the LPI treatment. The study also highlighted that most conflicts involved pedestrians arriving at the conflict area first, emphasizing the importance of giving pedestrians a head start to increase their visibility to drivers. Behavioral and demographic analyses revealed additional insights into the nature of these conflicts. The majority of conflicts involved adult pedestrians, with males more frequently involved than females.

A series of NB regression models were developed to evaluate the impact of LPI treatment on conflict frequencies, while accounting for pedestrian and turning vehicle volumes. Results consistently show a significant negative correlation between LPI implementation and conflict frequencies across various scenarios, with reductions ranging from approximately 10% to 15% for conflicts with PET ≤ 5 seconds and around 50% for severe conflicts (both for low PET and low PET high speed cases). The NB model results are used to predict hourly pedestrian-vehicle conflict frequencies with and without LPI treatment. Analysis indicates that LPI treatment significantly reduces conflict severity, especially in scenarios with high pedestrian (over 50 per hour) and turning vehicle volumes (over 200 vph). These reductions continue to increase as pedestrian volumes increase above 100 per hour, and turning vehicle volumes increase over 400 per hour.

In addition to conflict frequency, conflict severity was also analyzed. Results from the ordered logit model, which examine the severity of conflicts (low, medium, and high), further supports the efficacy of LPIs in reducing conflict severity. The LPI indicator demonstrated a significant reduction in the likelihood of high severity and medium severity conflicts. Factors contributing to increased conflict severity include right-turning vehicles, pedestrians crossing from the near side, initiating crossings during SDW signals, male pedestrian, driver violations like rolling stops, and evasive actions such as hard braking by drivers and hard stopping and swerving by pedestrians. Conversely, larger pedestrian group sizes were associated with lower severity conflicts.

NRTOR Evaluation: The NRTOR treatment was evaluated at the 51st and Baseline West crosswalk (Site 8) for EBRT traffic. The results showed a 28% decrease in conflicts of PET less than 5 sec with the NRTOR restriction in place; however, the reduction in high-severity conflicts was not substantial. The observed decrease in conflicts could be attributed to reduced average hourly turning vehicle volume and pedestrian volume during the NRTOR evaluation phase compared to the Before phase. However, more data are required to account for the impact of volume on conflict frequency and assess the treatment's effectiveness.

Another important consideration in assessing this treatment is compliance, as NRTOR is a restrictive measure. Despite the prohibition on crossing right turns under NRTOR, violations still occurred, with an average of 14.7 vehicles turning on red per hour—a number even higher than the 12.9 crossing right turns on green. Among the 27.6 hourly crossing right turning vehicles, more than 50% of those violated the NRTOR restriction. Moreover, driver violation increased after installing the NRTOR sign, with 16.5% of drivers involved in conflicts found to have violated the restriction. The study concludes that driver non-compliance compromises the effectiveness of NRTOR, and more comprehensive data from various sites is necessary for a complete evaluation.

The results presented in this chapter, as well as work presented in the crash analysis, will contribute towards data driven LPI implementation guidance. In particular, items such as crash history, intersection geometry and the built environment, pedestrian volume, and turning vehicle volumes have all been shown to be impactful in determining the level of pedestrian safety at a signalized intersection, and will be included in the developed guidance.

5 IMPLEMENTATION GUIDANCE

From the work conducted in this project, implementation guidance has been developed for LPIs within the City of Phoenix, in addition to recommendations for a Standard Operating Procedure for the pedestrian scramble.

5.1 Leading Pedestrian Interval

To determine whether an LPI should be Optional, Considered, or Recommended for a given pair of crosswalks, several steps will be followed. A flowchart shown in **Figure 34** provides an overview of the process. First, data needs to be collected regarding a given site under consideration, including crash history, vehicular level of service, pedestrian and vehicle volumes, and geometry and built environment attributes (**Table 34** lists the specific requirements for data collection).

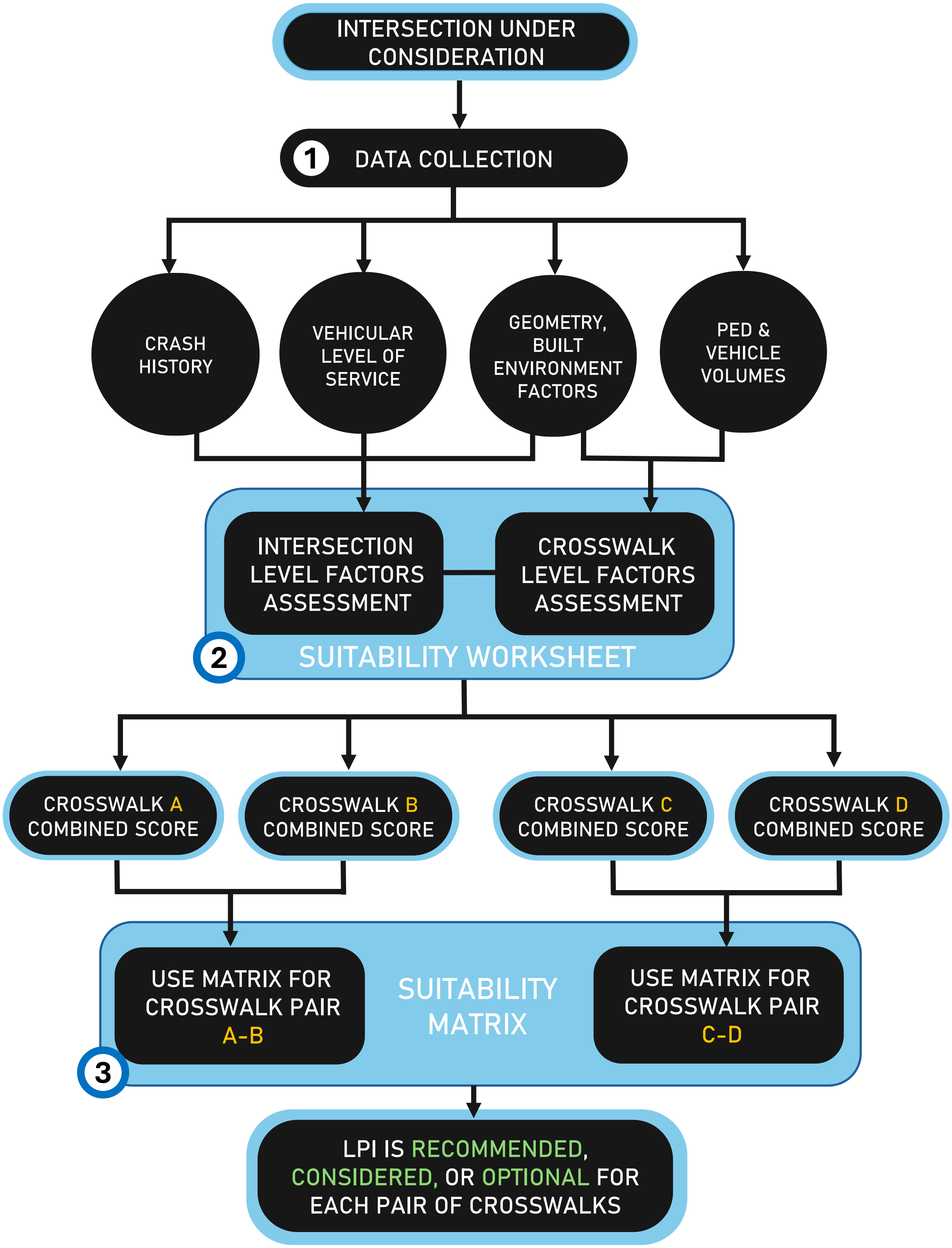


Figure 34: LPI Guidance Flowchart

Table 33: Data Collection for LPI Suitability Assessment

Factors	Data Collection Details	Data Collection Methods
Crash History	Number of turning vehicle-pedestrian crashes in the last 5 years in the intersection	Review crash records with appropriate filters.
Pedestrian Volume	Hourly pedestrian volume for each crosswalk	Collect Oct - April, weekday (non-holiday), 10 hrs (7AM-5PM) average preferred. If not in downtown, an average volume from 11AM-2PM is acceptable.
Turning Vehicle Volume	Hourly left and right turning vehicles for each crosswalk	Collect Oct - April, weekday (non-holiday), 10 hrs (7AM-5PM) average preferred. If not in downtown, an average volume from 11AM-2PM is acceptable.
T intersection	Crosswalk parallel with base of T-intersection	Site visit or Google Maps Satellite View
One-Way Street	Presence of one-way street in any approach	Site visit or Google Maps Satellite View
School and Transit Stop Distance	Measure distance from the center of intersection	Measurement using Google Maps
Sight Obstruction	Irregular intersection geometry, obstructions buildings, base of a bridge, trees, blinding sun angle, inferior lighting condition	Site visit or Google Maps Street View
Level of Service (LOS)	Calculate or estimate change in LOS	Traffic analysis software or manual calculations using traffic data

Then, with the data collected, the analyst proceeds to a worksheet and calculates a score for each crosswalk at the intersection based on Intersection level and Crosswalk level factors. Factors included in this assessment are shown in **Table 34**.

Table 34: LPI Suitability Worksheet

Intersection Level Assessment			
Factor	**Score**	**Score Allocation**	**Background**
Turning Vehicle - Pedestrian Crashes in recent 5 years	0 to 3	Three crashes or more = 3 Two crashes = 2 One crash = 1 None = 0	Through the literature, an LPI is shown to be effective in reducing this crash type.[1]
One Way Street	0 to 1	One or more approaches = 1 No approach = 0	Vehicles turning left on a one-way street do not need to wait for and yield to vehicles in the opposing direction.[1]
Intersection Distance from School	0 to 2	Less than 2800 ft = 2 More than 2800 ft = 0	Intersections within 2800 ft of a school are found to have increase probability of turning vehicle-pedestrian crashes.[2, 3, 4]
Intersection Distance from Transit Stop	0 to 1	Less than 300 ft = 1 More than 300 ft = 0	Intersections within 300 ft of transit stops are found to have increase probability of turning vehicle-pedestrian crashes. [2, 3]
Travel Delay	-3 to 0	-1 for each degradation of an approach below LOS C. For example, LOS C to LOS D would be -1; LOS C to LOS E would be minus 2, etc. -1 for each degradation of intersection below LOS below C. For example, LOS C to LOS D would be -1; LOS C to LOS E would be minus 2, etc. Maximum of -3.	High level of travel delay can reduce LPI effectiveness by causing driver frustration and risky behavior. This should be calculated using a preferred analysis software, for the peak hour which the agency deems most critical. [1]

Crosswalk Level Assessment			
Factor	**Score**	**Score Allocation**	**Reason**
Pedestrian Volume (per hour)	0 to 3	More than 100 = 3 51 to 100= 2 6 to 50= 1 Less than 6 = 0	Higher pedestrian volumes increase the likelihood of pedestrian-vehicle interactions. [2]
Turning Vehicle Volume (vph)	0 to 3	More than 600 = 3 401 to 600= 2 101 to 400= 1 Less than 101 = 0	Higher volumes of turning vehicles increase the pedestrian-vehicle interactions. [2]
T intersection	0 to 1	Crosswalk parallel with stalk of T intersection = 1 No = 0	In crosswalk parallel with the stalk of a T-intersection, all approaching vehicles turn left or right, with no need to wait for opposing traffic (Saneinejad & Lo, 2015). [1]
Sight Obstruction or Skewed Approach	0 to 1	Yes = 1 No = 0	A sight obstruction or skewed approach can make it more challenging for a vehicle to see a pedestrian on the corner. [1]
Highest Score	**15**		

Notes:
1. This is used in other published guidance.
2. This is based upon research conducted by NAU (Table 10, Figure 33).
3. Distance is measured from the center of the intersection, as the crow flies.
4. School is defined as public and charter K-12 schools

As an LPI must be implemented at crosswalks in pairs (due to a need for APS prompts to be consistent to cross a given street), the total score for each crosswalk is entered into the Suitability Matrix as a pair of crosswalks, with the crosswalk pairings shown in **Figure 35** and the Suitability Matrix shown in **Table 35**.

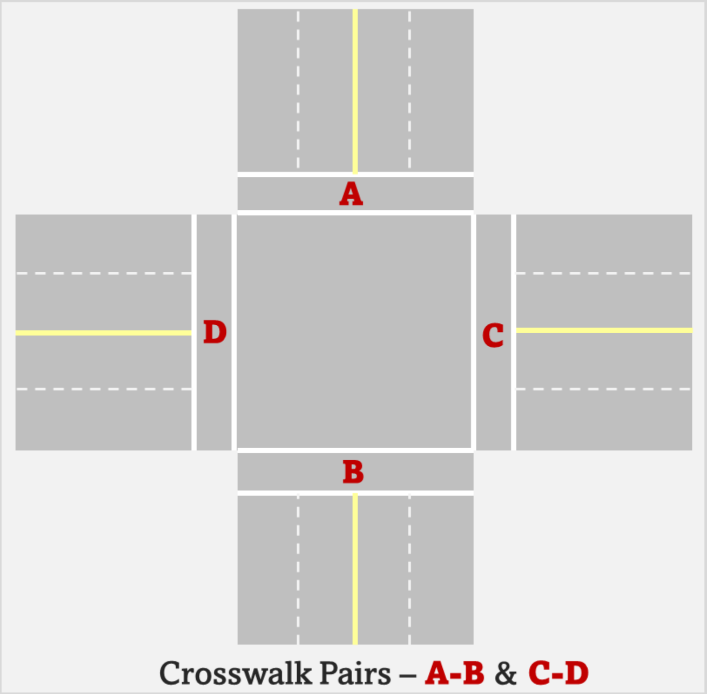


Figure 35: Crosswalk Pairs at an Intersection

Based on where each pair of crosswalks falls within the suitability matrix, an LPI is determined to be Optional, Considered, or Recommended, which are defined as the following within the context of this work:

- Optional
    - Minor safety benefit expected
- Considered
    - Moderate safety benefit expected
- Recommended
    - High safety benefit expected

Table 35: LPI Suitability Matrix

Crosswalk	**A (or C)**			
	Score	0-4	5-10	11-15
B (or D)	0-4	Optional	Optional	Considered
	5-10	Optional	Considered	Recommended
	11-15	Considered	Recommended	Recommended

Several other issues regarding LPI implementation should be noted:

1. If there is no adjacent crosswalk, use 0-4 for Optional, 5-10 for Considered, and 11-15 for Recommended.

2. If not already installed, APS units should be used with all LPI implementations.
3. Due to the need for the voice prompts on APS units to be consistent to cross a given street, an LPI must be installed in pairs such that both crosswalks across a roadway operate with an LPI. Additionally, the 'WALK' indication must start at the same time on both crosswalks.
4. At locations with LPIs, left turn protection should lag the through movement only. Leading left turn protection for a movement across an LPI crosswalk can result in vehicles turning into the LPI.
5. For locations with a Flashing Yellow Arrow, the indication shall remain red until the LPI ends.
6. The guidance provided in this work is based on a 5-second LPI. A shorter or longer LPI duration can be used, based on engineer judgment and MUTCD guidance.
7. On coordinated facilities, the offsets of the adjacent intersections should be adjusted such the vehicle platoons do not arrive during the LPI.
8. Upon implementation of an LPI, signage such as 'Traffic Control Change' or 'New Pedestrian Head Start' may be implemented to inform drivers of the traffic control change.
9. To improve vehicular compliance with the LPI, the following items may be implemented:
    a. Install visors to shield signal heads perpendicular to the LPI crosswalks so that drivers cannot anticipate the green interval. This is especially useful for skewed locations but can be an option at all locations.
    b. No Right Turn on Red should be considered on approaches parallel to the LPI crosswalk, as the literature shows it increases the effectiveness of the LPI.
    c. A 'Turning Vehicles Yield to Pedestrians' sign (R10-15) may be used to increase awareness of pedestrians to drivers.

5.1.1 Example Guidance Process

This section will work through the LPI guidance process at two of the crosswalks studied, the North and West crosswalks of Indian School and 19th Ave, shown in **Figure 36**.

Figure 36: Example Crosswalks for Analysis

Table 36: Example Worksheet

Intersection Level Assessment				
Factor	**Score**	**Score Allocation**	**North X-Walk**	**West X-Walk**
Turning Vehicle - Pedestrian Crashes in recent 5 years	0 to 3	Three crashes or more = 3 Two crashes = 2 One crash = 1 None = 0	**3 pts** 3 crashes from 2018-2022	
One Way Street	0 to1	One or more approaches = 1 No approach = 0	**0 pts** No one-way streets at location	
Intersection Distance from School	0 to 2	Less than 2800 ft = 2 More than 2800 ft = 0	**2 pts** School within 2800 ft	
Intersection Distance from Transit Stop	0 to 1	Less than 300 ft = 1 More than 300 ft = 0	**1 pt** Transit stop within 2800 ft	
Travel Delay	-2 to 0	One approach goes below LOS D = -1 Whole intersection goes below LOS D = -2	**0 pts** Presumed 0; insufficient data for analysis	
Crosswalk Level Assessment				
Factor	**Score**	**Score Allocation**	**North X-Walk**	**West X-Walk**
Pedestrian Volume (per hour)	0 to 3	More than 100 = 3 51 to 100= 2 6 to 50= 1 Less than 6 = 0	**1 pt** 28 ped/hr average over 11AM – 2 PM	**1 pt** 28 ped/hr average over 11AM – 2 PM
Turning Vehicle Volume (vph)	0 to 3	More than 600 = 3 401 to 600= 2 101 to 400= 1 Less than 101 = 0	**1 pt** 343 veh/hr average over 11AM – 2 PM	**2 pt** 343 veh/hr average over 11AM – 2 PM
T intersection	0 to 1	Crosswalk parallel with stalk of T intersection = 1 No = 0	**0 pts** Not a T-intersection	**0 pts** Not a T-intersection
Sight Obstruction or Skewed Approach	0 to 1	Yes = 1 No = 0	**0 pts** No skew or sight obstruction	**0 pts** No skew or sight obstruction
Total			**8**	**9**

From the worksheet, the North crosswalk scored 8 points, while the West crosswalk scored 9 points. Because we do not have data for the South and East crosswalks, we cannot calculate the crosswalk level values, but we will presume a score of 11 for the South crosswalk, and 8 for the East crosswalk. With all of the crosswalks scored, the next step is to enter those scores into the suitability matrix for each pair of crosswalks, illustrated in **Table 37** and **Table 38**.

Table 37: North / South Crosswalk Suitability Example

Crosswalk	**North (8 pts)**			
	Score	0-4	5-10	11-15
South (11 pts)	0-4	Optional	Optional	Considered
	5-10	Optional	Considered	Recommended
	11-15	Considered	**Recommended**	Recommended

Table 38: East / West Crosswalk Suitability Example

Crosswalk	**East (8 pts)**			
	Score	0-4	5-10	11-15
West (9 pts)	0-4	Optional	Optional	Considered
	5-10	Optional	**Considered**	Recommended
	11-15	Considered	Recommended	Recommended

In this example, an LPI for North / South crosswalk pair would be recommended, while an LPI for the East / West crosswalk pair should be considered.

5.2 Pedestrian Scramble SOP Recommendations

The recommendations for an SOP for pedestrian scramble (also known as Barnes Dance and Exclusive Pedestrian Phase) implementation are provided in this section. This content is derived from literature only and is not the result of any independent study by NAU researchers. Citations are noted differently in this section of the report to facilitate transformation of this content into an SOP by City of Phoenix personnel.

5.2.1 Location Type

Consider locations with the following characteristics:

- Pedestrian volumes. [LADOT, Chen et al]
    - LADOT recommends peak hour pedestrian volumes meet or exceed 30% of the peak hour vehicle volume ***OR*** 200 pedestrian crossings per hour during the peak hour in a single crosswalk.
    - Intersections in downtown areas with rapid influx of pedestrians. [Chen et al]
- Vehicle volumes [LADOT, NYCDOT, Chen et al]
    - LADOT recommends high turning volume across more than one crosswalk, where at least 200 vph per crosswalk during the peak hour.

    - NYCDOT recommends locations where dominant movement is turning vehicles.
    - Low vehicle volume intersections [NYCDOT]
- Pattern of turning vehicle vs pedestrian crashes [LADOT]
    - LADOT Guidance: at least 3 documented crashes within last 3 years.
- Geometry
    - Atypical intersections where diagonal crossing would have the shortest crossing distance [NYCDOT]
    - High demand for diagonal crossings [NYCDOT]
    - T Intersections [NYCDOT]
    - Small intersections [Chen et al]
- Additional characteristics
    - Intersections that can provide a safe and accessible configuration for people with disabilities. [NYCDOT]
    - Intersections where pedestrians are more likely to comply due to a greater risk of severe injury during the Don't Walk phase (high-speed, long crossing distances). [Zhang et al]

Locations where treatment may be less desirable:

- At or near at-grade rail crossings/ rail priority intersections. [LADOT]
- At or near freeway ramps where queue of waiting vehicles may backup to the freeway mainline. [LADOT]
- If there are few pedestrian turning-vehicle conflicts on one or more approaches (in this case, an LPI or protected-only turning vehicle movements should be considered). [LADOT]

5.2.2 Implementation Challenges

- Implementation of a pedestrian scramble typically increases the delay for all users.
- Non-compliance of the Walk/Don't Walk signal may increase, due to pedestrians being accustomed to a different traffic patten, or longer wait times
- Refuge spaces for pedestrians could be insufficient to accommodate the larger queues of pedestrians.

5.2.3 Design Recommendations

The MUTCD has the following recommendations:

For pedestrian scrambles that allow for diagonal crossings, use markings like those shown in **Figure 37.** The MUTCD states that the markings that denote the diagonal crossings should not be high-visibility markings, but crosswalks around the perimeter can use designs with high visibility markings.

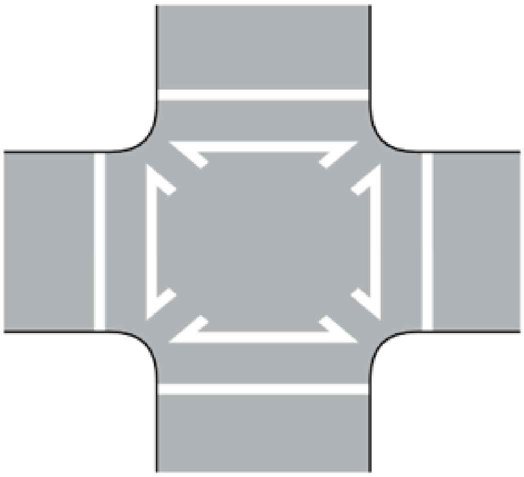


Figure 37: Example Markings (Source: MUTCD 11th ed.)

The PROWAG (Public Right-of-Way Accessibility Guidelines) by the US Access Board does not have specific guidance about pedestrian scrambles with diagonal crossings, but they should meet ADA compliance requirements for pedestrian facilities. The ADA compliant pedestrian facilities should include the following:

- High-visibility crosswalks.
- Refuge islands.
- Pedestrian crossing signs.
- Separate curb ramps with detectable warnings.
  - The curb ramps should be separate to improve orientation for visually impaired pedestrians.
  - This is not always possible, and a single combined curb ramp can be used if there is no alternative.

LADOT and NYCDOT recommend the following:

- Consider not including a diagonal crossing if it would exceed 100 feet. [LADOT]
- Consider "No Turn on Red" restrictions for all approaches. [LADOT, note that this is already required at all NYC intersections, and therefore would not be considered in their guidance]
- Adding signage explaining crossing requirements. [LADOT, NYCDOT]
- Consider adding pedestrian signal heads for diagonal crossings and new poles, if required. [NYCDOT]
- Consider the removal of protected-permissive left turn phases, specifically if they were implemented to address pedestrian conflicts. [LADOT]

The NYCDOT also recommends that Accessible Pedestrian Signals (APS) should be added for the perpendicular crosswalks, but not for the diagonal crosswalks due to the possibility of that leading to confusion for the visually impaired about the direction they should walk. The Canadian National Institute for the Blind and American Council of the Blind both recommend that all APS units at the intersections should have the same audible message, such as, "The walk sign is on for all crossings" to replace the conventional audible sound. *(Accessible Pedestrian Signals (APS) | American Council of the Blind, n.d.; Scrambled Crossings – Clearing Our Path Version 2.0, n.d.)*

6 CONCLUSION

Pedestrian safety is a critical transportation and public health issue, with fatalities increasing substantially over the past decade. Given this trend, it is important to understand where and when to most effectively implement countermeasures that help prevent pedestrian crashes, injuries, and fatalities. With the goal of improving safety for non-motorized user within the City of Phoenix, this project included the following activities:

- Literature review regarding implementation and operation of different pedestrian treatments at signalized intersections, as well as bicycle clearance intervals and confirmation lights for RRFBs and CRFBs,
- Laboratory tests of advanced pushbuttons to determine their suitability for application in low desert environments,
- Before and After safety assessment of the Leading Pedestrian Interval (LPI) and 'No Right Turn on Red' (NRTOR) treatments from field collected conflict data,
- The development of public facing LPI implementation guidelines, and
- Recommendations for a Standard Operating Procedure (SOP) for a pedestrian scramble.

Literature Review

The literature review provided an overview the effectiveness and implementation guidelines of pedestrian treatments such as LPIs, pedestrian scrambles, rectangular rapid flashing beacon RRFB and CRFB indicator beacons, and advanced push buttons. From the LPI implementation guidelines from California, Florida, Toronto, and Scottsdale, it was noticed that the suitability and duration of an LPI can vary due to numerous factors, including crash frequency, traffic volume, peak hour volume, visibility issue, intersection geometry (e.g., one-way or T-intersections), etc. In contrast, there is a lack of standardized guidelines for implementing a pedestrian scramble in North American jurisdiction, with only Los Angeles developing specific criteria and design guidance for pedestrian scrambles. Several research studies have evaluated safety factors Before and After the implementation of pedestrian scrambles in different areas, analyzing compliance with traffic rules and the number of crashes at those intersections. Typically, intersections with high traffic volumes, especially with a high number of turning vehicles, short diagonal crossing distances, and high pedestrian volumes, are recommended for the implementation of pedestrian scrambles. A detailed summary of factors considered in LPI, and pedestrian scramble implementation guidance of different North American jurisdictions were presented in tabular format in this report.

No official guideline or documentation regarding RRFB/CRFB confirmation lights was found. However, two distinct types of confirmation lights for RRFB systems installed on overhead and pole-mounted systems observed in Nevada and Indiana, respectively, have been discussed in the report. Since the onset of the COVID-19 pandemic, demand for touchless pedestrian pushbuttons has increased, yet, no official guidance related to the sensitivity of touchless pushbuttons has been published in any design manual or from any state transportation department. Finally, various guidelines for bicycle clearance signals were discussed. Among them, the NCHRP guideline is the most recent and describes the rules and recommendations in the most detailed format.

Pushbutton Laboratory Tests

Laboratory tests of advanced pushbuttons involved performance evaluation experiments on Polara iNS3 and Guardian Wave pushbutton devices, testing their touchless detection, extended press capabilities, and responsiveness under various conditions. Both devices were evaluated for their range, sensitivity, and other settings, with a particular focus on environmental impacts such as dark conditions, gloves, and heated buttons. The Polara's minimum wave time settings and Guardian Wave's sensitivity and delay settings significantly influenced their detection fields. The Polara unit's centroid height was above the button's centerline, whereas the Guardian Wave's was below. Both units' extended press and Polara's rain lockout functionalities worked as intended, with the Polara PedApp also providing effective accessibility features.

LPI Implementation Guidance

To develop LPI implementation guidance tailored to the city of Phoenix, analysis of field collected pedestrian conflicts and were performed along with the review of existing guidelines. To identify the sites for field data collection, pedestrian crash data for Phoenix from 2016 to 2022 was analyzed. Since this project is primarily focused on LPI treatment, turning vehicle-pedestrian crashes that would be most impacted by an LPI were prioritized. Using a 150ft buffer, crashes of this type were assigned to signalized intersections within the Phoenix city limits which were then ranked by turning vehicle-pedestrian crash frequency. The top 85 intersections, with three or more crashes, were tiered for data collection consideration.

From these intersections, seven were selected for volume analysis by City of Phoenix staff based on video collection feasibility, expected pedestrian/vehicle conflict exposure, and potential for signal timing/signing changes. Volume analysis was conducted to identify the specific crosswalks with the highest exposure of pedestrians to turning vehicles. Vehicle and pedestrian counts were collected for one day at each intersection, during both lunchtime and evening rush hour, to capture a representative sample of traffic patterns. The data was then analyzed to identify the crosswalks with the highest pedestrian volume, conflicting vehicles, and cross-product (a measure of the interaction between pedestrians and vehicles). Eight crosswalks from four intersections were identified for data collection:

- Site 1: Washington St and 3rd St South crosswalk
- Site 2: Washington St and 3rd St West crosswalk
- Site 3: Indian School Rd and 51st Ave South crosswalk
- Site 4: Indian School Rd and 51st Ave West crosswalk
- Site 5: Indian School Rd and 19th Ave North crosswalk
- Site 6: Indian School Rd and 19th Ave West crosswalk
- Site 7: W Baseline Rd and 51st Ave North crosswalk
- Site 8: W Baseline Rd and 51st Ave West crosswalk

The pedestrian treatments to be evaluated at each crosswalk were chosen in consultation with the City of Phoenix Street Transportation Department. LPI assessments at each crosswalk and a No Right Turn on Red (NRTOR) assessment at Site 8 were conducted. LPIs were implemented for 5 seconds at each selected site. The Phoenix technician team collected 170 hours of video total for both the Before and After phases (80 before, 80 with LPI, and 10 with NRTOR).

Conflict data were manually reduced from field-collected videos, focusing on incidents where the Post Encroachment Time (PET) was 5 seconds or less. PET measures the time gap between the first unit (pedestrian or vehicle) leaving and the second unit entering the conflict area, providing a quantitative metric for evaluating conflict severity. Conflicts were categorized into high, medium, and low severity based on PET thresholds, with high severity defined as PET ≤ 1.5 seconds. The results indicated a significant reduction in both the frequency and severity of vehicle-pedestrian conflicts after LPI treatment. Additionally, a new method to categorize conflict severity was used considering both PET and vehicle speed. Six severity categories were defined with the most severe being ‘low PET-high vehicle speed’ and least severe being ‘high PET-low vehicle speed’. There was a marked decrease in high-severity conflicts, particularly those involving high severity high-speed conflict following LPI implementation. The data showed that right-turning vehicles were more frequently involved in conflicts compared to left-turning ones, likely due to the presence of protected and permitted left-turn phases at most sites. The study also highlighted that most conflicts involved pedestrians arriving at the conflict area first which emphasize the importance of giving pedestrians a head start to increase their visibility to drivers.

Negative Binomial (NB) regression models were developed to evaluate the impact of LPI treatment on conflict frequencies, while accounting for pedestrian and turning vehicle volumes. Results consistently found a significant negative correlation between LPI implementation and conflict frequency across various scenarios, with reductions ranging from approximately 10% to 15% for conflicts with PET ≤ 5 seconds and around 50% for severe conflicts (both for low PET and low PET high speed cases). The NB model results were then used to predict hourly pedestrian-vehicle conflict frequencies with and without LPI treatment. Findings from this analysis indicate that LPI treatment significantly reduces conflict severity, especially in scenarios with high pedestrian (over 100 per hour) and turning vehicle volumes (over 200 vehicle per hour).

In addition to conflict frequency, conflict severity was also analyzed. The ordered logit model results, which examine the severity of conflicts (low, medium, and high), further support the efficacy of LPIs in reducing conflict severity. Based on model results, the presence of an LPIindicated a significant reduction in the likelihood of high severity and medium severity conflicts. Factors contributing to increased conflict severity include right-turning vehicles (as opposed to left-turning), pedestrians crossing from the near side, initiating crossings during SDW signals, male pedestrian, driver violations like rolling stops, and evasive actions. Conversely, larger pedestrian group sizes are associated with lower severity conflicts.

Building on the crash and conflict analyses conducted in this work and informed by other published guidance, a set of public-facing implementation guidelines for LPIs was developed.

Incorporating a flowchart and a worksheet, these guidelines use intersection level factors, such as crash history, geometry and the built environment, and vehicular level of service, along with crosswalk level factors, such as pedestrian and conflicting turning vehicle volumes, to develop a score for each analyzed crosswalk. As LPIs should be implemented in pairs, the scores of each crosswalk in a pair are then entered into a suitability matrix to determine if implementation of an LPI at those crosswalks would be expected to have a low, medium, or high safety benefit.

Pedestrian Scramble SOP Recommendations

Finaly, recommendations for an SOP for the pedestrian scramble treatment were developed. While only one city, Los Angeles, was found to have somewhat robust implementation guidance, a comprehensive review of the literature allowed the development of guidance regarding locations that may or may not be suitable for a pedestrian scramble, implementation challenges, and design and operational recommendations.

Limitations and Future Work

While this work included robust crash and conflict analyses, several limitations should be noted. Regarding the crash analysis, this was conducted at the intersection, and not the crosswalk level. Additionally, pedestrian volumes were absent from the analysis. For the conflict analysis, as with any manually reduced data, there may be small errors in the dataset due to the nature of the work. Also, due to the lack of event-based phase and pedestrian data, the research team relied on visual observation to determine phase start and end times, which were challenging to observe at times due to occlusion and sun angle.

Looking forward, the SOP recommendations for the pedestrian scramble could be improved through further research on the topic. A practitioner survey to uncover other, unpublished implementation and operational guidance would provide additional insight into how other agencies are using the treatment, while a field calibrated simulation / sensitivity analysis of the treatment based upon local operational characteristics could provide additional guidance on the effectiveness of the treatment, and the impact it has on user behavior (violation, conflicts, etc.).

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APPENDICES

Appendix A: Polara Wave Detection Experiment Results

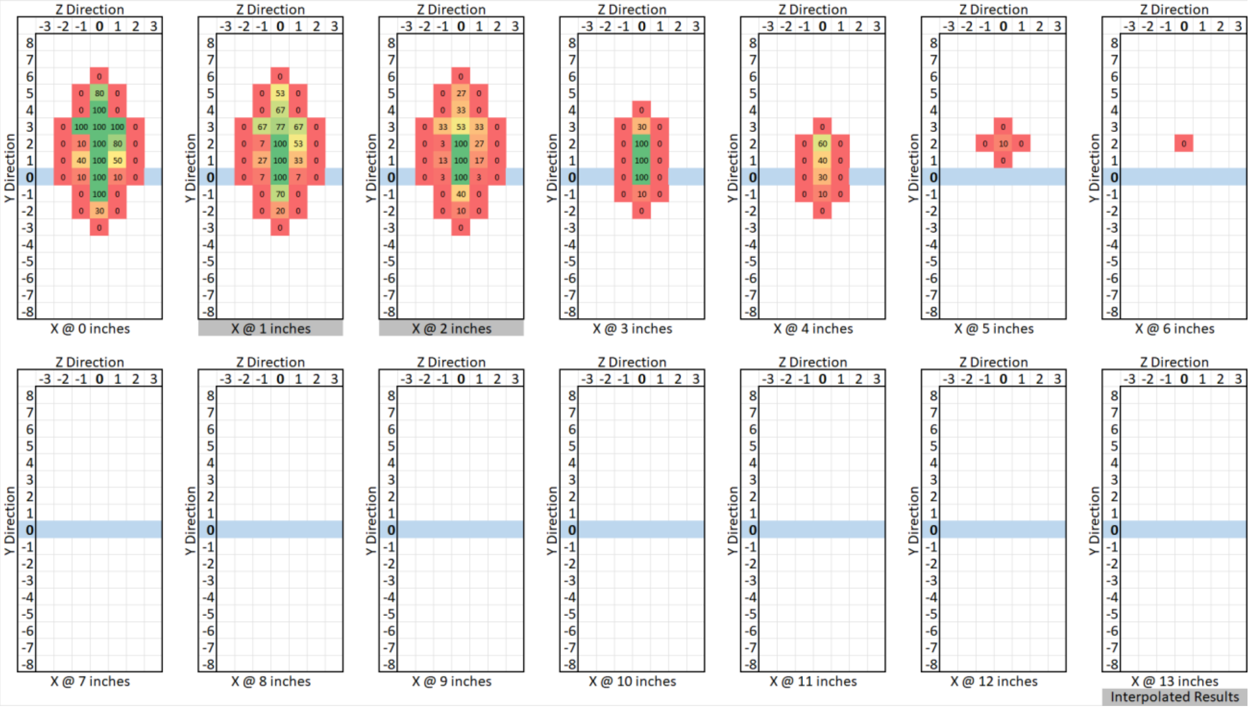
C1: Experiment 1: Range Zero

The first experiment was performed at range zero.

Range 0 Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 0 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 25in^3	

Range 0 Results



	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	80	0		
4			0	100	0		
3		0	100	100	100	0	
2		0	10	100	80	0	
1		0	40	100	50	0	
0		0	10	100	10	0	
-1			0	100	0		
-2			0	30	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 0 inches

	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	53	0		
4			0	67	0		
3		0	67	77	67	0	
2		0	7	100	53	0	
1		0	27	100	33	0	
0		0	7	100	7	0	
-1			0	70	0		
-2			0	20	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 1 inches

	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	27	0		
4			0	33	0		
3		0	33	53	33	0	
2		0	3	100	27	0	
1		0	13	100	17	0	
0		0	3	100	3	0	
-1			0	40	0		
-2			0	10	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 2 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4				0			
3			0	30	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	10	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 3 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	60	0		
1			0	40	0		
0			0	30	0		
-1			0	10	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 4 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	10	0		
1				0			
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 5 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 6 inches

X @ 7 inches

X @ 8 inches

X @ 9 inches

X @ 10 inches

X @ 11 inches

X @ 12 inches

X @ 13 inches

Interpolated Results

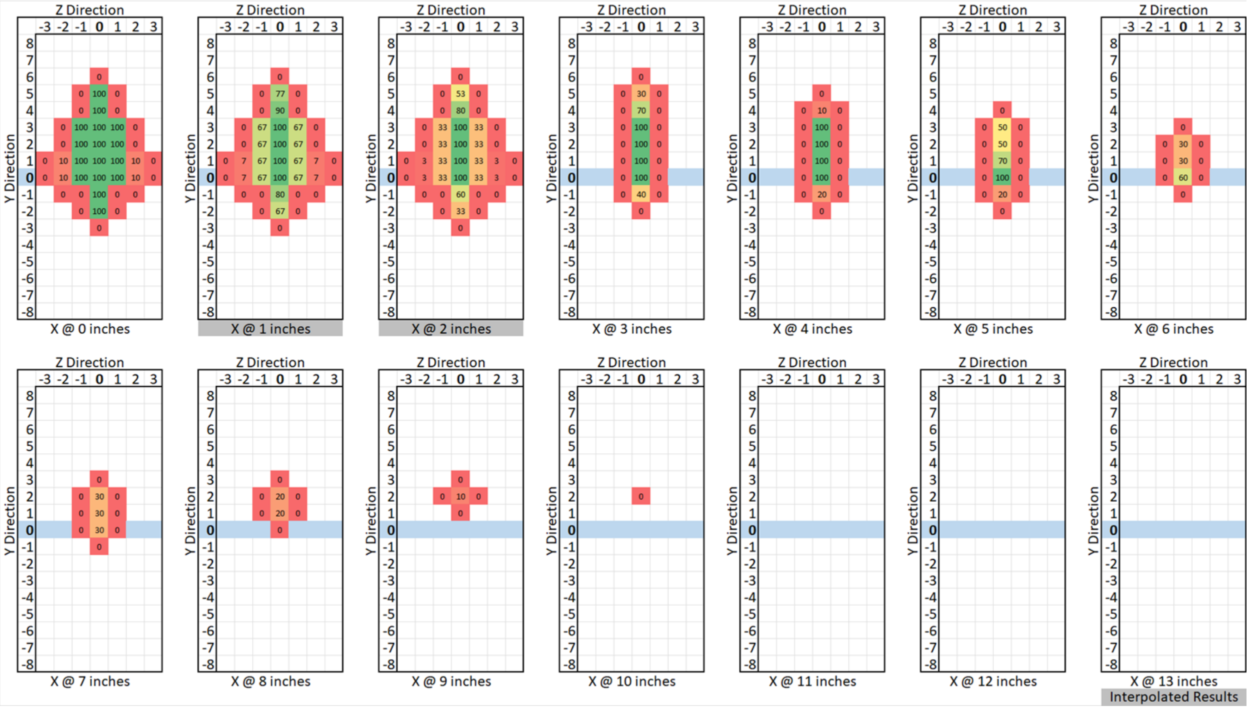
C2: Experiment 2: Range Three

The second experiment was performed at range three.

Range 3 Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 46in^3	

Range 3 Results



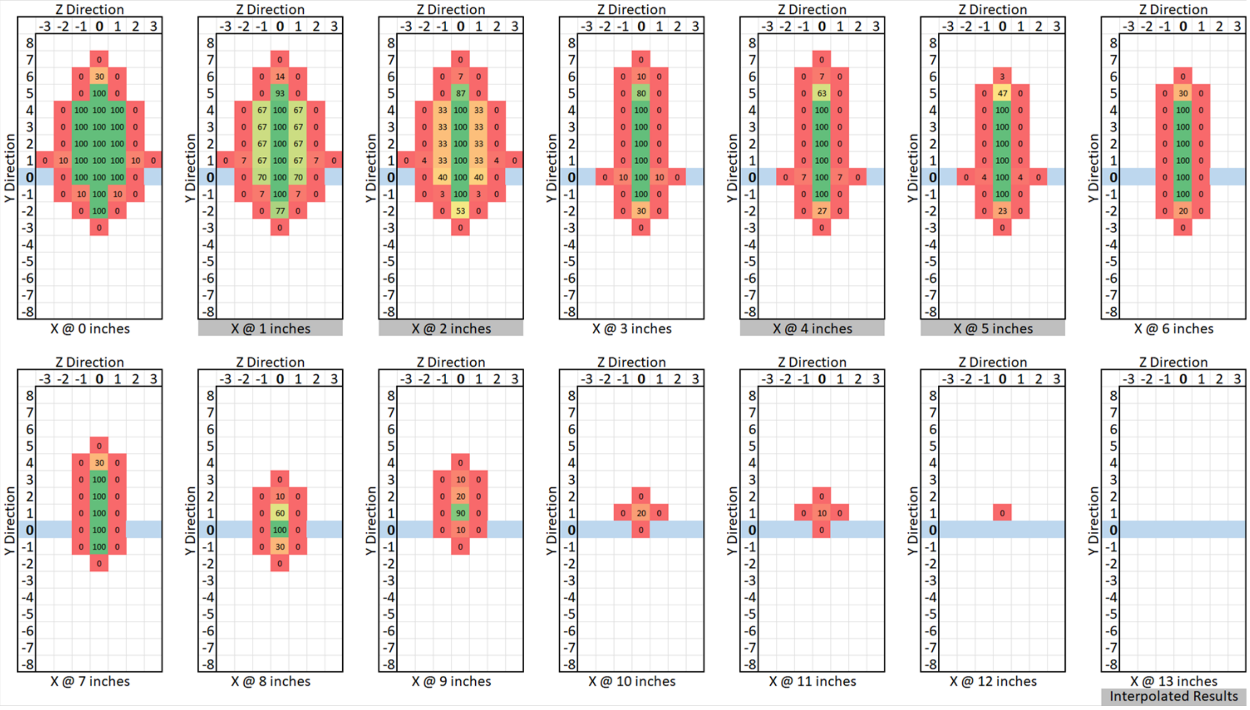
C3: Experiment 3: Range Six

The third experiment was performed at range six.

Range 6 Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 97in^3	

Range 6 Results



Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	30	0		
5			0	100	0		
4		0	100	100	100	0	
3		0	100	100	100	0	
2		0	100	100	100	0	
1	0	10	100	100	100	10	0
0		0	100	100	100	0	
-1		0	10	100	10	0	
-2			0	100	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 0 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	14	0		
5			0	93	0		
4		0	67	100	67	0	
3		0	67	100	67	0	
2		0	67	100	67	0	
1	0	7	67	100	67	7	0
0		0	70	100	70	0	
-1		0	7	100	7	0	
-2			0	77	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 1 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	7	0		
5			0	87	0		
4		0	33	100	33	0	
3		0	33	100	33	0	
2		0	33	100	33	0	
1	0	4	33	100	33	4	0
0		0	40	100	40	0	
-1		0	3	100	3	0	
-2			0	53	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 2 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	10	0		
5			0	80	0		
4			0	100	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0		0	10	100	10	0	
-1			0	100	0		
-2			0	30	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 3 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	7	0		
5			0	63	0		
4			0	100	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0		0	7	100	7	0	
-1			0	100	0		
-2			0	27	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 4 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				3			
5			0	47	0		
4			0	100	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0		0	4	100	4	0	
-1			0	100	0		
-2			0	23	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 5 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	30	0		
4			0	100	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	20	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 6 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5				0			
4			0	30	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 7 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	10	0		
1			0	60	0		
0			0	100	0		
-1			0	30	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 8 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4				0			
3			0	10	0		
2			0	20	0		
1			0	90	0		
0			0	10	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 9 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	20	0		
0				0			
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 10 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	10	0		
0				0			
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 11 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1				0			
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 12 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 13 inches

Interpolated Results

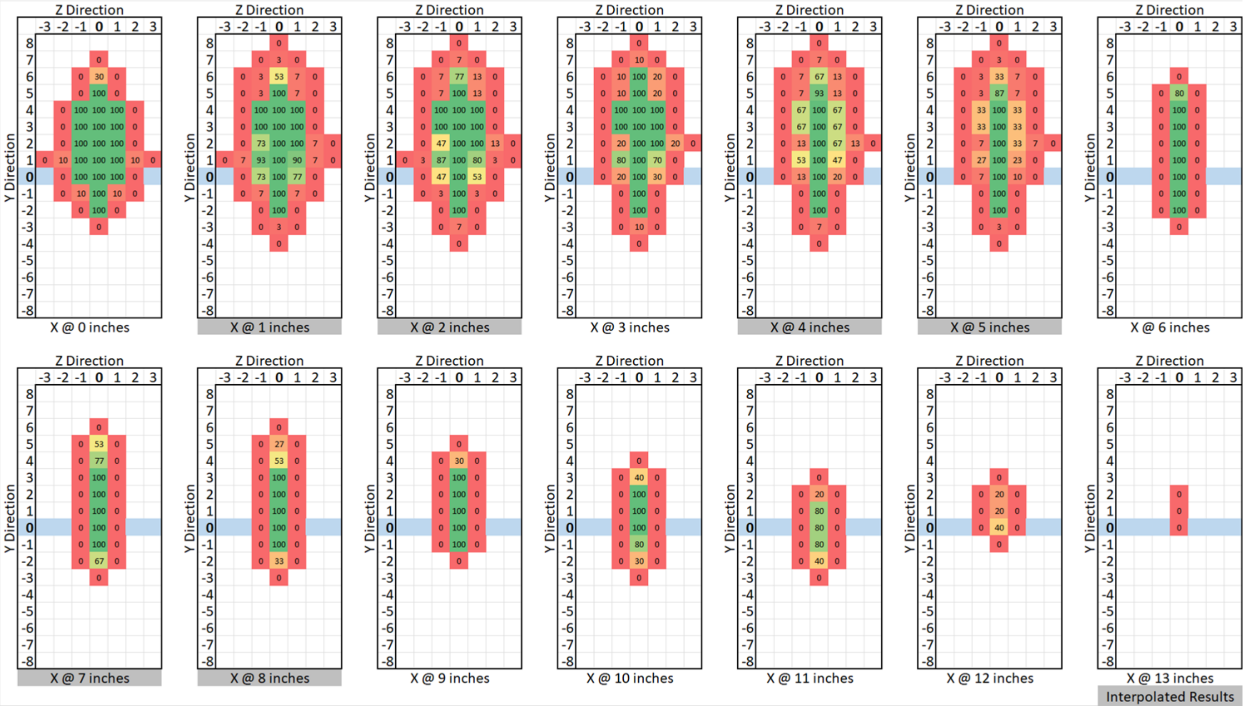
C4: Experiment 4: Range Nine

The fourth experiment was performed at range nine.

Range 9 Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 9 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 156in^3	

Range 9 Results



Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	30	0		
5			0	100	0		
4		0	100	100	100	0	
3		0	100	100	100	0	
2		0	100	100	100	0	
1	0	10	100	100	100	10	0
0		0	100	100	100	0	
-1		0	10	100	10	0	
-2			0	100	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 0 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8				0			
7			0	3	0		
6		0	3	53	7	0	
5		0	3	100	7	0	
4		0	100	100	100	0	
3		0	100	100	100	0	
2		0	73	100	100	7	0
1	0	7	93	100	90	7	0
0		0	73	100	77	0	
-1		0	7	100	7	0	
-2			0	100	0		
-3			0	3	0		
-4				0			
-5							
-6							
-7							
-8							

X @ 1 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8				0			
7			0	7	0		
6		0	7	77	13	0	
5		0	7	100	13	0	
4		0	100	100	100	0	
3		0	100	100	100	0	
2		0	47	100	100	13	0
1	0	3	87	100	80	3	0
0		0	47	100	53	0	
-1		0	3	100	3	0	
-2			0	100	0		
-3			0	7	0		
-4				0			
-5							
-6							
-7							
-8							

X @ 2 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8				0			
7			0	10	0		
6		0	10	100	20	0	
5		0	10	100	20	0	
4		0	100	100	100	0	
3		0	100	100	100	0	
2		0	20	100	100	20	0
1		0	80	100	70	0	
0		0	20	100	30	0	
-1			0	100	0		
-2			0	100	0		
-3			0	10	0		
-4				0			
-5							
-6							
-7							
-8							

X @ 3 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8				0			
7			0	7	0		
6		0	7	67	13	0	
5		0	7	93	13	0	
4		0	67	100	67	0	
3		0	67	100	67	0	
2		0	13	100	67	13	0
1		0	53	100	47	0	
0		0	13	100	20	0	
-1			0	100	0		
-2			0	100	0		
-3			0	7	0		
-4				0			
-5							
-6							
-7							
-8							

X @ 4 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8				0			
7			0	3	0		
6		0	3	33	7	0	
5		0	3	87	7	0	
4		0	33	100	33	0	
3		0	33	100	33	0	
2		0	7	100	33	7	0
1		0	27	100	23	0	
0		0	7	100	10	0	
-1			0	100	0		
-2			0	100	0		
-3			0	3	0		
-4				0			
-5							
-6							
-7							
-8							

X @ 5 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	80	0		
4			0	100	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 6 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	53	0		
4			0	77	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	67	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 7 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	27	0		
4			0	53	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	33	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 8 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5				0			
4			0	30	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 9 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4				0			
3			0	40	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	80	0		
-2			0	30	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 10 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	20	0		
1			0	80	0		
0			0	80	0		
-1			0	80	0		
-2			0	40	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 11 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	20	0		
1			0	20	0		
0			0	40	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 12 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1				0			
0				0			
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 13 inches

Interpolated Results

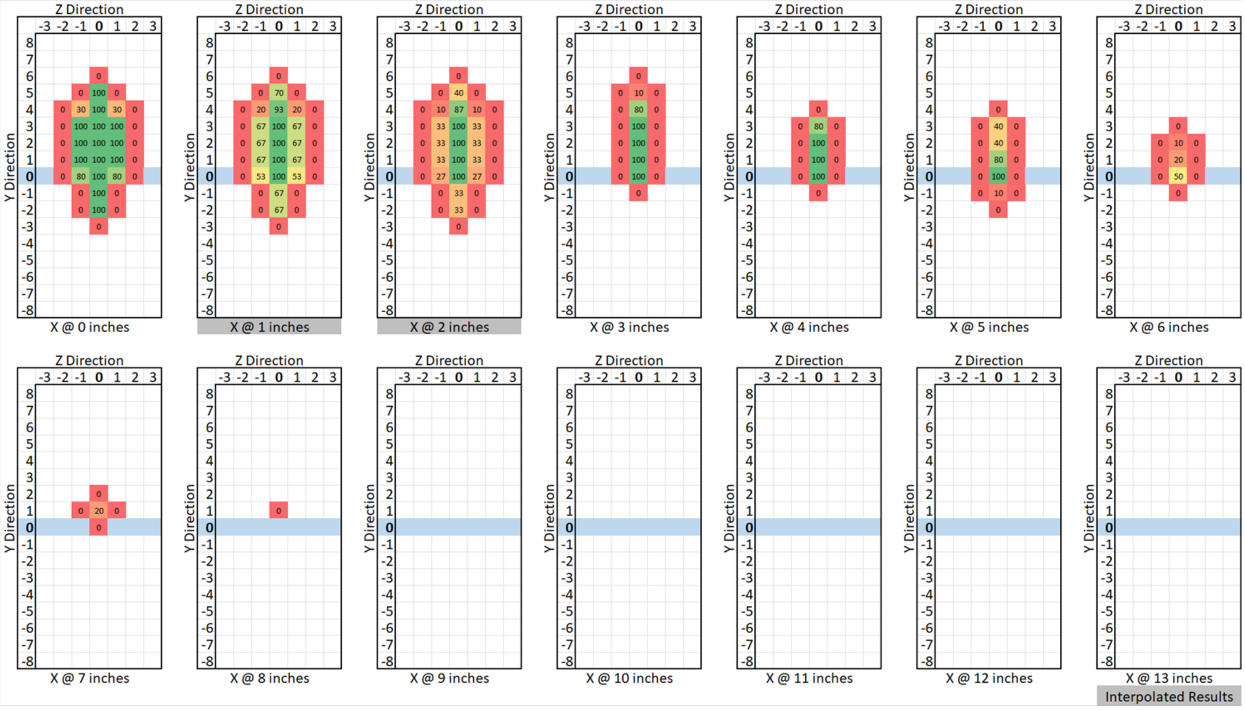
C5: Experiment 5: Wave Detection with Gloves

The fifth experiment was performed at range three, but the hand was covered in a glove. Table below shows the 100% field volume, the settings for the experiment, and the environmental conditions during experimentation.

Wave Detection with Gloves Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Glove Temperature = 85.7°F – 90.3°F • Light: 92 Lux
100% Field Volume: 43in^3	

Wave Detection with Gloves Results



Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	100	0		
4		0	30	100	30	0	
3		0	100	100	100	0	
2		0	100	100	100	0	
1		0	100	100	100	0	
0		0	80	100	80	0	
-1			0	100	0		
-2			0	100	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 0 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	70	0		
4		0	20	93	20	0	
3		0	67	100	67	0	
2		0	67	100	67	0	
1		0	67	100	67	0	
0		0	53	100	53	0	
-1			0	67	0		
-2			0	67	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 1 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	40	0		
4		0	10	87	10	0	
3		0	33	100	33	0	
2		0	33	100	33	0	
1		0	33	100	33	0	
0		0	27	100	27	0	
-1			0	33	0		
-2			0	33	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 2 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	10	0		
4			0	80	0		
3			0	100	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 3 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4				0			
3			0	80	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 4 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4				0			
3			0	40	0		
2			0	40	0		
1			0	80	0		
0			0	100	0		
-1			0	10	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 5 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	10	0		
1			0	20	0		
0			0	50	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 6 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	20	0		
0				0			
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 7 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1				0			
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 8 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 9 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 10 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 11 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 12 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 13 inches

Interpolated Results

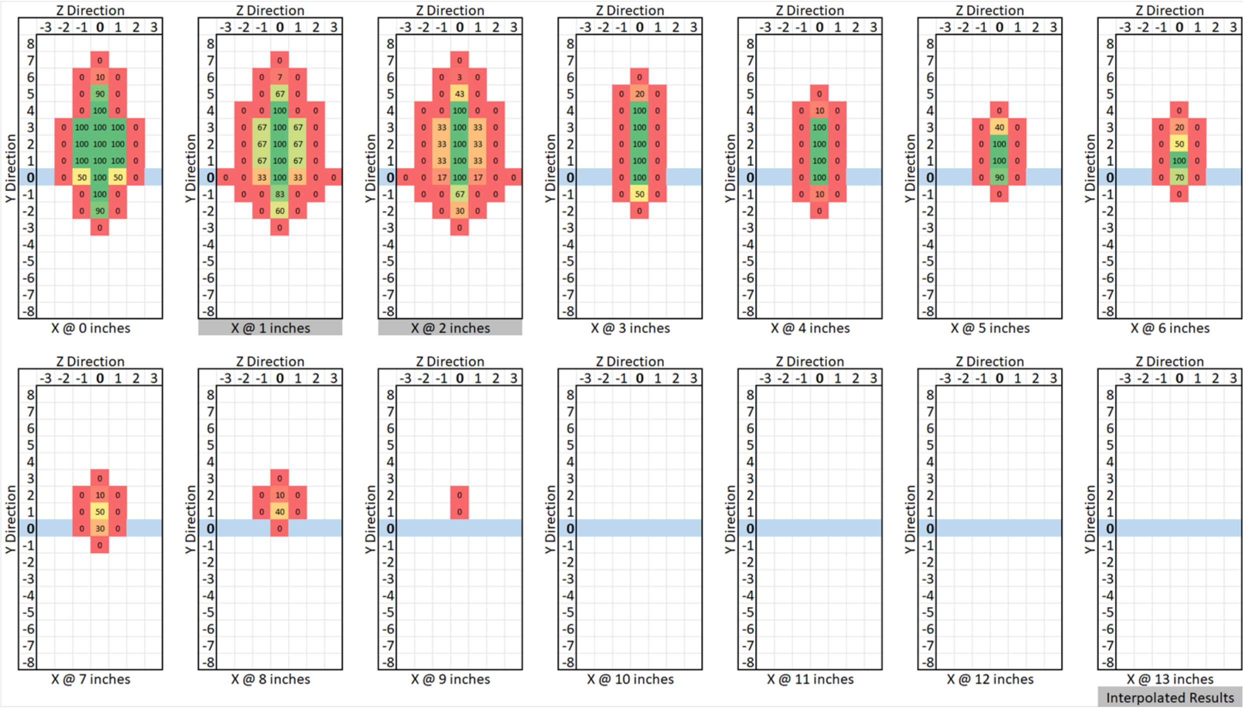
C6: Experiment 6: Heated Pushbutton

The sixth experiment was performed at range three, but the pushbutton was heated to a higher temperature. This experiment used a small space heater to heat the pushbuttons. The heater was aimed towards the pushbutton around the button area.

Heated Pushbutton Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3 • Extended Press = 1 Second • Minimum Wave Time = 50ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Pushbutton Temperature = Avg 110°F • Light: 92 Lux
100% Field Volume: 53in^3	

Wave Detection with Gloves Results



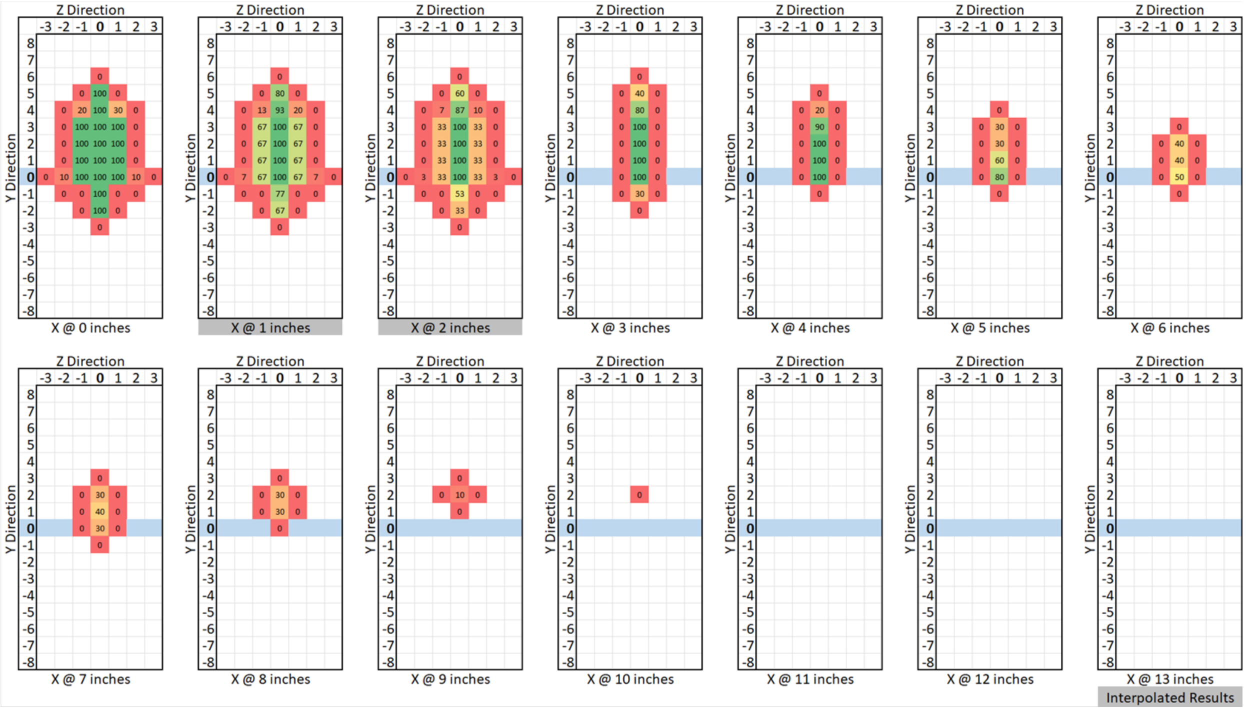
C7: Experiment 7: Wave Detection in Dark Environment

The seventh experiment was performed at range three, but the lights in the lab were turned off.

Wave Detection in Dark Environment Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
- Range = 3 - Extended Press = 1 Second - Minimum Wave Time = 50ms - Rain Lockout = Off	- Room Temperature = 75°F - 80°F - Hand Temperature = 90.3°F – 92.8°F - Light: 1.5-4.8 Lux
100% Field Volume: 42in^3	

Wave Detection in Dark Environment Results



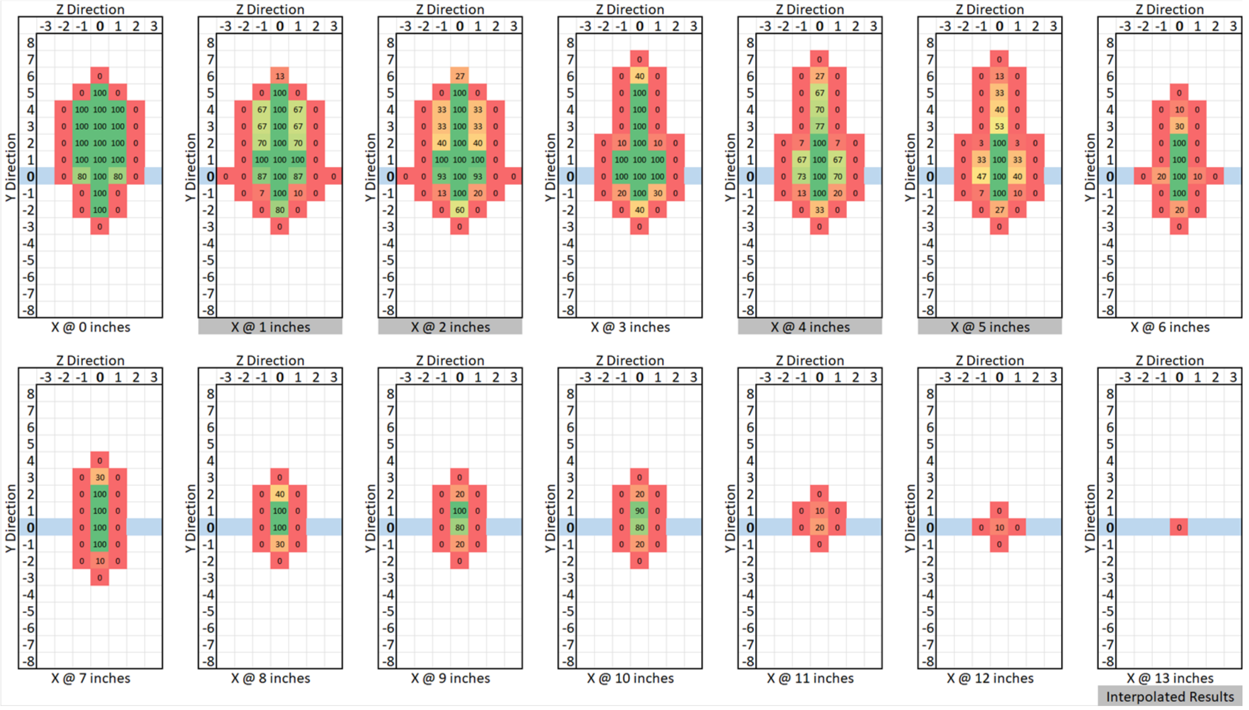
C8: Experiment 8: 0ms Minimum Wave Time

The eighth experiment was performed at range three, but the minimum wave time was changed to 0ms, the minimum allowed value.

0ms Minimum Wave Time Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3 • Extended Press = 1 Second • Minimum Wave Time = 0ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 92 Lux
100% Field Volume: 100in^3	

0ms Minimum Wave Time Results



Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6				0			
5			0	100	0		
4		0	100	100	100	0	
3		0	100	100	100	0	
2		0	100	100	100	0	
1		0	100	100	100	0	
0		0	80	100	80	0	
-1			0	100	0		
-2			0	100	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 0 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6				13			
5			0	100	0		
4		0	67	100	67	0	
3		0	67	100	67	0	
2		0	70	100	70	0	
1		0	100	100	100	0	
0	0	0	87	100	87	0	0
-1		0	7	100	10	0	
-2			0	80	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 1 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6				27			
5			0	100	0		
4		0	33	100	33	0	
3		0	33	100	33	0	
2		0	40	100	40	0	
1		0	100	100	100	0	
0	0	0	93	100	93	0	0
-1		0	13	100	20	0	
-2			0	60	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 2 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	40	0		
5			0	100	0		
4			0	100	0		
3			0	100	0		
2		0	10	100	10	0	
1		0	100	100	100	0	
0		0	100	100	100	0	
-1		0	20	100	30	0	
-2			0	40	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 3 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	27	0		
5			0	67	0		
4			0	70	0		
3			0	77	0		
2		0	7	100	7	0	
1		0	67	100	67	0	
0		0	73	100	70	0	
-1		0	13	100	20	0	
-2			0	33	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 4 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7				0			
6			0	13	0		
5			0	33	0		
4			0	40	0		
3			0	53	0		
2		0	3	100	3	0	
1		0	33	100	33	0	
0		0	47	100	40	0	
-1		0	7	100	10	0	
-2			0	27	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 5 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5				0			
4			0	10	0		
3			0	30	0		
2			0	100	0		
1			0	100	0		
0		0	20	100	10	0	
-1			0	100	0		
-2			0	20	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 6 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4				0			
3			0	30	0		
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	10	0		
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 7 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	40	0		
1			0	100	0		
0			0	100	0		
-1			0	30	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 8 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	20	0		
1			0	100	0		
0			0	80	0		
-1			0	20	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 9 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	20	0		
1			0	90	0		
0			0	80	0		
-1			0	20	0		
-2				0			
-3							
-4							
-5							
-6							
-7							
-8							

X @ 10 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	10	0		
0			0	20	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 11 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1				0			
0			0	10	0		
-1				0			
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 12 inches

Z Direction

Y Direction

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0				0			
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 13 inches

Interpolated Results

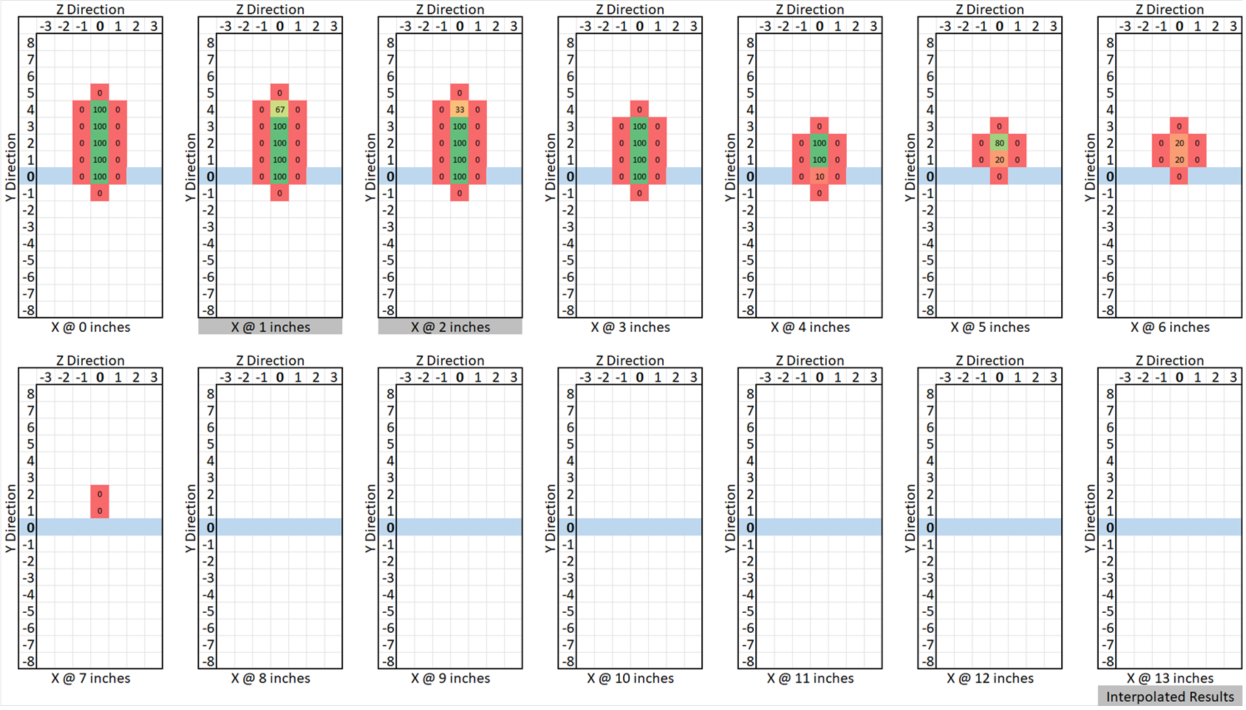
C9: Experiment 9: 500ms Minimum Wave Time

The ninth experiment was performed at range three, but the minimum wave time was changed to 500ms, the maximum allowed value.

500ms Minimum Wave Time Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3 • Extended Press = 1 Second • Minimum Wave Time = 500ms • Rain Lockout = Off	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 92 Lux
100% Field Volume: 33in^3	

500ms Minimum Wave Time Results



Appendix B: Guardian Wave Detection Experiment Results

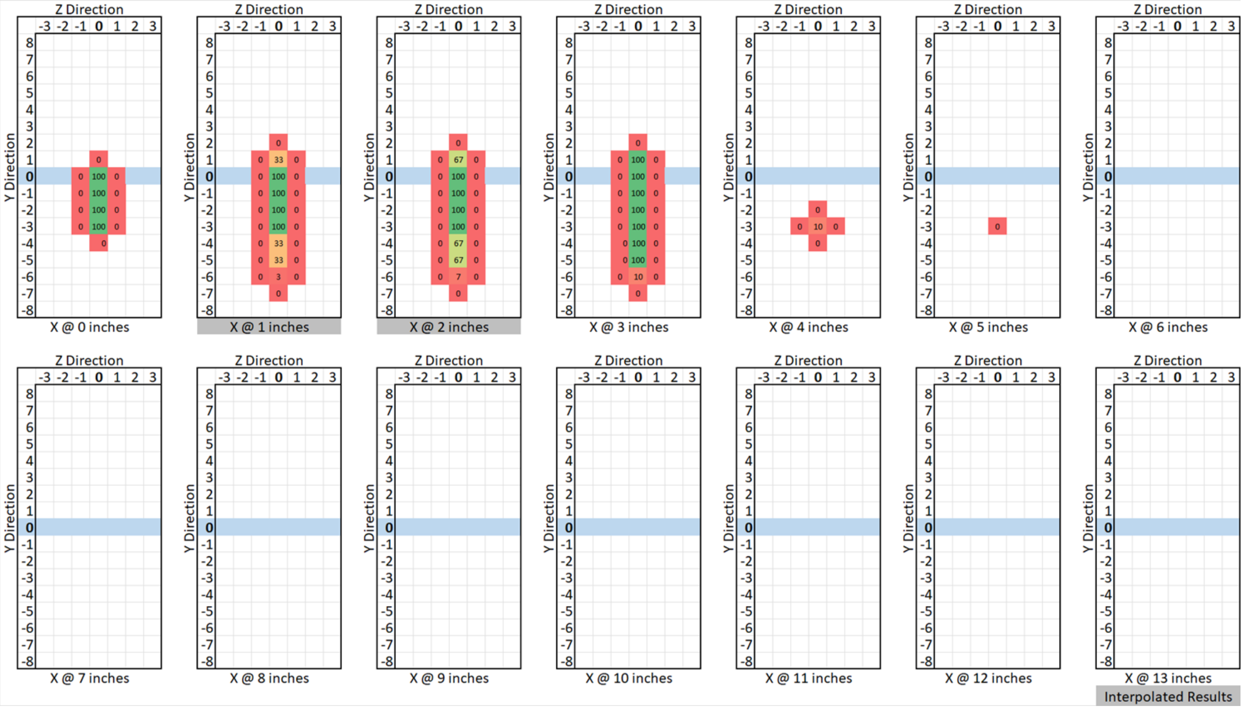
C1: Experiment 1: Three-Inch Range

The first Guardian Wave experiment was performed at the three-inch range.

3-inch Range Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 3-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: $34in^3$	

3-inch Range Results



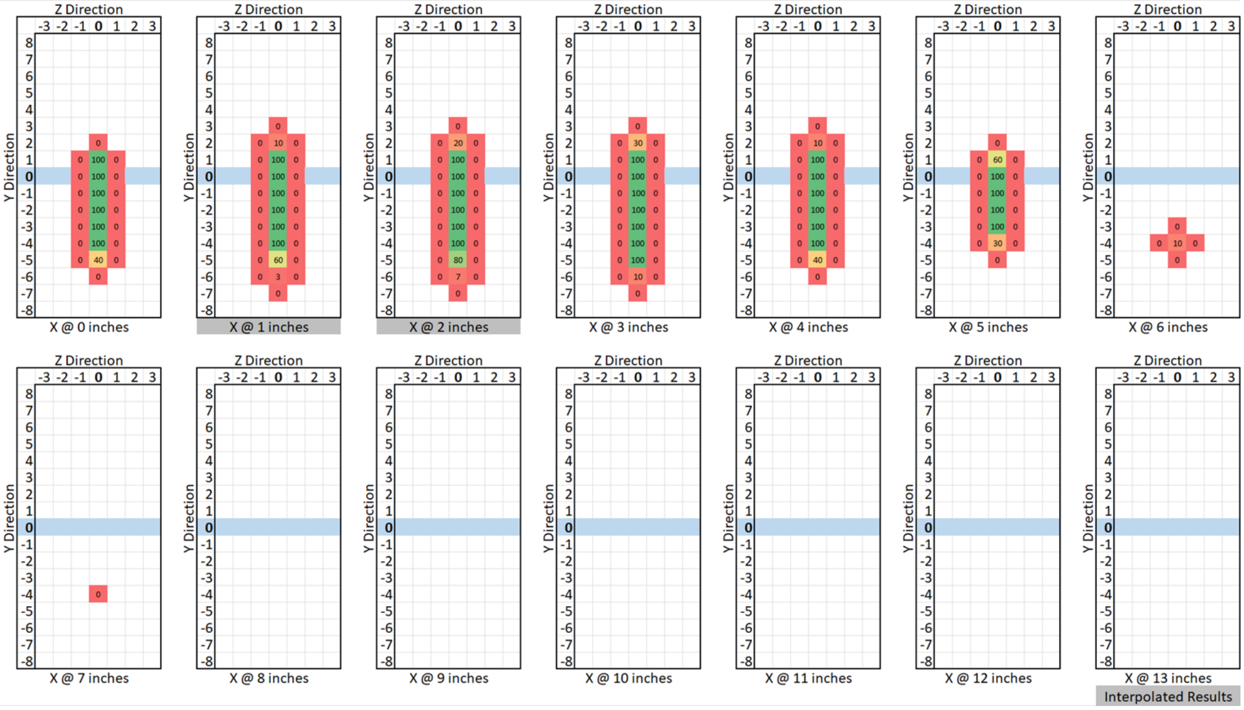
C2: Experiment 2: Six-Inch Range

The second Guardian Wave experiment was performed at the six-inch range.

6-inch Range Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 64in^3	

6-inch Range Results



X @ 0 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	40	0		
-6				0			
-7							
-8							

X @ 1 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	10	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	60	0		
-6			0	3	0		
-7				0			
-8							

X @ 2 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	20	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	80	0		
-6			0	7	0		
-7				0			
-8							

X @ 3 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	30	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	100	0		
-6			0	10	0		
-7				0			
-8							

X @ 4 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	10	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	40	0		
-6				0			
-7							
-8							

X @ 5 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	60	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	30	0		
-5				0			
-6							
-7							
-8							

X @ 6 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3				0			
-4			0	10	0		
-5				0			
-6							
-7							
-8							

X @ 7 inches

	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4				0			
-5							
-6							
-7							
-8							

X @ 8 inches

X @ 9 inches

X @ 10 inches

X @ 11 inches

X @ 12 inches

X @ 13 inches

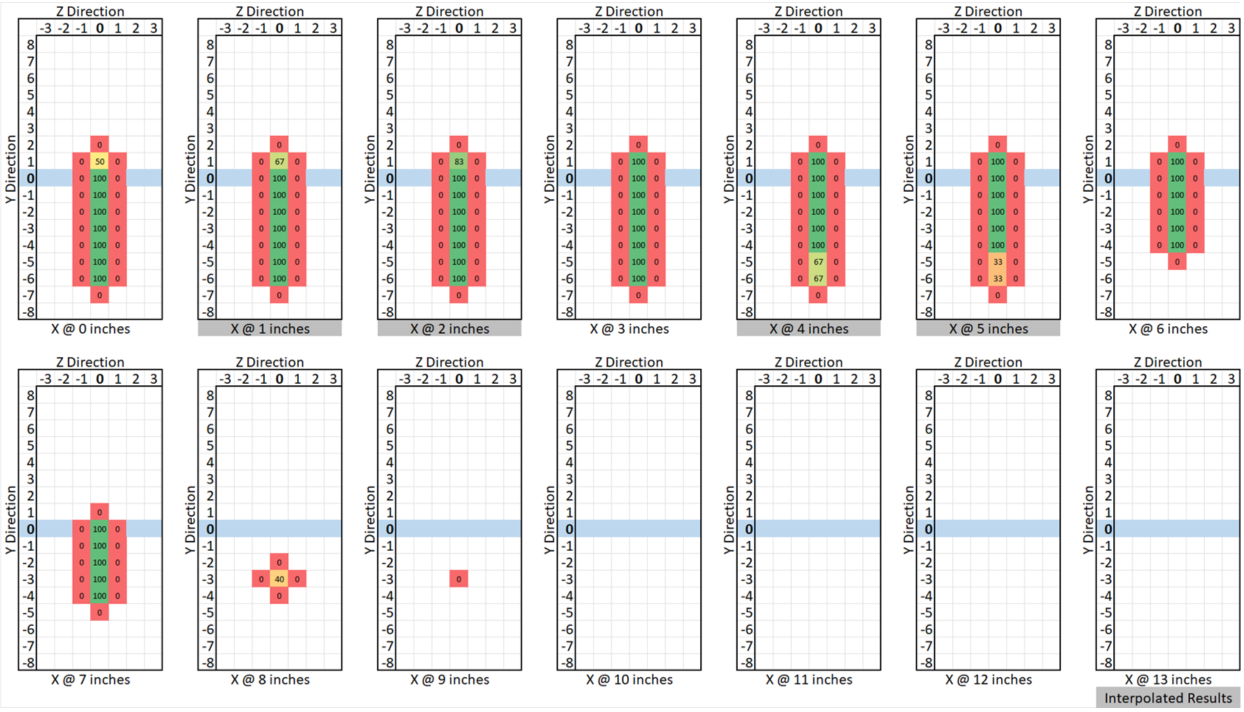
C3: Experiment 3: Nine-Inch Range

The third Guardian Wave experiment was performed at the nine-inch range.

9-inch Range Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 9-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 144 Lux
100% Field Volume: 97in^3	

9-inch Range Results



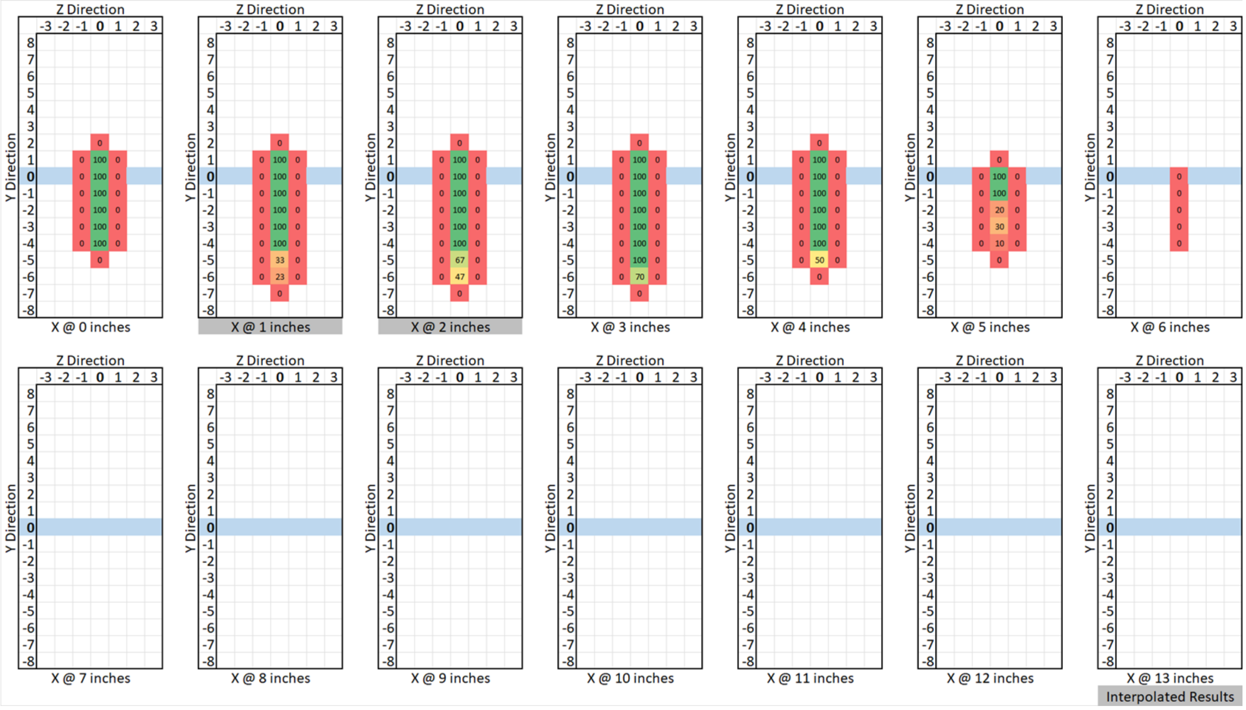
C4: Experiment 4: Wave Detection with Gloves

The fourth Guardian Wave experiment was performed at the six-inch range, but the tester's hands were covered in gloves.

Wave Detection with Gloves Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Glove Temperature = 85.7°F – 90.3°F • Light: 144 Lux
100% Field Volume: 60in^3	

Wave Detection with Gloves Results



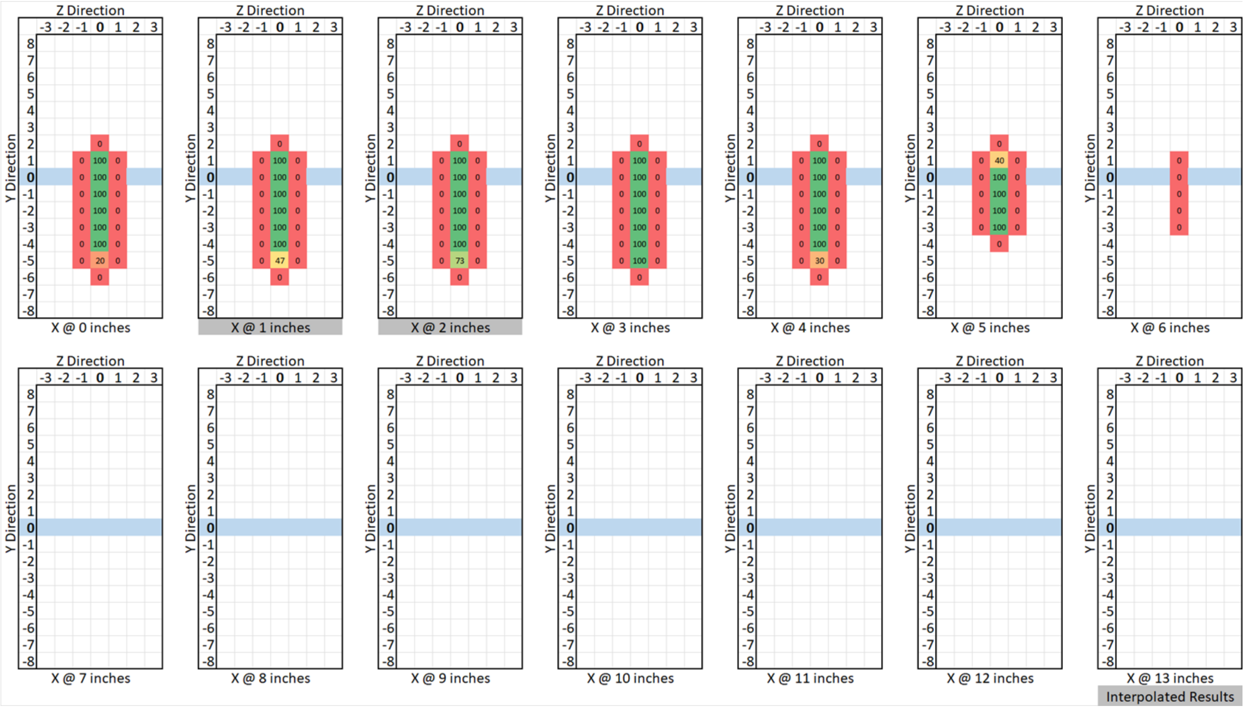
C5: Experiment 5: Heated Pushbutton

The fifth Guardian Wave experiment was performed at the six-inch range, but the pushbutton was heated to a higher temperature. This experiment used a small space heater to heat the pushbuttons. The heater was aimed towards the pushbutton around the button area.

Heated Pushbutton Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Pushbutton Temperature = Avg 102.5°F • Light: 144 Lux
100% Field Volume: 64in^3	

Heated Pushbutton Results



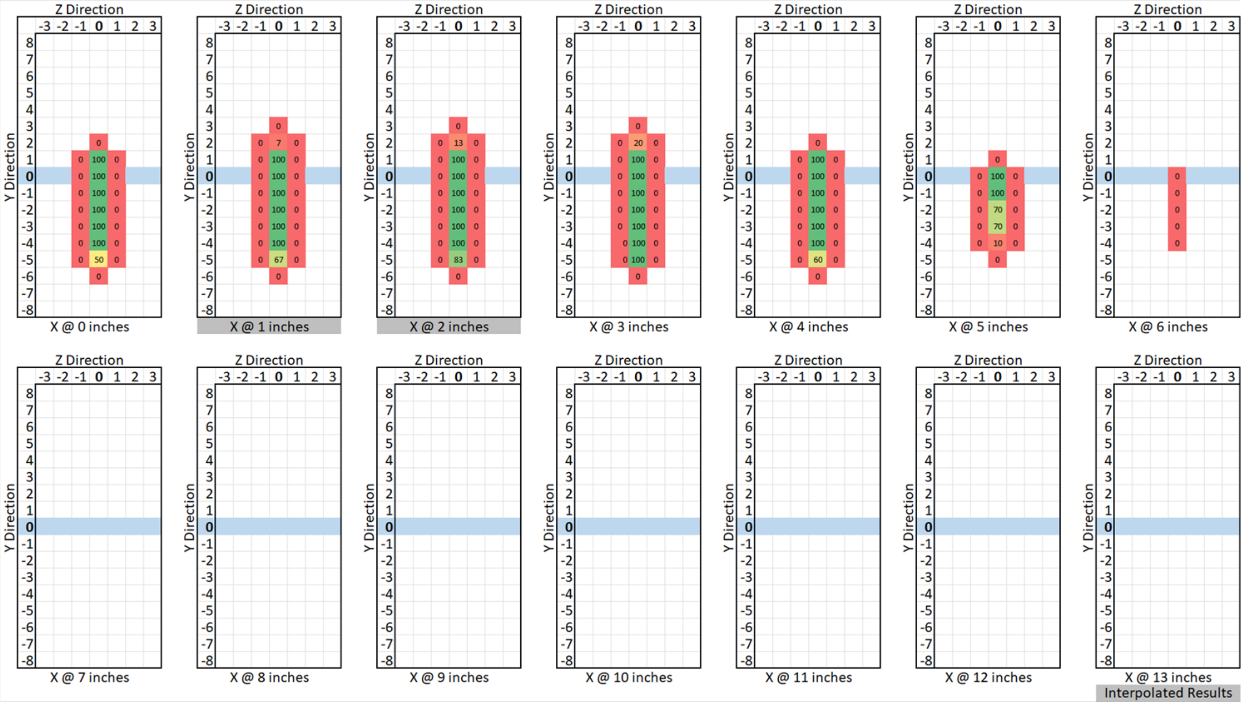
C6: Experiment 6: Wave Detection in Dark Environment

The sixth Guardian Wave experiment was performed at the six-inch range, but the lights in the lab were turned off.

Wave Detection in Dark Environment Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 1.5-4.8 Lux
100% Field Volume: 60in^3	

Wave Detection in Dark Environment Results



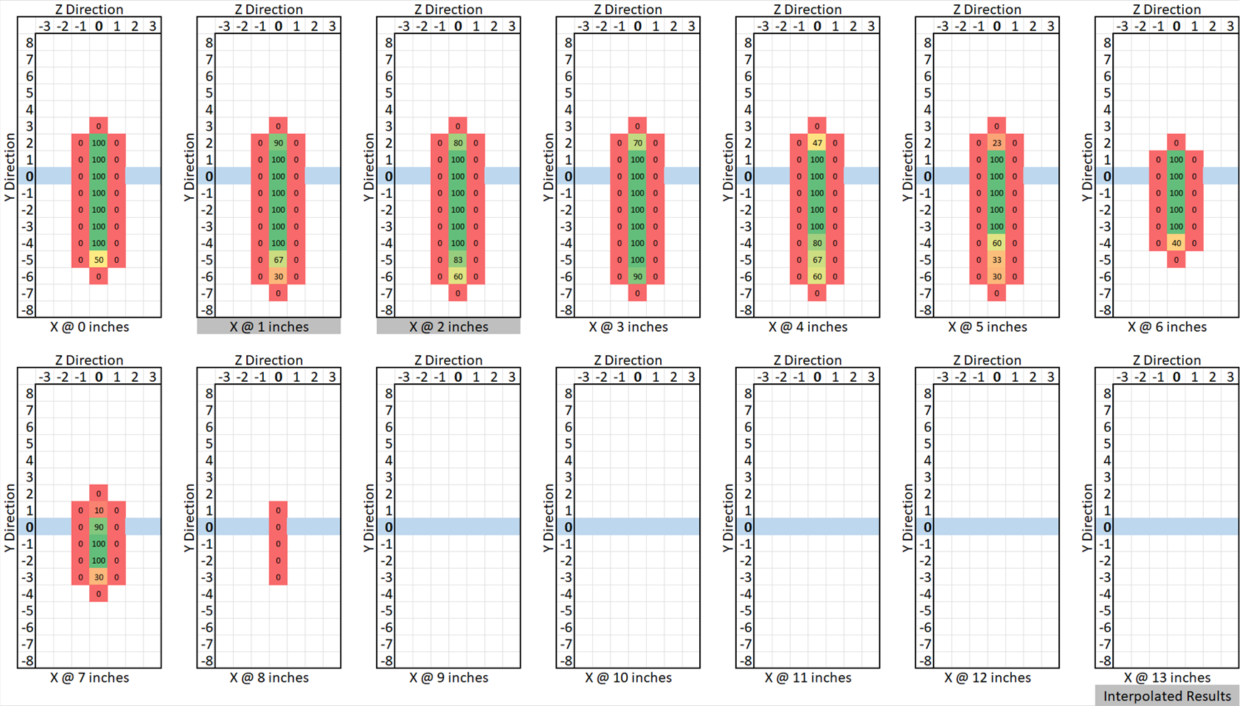
C7: Experiment 7: Fast Sensitivity

The Seventh Guardian Wave experiment was performed at the six-inch range, but the sensitivity was changed to the “Fast” setting

Fast Sensitivity Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 1 (Fast) • Delay = 100ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 92 Lux
100% Field Volume: 79in^3	

Fast Sensitivity Results



Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	100	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	50	0		
-6				0			
-7							
-8							

X @ 0 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	90	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	67	0		
-6			0	30	0		
-7				0			
-8							

X @ 1 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	80	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	83	0		
-6			0	60	0		
-7				0			
-8							

X @ 2 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	70	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	100	0		
-5			0	100	0		
-6			0	90	0		
-7				0			
-8							

X @ 3 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	47	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	80	0		
-5			0	67	0		
-6			0	60	0		
-7				0			
-8							

X @ 4 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3				0			
2			0	23	0		
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	60	0		
-5			0	33	0		
-6			0	30	0		
-7				0			
-8							

X @ 5 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	100	0		
0			0	100	0		
-1			0	100	0		
-2			0	100	0		
-3			0	100	0		
-4			0	40	0		
-5				0			
-6							
-7							
-8							

X @ 6 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2				0			
1			0	10	0		
0			0	90	0		
-1			0	100	0		
-2			0	100	0		
-3			0	30	0		
-4				0			
-5							
-6							
-7							
-8							

X @ 7 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1				0			
0				0			
-1				0			
-2				0			
-3				0			
-4							
-5							
-6							
-7							
-8							

X @ 8 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 9 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 10 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 11 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 12 inches

Z Direction

Y Direction	-3	-2	-1	0	1	2	3
8							
7							
6							
5							
4							
3							
2							
1							
0							
-1							
-2							
-3							
-4							
-5							
-6							
-7							
-8							

X @ 13 inches

Interpolated Results

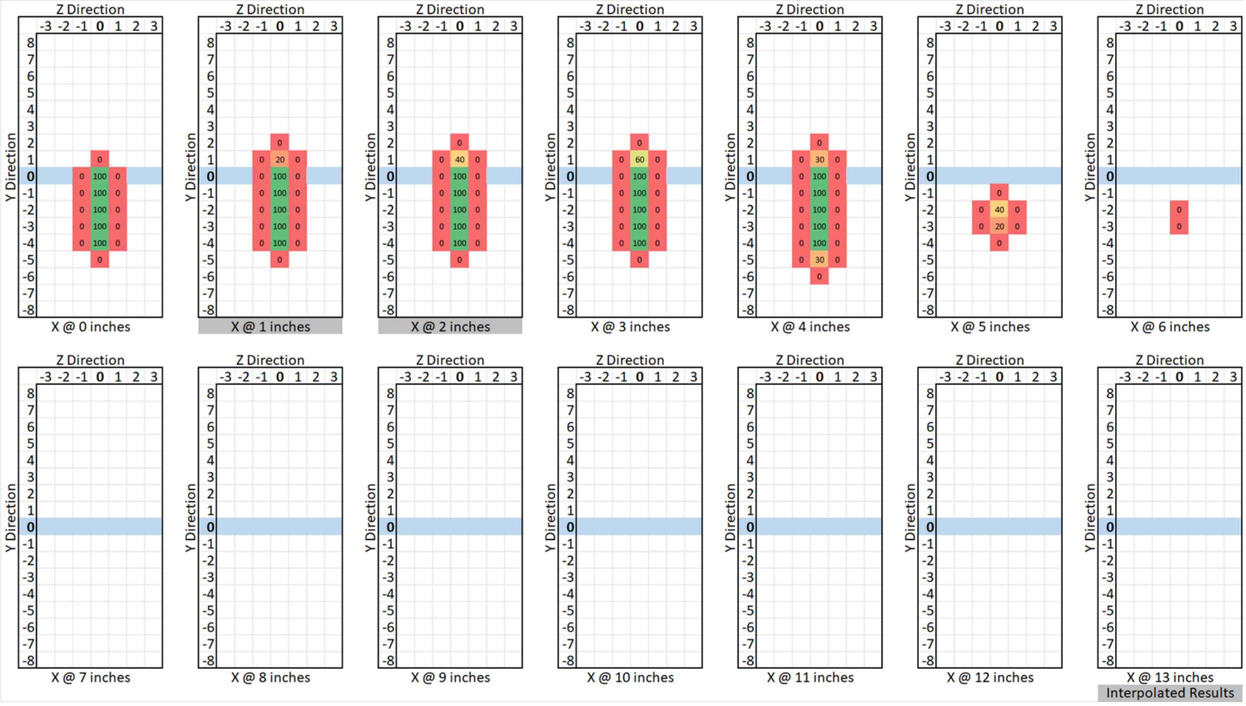
C8: Experiment 8: Slow Sensitivity

The eighth Guardian Wave experiment was performed at the six-inch range, but the sensitivity was changed to the “Slow” setting.

Slow Sensitivity Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
Range = 6-inch Sensitivity = 12 (Slow) Delay = 100ms Extended Press Time = 1000ms	Room Temperature = 75°F - 80°F Hand Temperature = 90.3°F – 92.8°F Light: 92 Lux
100% Field Volume: 45in^3	

Slow Sensitivity Results



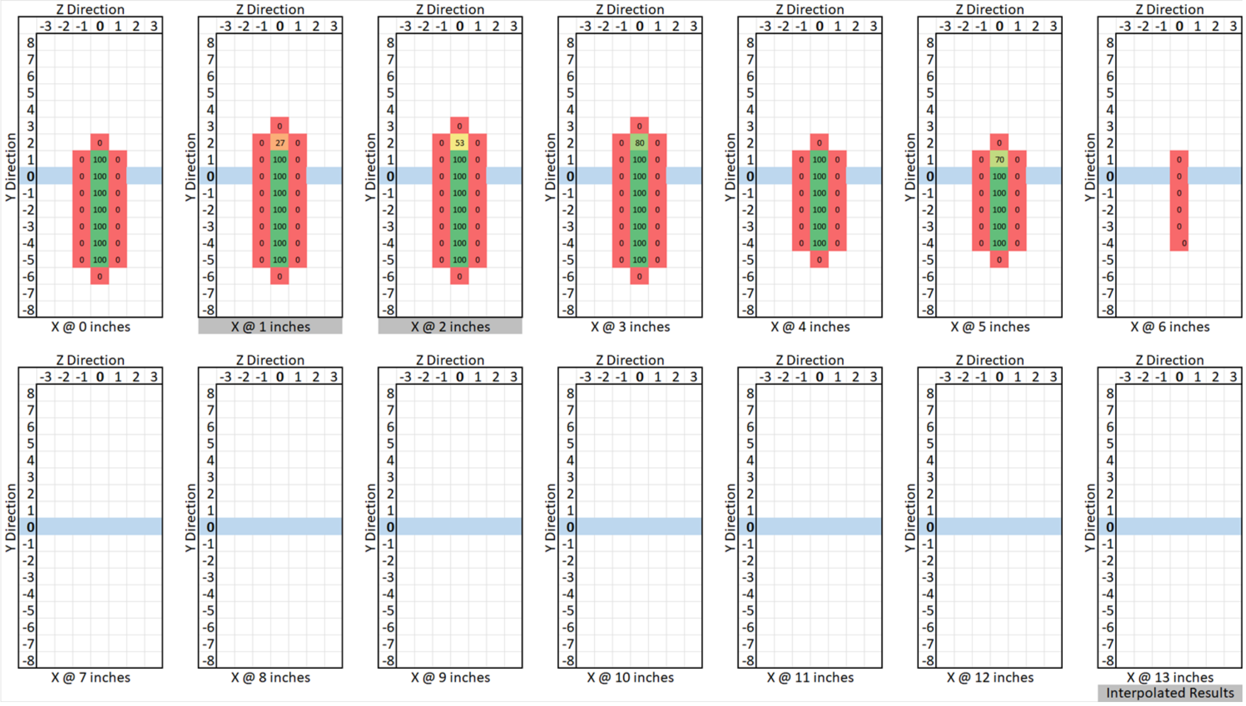
C9: Experiment 9: Minimum Delay

The ninth Guardian Wave experiment was performed at the six-inch range, but the delay setting was changed to the minimum allowed value.

Minimum Delay Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 5ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 92 Lux
100% Field Volume: 71in^3	

Minimum Delay Results



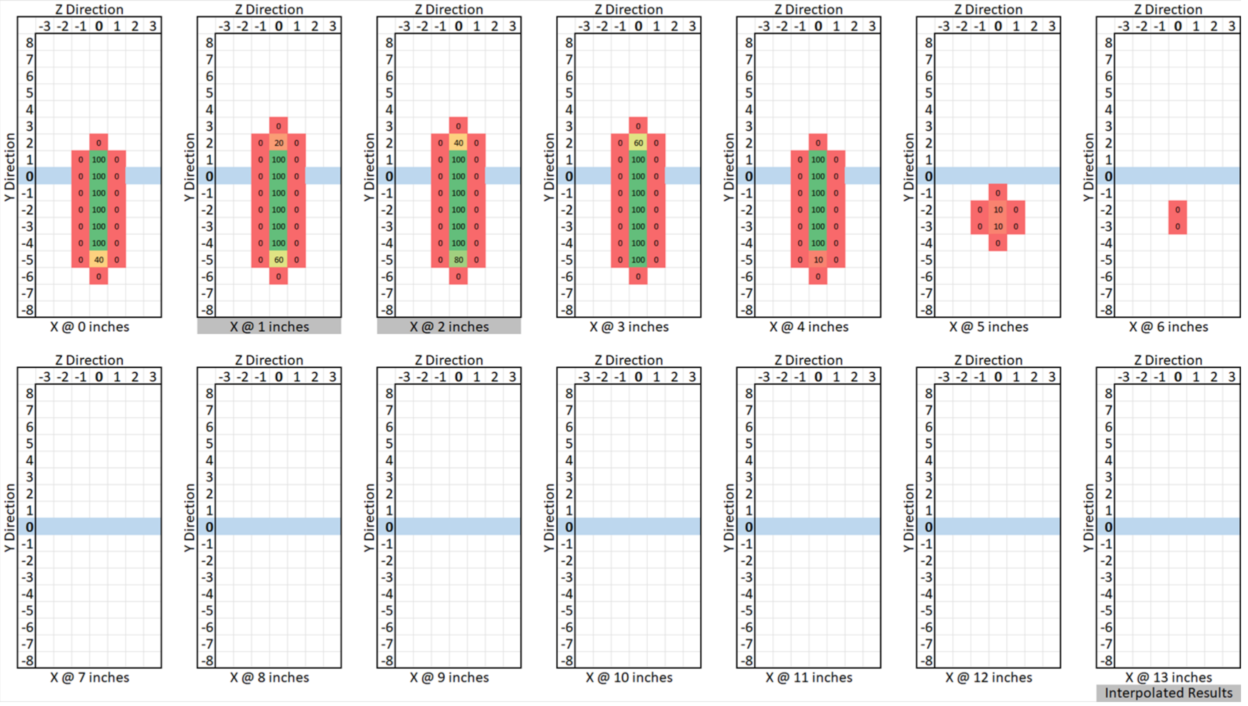
C10: Experiment 10: Maximum Delay

The tenth Guardian Wave experiment was performed at the six-inch range, and the delay setting was changed to the maximum allowed value.

Maximum Delay Settings, Environmental Conditions, and 100% Field Volume

Settings:	**Environmental Conditions:**
• Range = 6-inch • Sensitivity = 3 • Delay = 1000ms • Extended Press Time = 1000ms	• Room Temperature = 75°F - 80°F • Hand Temperature = 90.3°F – 92.8°F • Light: 92 Lux
100% Field Volume: 56in^3	

Maximum Delay Results



Appendix C: Site Identifications for Field Test

This section is focused on the selection of sites for the field test of advanced pushbuttons.

C1: Pushbutton Sites Data Overview

The City of Phoenix provided signal performance measure (SPM) dataset of total fourteen intersections in three stages. The dataset contains details about intersection ID, event code, event time and date, and phase related information. Event Code 45 signifies the registration of a pedestrian call, while Event Code 21 denotes the beginning of pedestrian WALK signal. The intersections that data were provided for are listed in **below.**

Intersection Locations for Provided by the City of Phoenix

	Site	Intersection
Group 1	1	Camelback & 15th Ave
	2	Bell & 19th Ave
	3	Indian School & 19th Ave
	4	Southern & 19th Ave
	5	Washington & 3rd St
	6	Baseline & 51st Ave
	7	Indian School & 51st Ave
Group 2	8	Camelback and 44th St
	9	Indian School and 15th Ave
	10	Indian School and 75th Ave
	11	Northern and 35th Ave
	12	Thunderbird and 19th Ave
Group 3	13	Indian School and 16th St
	14	Indian School and 7th Ave

C2: Data Analysis for Site Selection

The provided data was examined to identify intersections where pedestrian signals operate on button pushes rather than pedestrian recall. For each intersection in the SPM dataset, data was extracted regarding the number of pedestrian actuations and WALK indications for Phases 2/6 and Phases 4/8 for one day at each location. It is presumed that an intersection is operating in Call to Non-Actuated (CNA) / Pedestrian Recall if the number of WALK indications is equal to or greater than the number of pedestrian actuations. Any location where the number of pedestrian actuations exceeds the number of WALK indications was pedestrian actuated for the purposes of this work. The count of registered pedestrian calls and pedestrian WALK signals were documented, and the data was summarized based on each specific phase of signal operation. A condensed summary of pedestrian call information for each intersection is presented, with those presumed to be pedestrian actuated highlighted in bold text.

A brief summary of pedestrian call information for each intersection

Intersection	Pedestrian Call Information
Indian School and 7th Ave	Pedestrian WALK signal came on more than the number of pedestrian calls for all phases. Presumed to be CNA / Ped Recall.
Indian School and 16th St	Pedestrian WALK signal came on more than the number of pedestrian calls for all phases. Presumed to be CNA / Ped Recall.
Indian School and 15th Ave	Pedestrian WALK signal came on more than the number of pedestrian calls for all phases. Presumed to be CNA / Ped Recall.
Indian School and 75th Ave	**Pedestrian Calls Registered for all phases, with more Pedestrian Calls registered than WALK indications. Ped phases presumed to be actuated.**
Northern and 35th Ave	Pedestrian Walk signal came on more than the number of pedestrian calls for all phases. Presumed to be CNA / Ped Recall.
Camelback and 44th St	WALK signals came on more than the number of pedestrian calls for all phases. Presumed to be CNA / Ped Recall.
Thunderbird and 19th Ave	For phase 2 and 6 are on pedestrian recall. For phase 4 and 6, pedestrian WALK signals appeared more than the pedestrian registered calls. Presumed to be CNA / Ped Recall.
Southern and 19th Ave	**Pedestrian Calls Registered for all phases, with more Pedestrian Calls registered than WALK indications. Ped phases presumed to be actuated.**
Indian school and 19th Ave	Pedestrian calls registered for Phases 2 and 6, but Phases 2 and 6 WALK came on more than the number of ped calls. Presumed to be CNA / Ped Recall.
Indian school and 51st Ave	No Pedestrian Call Registered
Camelback and 15th Ave	Pedestrian Recall. Equal number of pedestrian calls and WALK indications.
Bell and 19th Ave	No Pedestrian Call Registered
Baseline and 51st Ave	No Pedestrian Call Registered

Washington and 3rd Street	Pedestrian Recall. Equal number of pedestrian calls and WALK indications.

C3: Selected Intersections for Field Data Analysis

From the analysis of pedestrian signal activations, only two intersections, 'Indian School and 75th Ave' and 'Southern and 19th Ave,' were found with more pedestrian calls than WALK indications. These two intersections are presumed fully actuated by pedestrian calls. Subsequent confirmation from Phoenix affirmed that all crosswalks at these locations are indeed actuated. Pedestrian signal statistics spanning 24 hours for these intersections are provided below.

Pedestrian call and WALK indication information of selected intersections.

Intersection & Date	Phase Number	Pedestrian Call Registered	WALK Indication Appeared
Indian School and 75th Ave Date: 09-11-2023	Phase 2	195 times	191 times
	Phase 6	199 times	194 times
	Phase 4	253 times	247 times
	Phase 8	251 times	246 times
Southern and 19th Ave Date: 08-24-2023	Phase 2	100 times	97 times
	Phase 6	105 times	101 times
	Phase 4	138 times	119 times
	Phase 8	137 times	116 times

Appendix D: Priority Intersections Categorized into Tier 1, Tier 2, and Tier 3

Inter-section #	Tier #	Street 1 Name	Street 2 Name	Pedestrian-Turning Vehicle Crashes	Intersection Rank
1	1	35TH AVE	PEORIA AVE	9	1
2	1	INDIAN SCHOOL RD	19TH AVE	8	2
3	1	UNION HILLS DR	19TH AVE	7	3
4	1	27TH AVE	INDIAN SCHOOL RD	7	3
5	1	CAVE CREEK RD	BELL RD	6	4
6	1	27TH AVE	BETHANY HOME RD	6	4
7	1	19TH AVE	PEORIA AVE	6	4
8	1	THOMAS RD	43RD AVE	6	4
9	1	MCDOWELL RD	36TH ST	5	5
10	1	19TH AVE	BELL RD	5	5
11	1	43RD AVE	BETHANY HOME RD	5	5
12	1	GREENWAY PKWY	CAVE CREEK RD	5	5
13	1	THOMAS RD	CENTRAL AVE	5	5
14	1	NORTHERN AVE	27TH AVE	5	5
15	1	SWEETWATER AVE	CAVE CREEK RD	5	5
16	2	19TH AVE	THUNDERBIRD RD	4	6
17	2	CAMELBACK RD	15TH AVE	4	6
18	2	PEORIA AVE	28TH DR	4	6
19	2	THOMAS RD	36TH ST	4	6
20	2	THOMAS RD	16TH ST	4	6
21	2	75TH AVE	THOMAS RD	4	6
22	2	MCDOWELL RD	CENTRAL AVE	4	6
23	2	INDIAN SCHOOL RD	51ST AVE	4	6
24	2	35TH AVE	GLENDALE AVE	4	6
25	2	75TH AVE	INDIAN SCHOOL RD	4	6

Inter-section #	Tier #	Street 1 Name	Street 2 Name	Pedestrian-Turning Vehicle Crashes	Intersection Rank
26	2	CAMELBACK RD	44TH ST	4	6
27	2	35TH AVE	UNION HILLS DR	4	6
28	2	27TH AVE	MISSOURI AVE	4	6
29	2	THOMAS RD	35TH AVE	4	6
30	2	THUNDERBIRD RD	N METRO NORTH CORPORATE PARK	4	6
31	2	15TH AVE	INDIAN SCHOOL RD	4	6
32	2	NORTHERN AVE	23RD AVE	4	6
33	2	THOMAS RD	15TH AVE	4	6
34	2	3RD ST	WASHINGTON ST	4	6
35	2	43RD AVE	PEORIA AVE	4	6
36	2	BETHANY HOME RD	35TH AVE	4	6
37	3	CAMPBELL AVE	51ST AVE	3	7
38	3	VAN BUREN ST	32ND ST	3	7
39	3	DUNLAP AVE	23RD AVE	3	7
40	3	19TH AVE	GLENDALE AVE	3	7
41	3	BUCKEYE RD	67TH AVE	3	7
42	3	DUNLAP AVE	15TH AVE	3	7
43	3	43RD AVE	CAMELBACK RD	3	7
44	3	NORTHERN AVE	21ST AVE	3	7
45	3	67TH AVE	MCDOWELL RD	3	7
46	3	CAVE CREEK RD	GREENWAY RD	3	7
47	3	INDIAN SCHOOL RD	23RD AVE	3	7
48	3	NORTHERN AVE	35TH AVE	3	7
49	3	INDIAN SCHOOL RD	7TH AVE	3	7
50	3	19TH AVE	WOOD DR	3	7
51	3	19TH AVE	BASELINE RD	3	7
52	3	43RD AVE	BELL RD	3	7
53	3	16TH ST	INDIAN SCHOOL RD	3	7
54	3	INDIAN SCHOOL RD	CENTRAL AVE	3	7
55	3	CAMELBACK RD	12TH ST	3	7

Inter-section #	Tier #	Street 1 Name	Street 2 Name	Pedestrian-Turning Vehicle Crashes	Intersection Rank
56	3	CAMELBACK RD	16TH ST	3	7
57	3	7TH ST	GREENWAY PKWY	3	7
58	3	35TH AVE	GREENWAY RD	3	7
59	3	32ND ST	THOMAS RD	3	7
60	3	SOUTHERN AVE	19TH AVE	3	7
61	3	3RD ST	BELL RD	3	7
62	3	MCDOWELL RD	44TH ST	3	7
63	3	51ST AVE	CACTUS RD	3	7
64	3	48TH ST	VAN BUREN ST	3	7
65	3	51ST AVE	BASELINE RD	3	7
66	3	24TH ST	CAMELBACK RD	3	7
67	3	INDIAN SCHOOL RD	83RD AVE	3	7
68	3	GLENDALE AVE	17TH DR	3	7
69	3	DEER VALLEY RD	27TH AVE	3	7
70	3	ENCANTO BLVD	43RD AVE	3	7
71	3	THOMAS RD	52ND ST	3	7
72	3	GREENWAY RD	TATUM BLVD	3	7
73	3	INDIAN SCHOOL RD	3RD ST	3	7
74	3	CAMELBACK RD	40TH ST	3	7
75	3	THOMAS RD	44TH ST	3	7
76	3	VAN BUREN ST	11TH ST	3	7
77	3	INDIAN SCHOOL RD	56TH ST	3	7
78	3	16TH ST	SOUTHERN AVE	3	7
79	3	19TH AVE	MARYLAND AVE	3	7
80	3	23RD AVE	BETHANY HOME RD	3	7
81	3	ROOSEVELT ST	32ND ST	3	7
82	3	35TH AVE	BELL RD	3	7
83	3	32ND ST	OAK ST	3	7
84	3	MCDOWELL RD	43RD AVE	3	7
85	3	OSBORN RD	16TH ST	3	7

Appendix E: Phoenix Signalized Intersection Spreadsheet Column/Variable Definitions

Column A: Site #

Unique site ID number assigned to each intersection.

Columns B and C: Street 1 and Street 2 Name

Names of the intersection streets for each signalized intersection.

Column D: Number of Pedestrian-Turning Vehicle Crashes

Number of crashes that involved a turning vehicle (left or right) and a crossing pedestrian at each intersection for the years 2016-2022.

Column E: Intersection Rank based on Number of Pedestrian-Turning Vehicle Crashes

Rank of each intersection based on the number of crashes in Column D. Note that a lower rank means higher crashes, and there are many intersections with tied ranks.

Columns F and G: Latitude and Longitude

GPS coordinates for each intersection.

Column H: Google Maps Hyperlink

Hyperlink to the Google Map view of each intersection.

Column I: T-intersection (0 or 1)

This is a binary feature indicating whether the intersection is a T-intersection, which means, one road ends at the intersection whereas, the ending road's perpendicular road goes through the intersection, ultimately forming a T-shaped geometry. The identification was done manually by looking at the location on Google Maps.

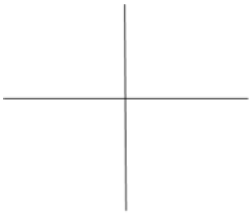
From the literature review and guidelines by several jurisdictions (as described in Task 2), it has been observed that LPI is recommended in T-intersections because there are only turning vehicles from the cross street to the main street. The identification was done manually by looking at the location on Google Maps.

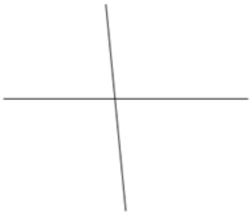
Columns J-M: One-way Street (0 or 1)

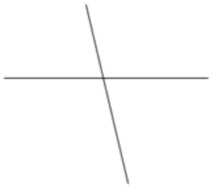
Columns J-M are binary indicators for whether the street is one-way (marked as 1) for the North, South, East, and West Leg of the intersection, respectively.

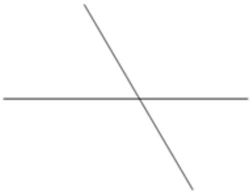
Column N: Intersection skewed approx >15 degrees? (0 or 1)

Skewed intersections can play a role in the decision of LPI installment for their unique challenges, such as lower visibility, higher vehicle turning time in select directions, and even higher crossing time for pedestrians due to the higher length of the slanted crosswalks. For every intersection, an imaginary line was drawn through the centerline of each roadway. The two lines share a point in the center of the intersection. If the acute angle is at least 15 degrees, the intersection is marked as skewed with the binary variable 'skewed' set to 1 in the dataset. Otherwise, the variable is set to 0 for that intersection. Some examples are presented below.


0 degree skew
(enter 0)


Minor skew
<15 degrees
(enter 0)


15 degree
Skew example
(enter 1)


>15 degree
Skew (enter 1)

Columns O-R: Obvious sight obstructions at intersection corners (0 or 1)

Each corner in the sidewalk area of the intersections was checked between the crossing ramps for any potential sight obstructions. Obstructions can be created by many different objects, such as utility boxes, vegetation, etc. Four binary variables were needed to represent this condition for each intersection as there are four corners of a usual intersection- Northeast, Southeast, Southwest, and Northwest corners. Obstructions were be specified for each of them separately. An example of the area which was checked on each corner is presented in the figure below.

Columns S-V: Median Present Through Crosswalk? (0 or 1)

A median through the crosswalk can create a potential refuge island for pedestrians. This feature was set to ‘1’ if there was a median through the crosswalk in the intersection, otherwise, it was set to 0. For every intersection, four binary variables were needed, one for each leg of the four crosswalks - North, East, South, and West legs. A hypothetical example of a case where a median is present through the crosswalk is presented in the figure below.

Columns W-Z: Crosswalk Length in ft (enter 0 if crosswalk doesn't exist)

Crosswalk length was measured in feet from the edge of a curb to the edge of the curb on the opposite side through the middle of the crosswalk. If there is no crosswalk in a leg of an intersection, ‘NA’ was entered in the spreadsheet. Four values were needed for each intersection, one for each leg.

Columns AA-AD: No Right Turn on Red (NTROR) sign (0 or 1)
The street view of Google Maps was utilized for each intersection to find out whether the intersection had a “No Right Turn On Red” sign. For every intersection, there are four binary variables, one for each intersection approach - Northbound, Southbound, Eastbound, and Westbound. If a NTROR sign is present for a particular approach, 1 is entered for that approach in the spreadsheet, otherwise 0.

Columns AE-AH: Protected turn phase (L = protected left turn phase, R = protected right turn phase, LR = both, 0 if neither)
For each approach of an intersection, it was identified whether there is a signalized protected turn phase based on observation of left turn signal heads. A protected left turn phase was considered to be either a protected left turn or a protected-permissive left turn. For right turns, the existence of right-turn signal heads was investigated. Based on the existence of the left turn signal heads, right turn signal heads, both, or neither, the variable for the corresponding direction was set to L, R, LR, or 0 as defined in the spreadsheet column heading.

Columns AI-AL: Exclusive turn lanes? (L = exclusive left turn lane (LL for dual), R = exclusive right turn lane (RR for dual), LR=both, 0 if neither)
From the street views and aerial views of Google maps, it was identified for each approach of an intersection whether there are exclusive turning lanes. Both exclusive left and right turn lanes (and whether they were dual) were recorded for each approach as defined in the spreadsheet column heading.

Columns AM-AP: Push Button at intersection corners? (0 or 1)
For each leg of the intersection, Google Street view was used determine whether pedestrian push buttons were present (coded as a 1 if buttons were present, 0 otherwise).

Columns AQ-AS: Located within Specified Distance from a School
For each of these three columns, the spreadsheet specifies whether the intersection is located within the distance range (as specified in each column heading) from a school. These columns are marked with a yes (Y) or no (N) and were determined using GIS.

Columns AT and AU: Located within Specified Distance from a Transit Stop
For each of these two columns, the spreadsheet specifies whether the intersection is located within the distance range (as specified in each column heading) from a transit. These columns are marked with a yes (Y) or no (N) and were determined using GIS.

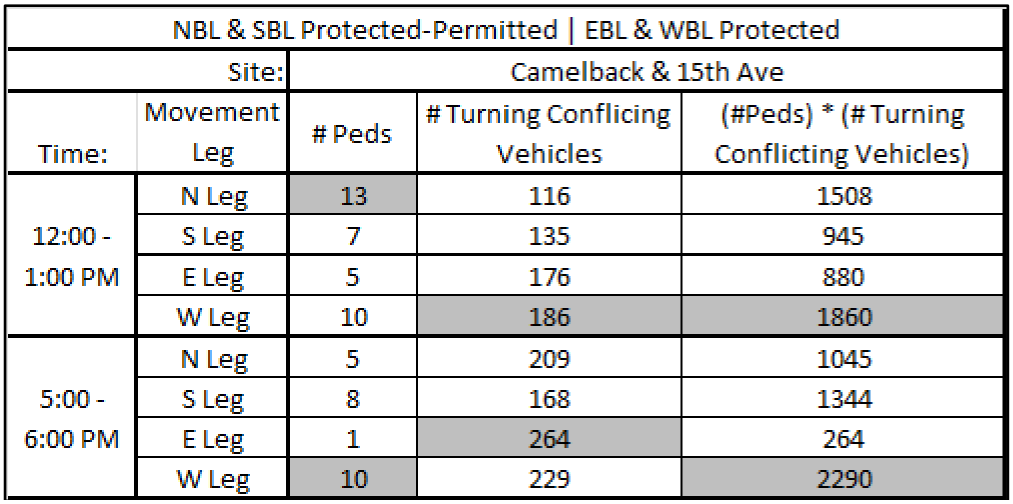
Column AV: Additional Notes/Comments
This column was used by data collectors to note any atypical conditions/characteristics observed during the course of Google Maps/Street view data collection such as irregular geometry, presence of light rail in or near the intersection, etc.

Appendix F: Crosswalk Rank Detailed Results for LPI Site Selection

Camelback & 15th Ave Results

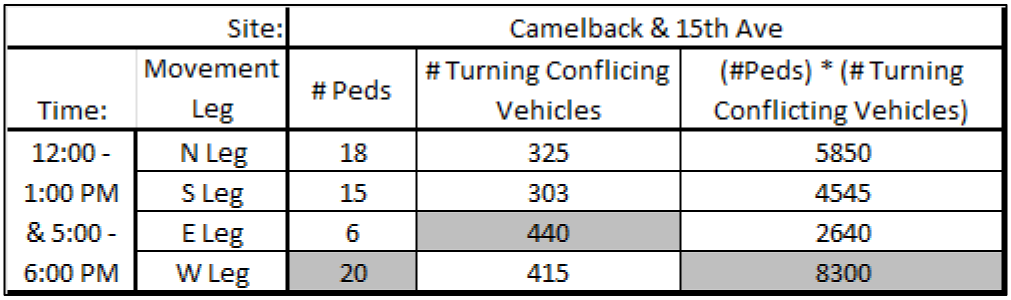
The initial result shows the data collected when the phases were in the permitted portion of the protected-permitted phases and protected for the always protected phases at Camelback & 15th Ave. The intermediate result shows the data collected over the combined period.

Initial Results for Camelback & 15th Ave



NBL & SBL Protected-Permitted | EBL & WBL Protected				
	Site:	Camelback & 15th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicting Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	13	116	1508
	S Leg	7	135	945
	E Leg	5	176	880
	W Leg	10	186	1860
5:00 - 6:00 PM	N Leg	5	209	1045
	S Leg	8	168	1344
	E Leg	1	264	264
	W Leg	10	229	2290

Intermediate Results for Camelback & 15th Ave

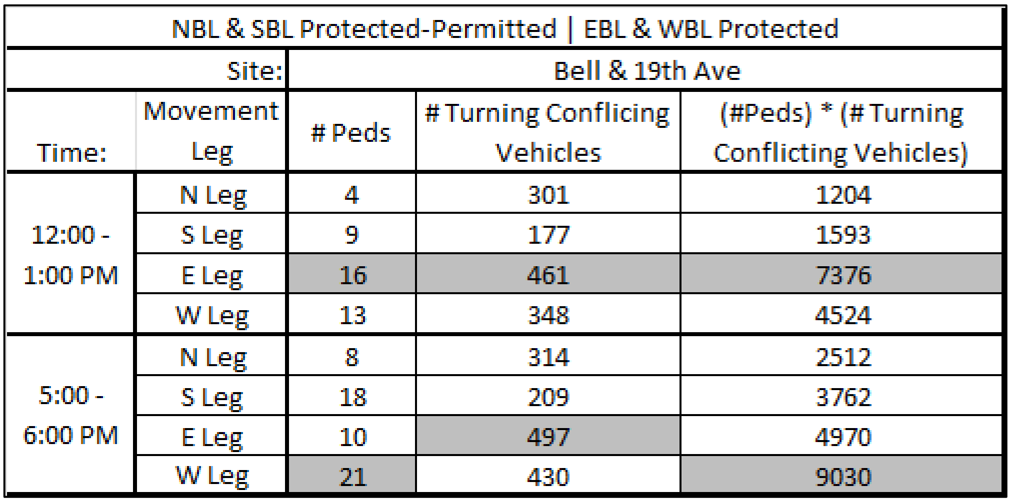


	Site:	Camelback & 15th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicting Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	18	325	5850
	S Leg	15	303	4545
	E Leg	6	440	2640
	W Leg	20	415	8300

Bell & 19th Ave Results

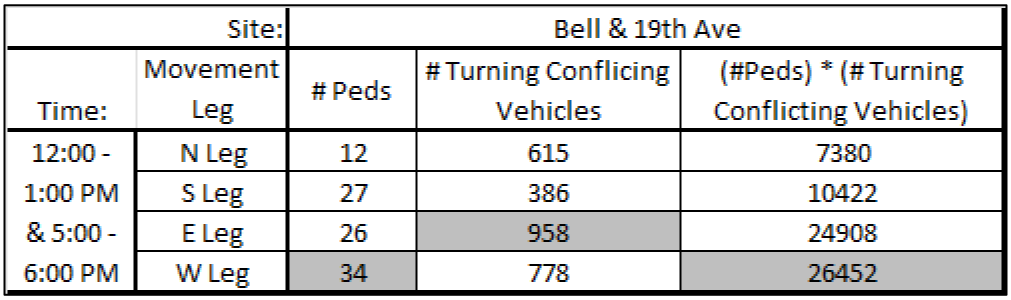
The initial result shows the data collected when the phases were in the permitted portion of the protected-permitted phases and protected for the always protected phases at Bell & 19th Ave. The intermediate result shows the data collected over the combined period.

Initial Results for Bell & 19th Ave



NBL & SBL Protected-Permitted | EBL & WBL Protected				
	Site:	Bell & 19th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	4	301	1204
	S Leg	9	177	1593
	E Leg	16	461	7376
	W Leg	13	348	4524
5:00 - 6:00 PM	N Leg	8	314	2512
	S Leg	18	209	3762
	E Leg	10	497	4970
	W Leg	21	430	9030

Intermediate Results for Bell & 19th Ave

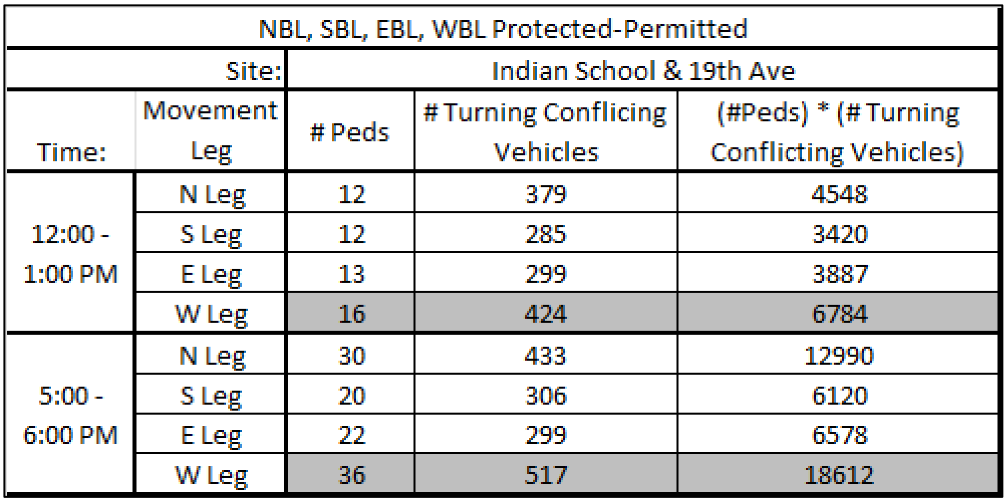


	Site:	Bell & 19th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	12	615	7380
	S Leg	27	386	10422
	E Leg	26	958	24908
	W Leg	34	778	26452

Indian School & 19th Ave Results

The initial result shows the data collected when the phases were in the permitted portion of the protected-permitted phases at Indian School Rd & 19th Ave. The intermediate result shows the data collected over the combined period.

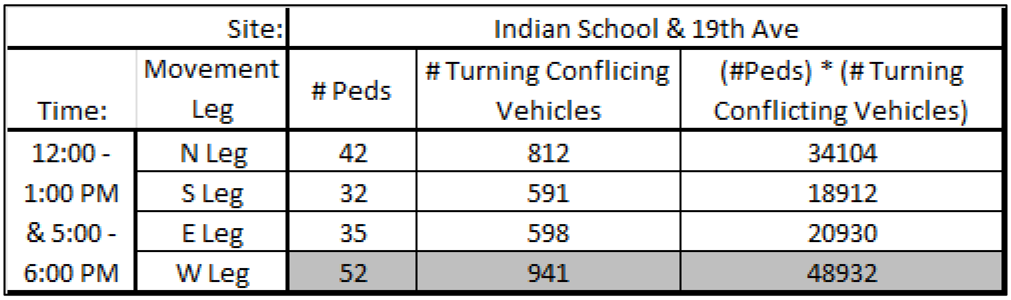
Initial Results for Indian School & 19th Ave



NBL, SBL, EBL, WBL Protected-Permitted

	Site:	Indian School & 19th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	12	379	4548
	S Leg	12	285	3420
	E Leg	13	299	3887
	W Leg	16	424	6784
5:00 - 6:00 PM	N Leg	30	433	12990
	S Leg	20	306	6120
	E Leg	22	299	6578
	W Leg	36	517	18612

Intermediate Results for Indian School & 19th Ave



	Site:	Indian School & 19th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	42	812	34104
	S Leg	32	591	18912
	E Leg	35	598	20930
	W Leg	52	941	48932

Southern & 19th Ave Results

The initial result shows the data collected when the phases were in the permitted portion of the protected-permitted phases at Southern & 19th Ave. The intermediate result shows the data collected over the combined period.

Initial Results for Southern & 19th Ave

NBL, SBL, EBL, WBL Protected-Permitted				
	Site:	Southern & 19th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	4	309	1236
	S Leg	7	403	2821
	E Leg	14	352	4928
	W Leg	4	216	864
5:00 - 6:00 PM	N Leg	5	403	2015
	S Leg	12	399	4788
	E Leg	11	347	3817
	W Leg	11	401	4411

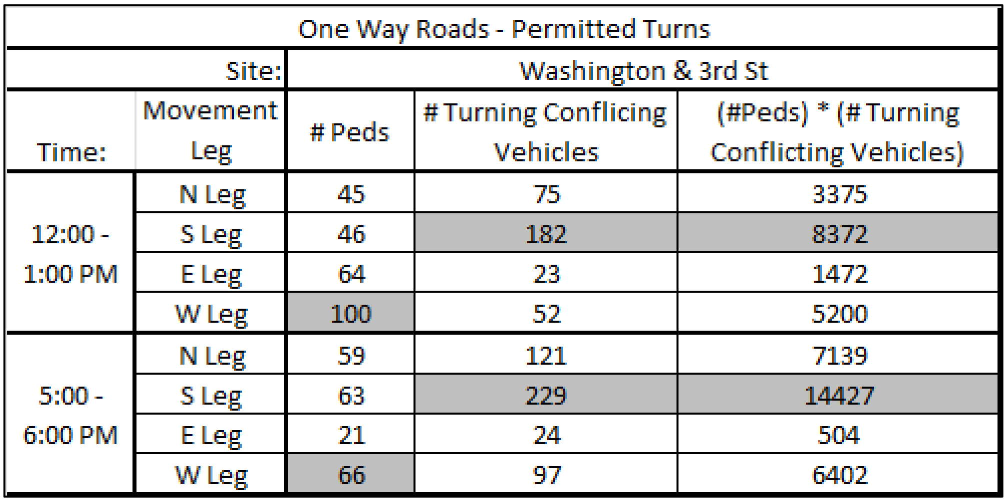
Intermediate Results for Southern & 19th Ave

	Site:	Southern & 19th Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	9	712	6408
	S Leg	19	802	15238
	E Leg	25	699	17475
	W Leg	15	617	9255

Washington & 3rd St Results

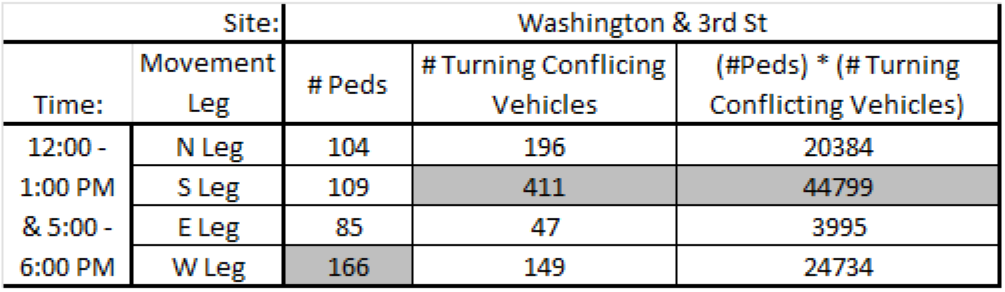
The initial result shows the data collected in the permitted phases at Washington and 3rd St. The intermediate result shows the data collected over the combined period.

Initial Results for Washington & 3rd St Permitted Phases



One Way Roads - Permitted Turns				
	Site:	Washington & 3rd St		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	45	75	3375
	S Leg	46	182	8372
	E Leg	64	23	1472
	W Leg	100	52	5200
5:00 - 6:00 PM	N Leg	59	121	7139
	S Leg	63	229	14427
	E Leg	21	24	504
	W Leg	66	97	6402

Intermediate Results for Washington & 3rd St

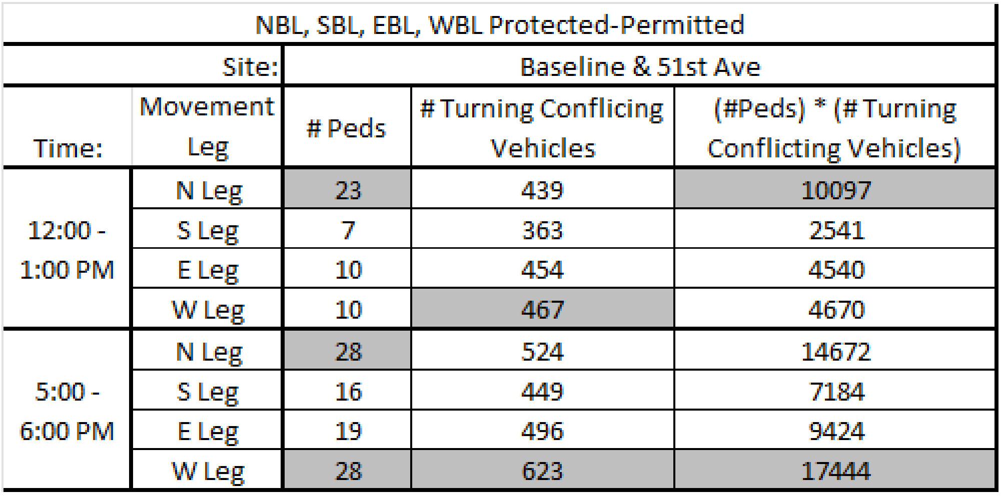


	Site:	Washington & 3rd St		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	104	196	20384
	S Leg	109	411	44799
	E Leg	85	47	3995
	W Leg	166	149	24734

Baseline & 51st Ave Results

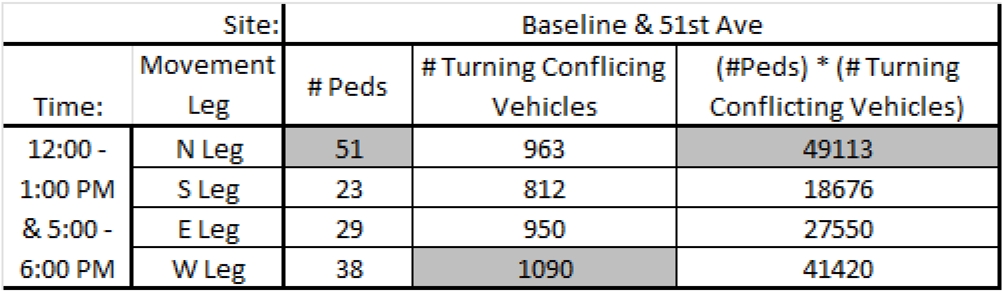
The initial result shows the data collected when the phases were in the permitted portion of the protected-permitted phases at Baseline & 51st Ave. The intermediate result shows the data collected over the combined period.

Initial Results for Baseline & 51st Ave



NBL, SBL, EBL, WBL Protected-Permitted				
	Site:	Baseline & 51st Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM	N Leg	23	439	10097
	S Leg	7	363	2541
	E Leg	10	454	4540
	W Leg	10	467	4670
5:00 - 6:00 PM	N Leg	28	524	14672
	S Leg	16	449	7184
	E Leg	19	496	9424
	W Leg	28	623	17444

Intermediate Results for Baseline & 51st Ave

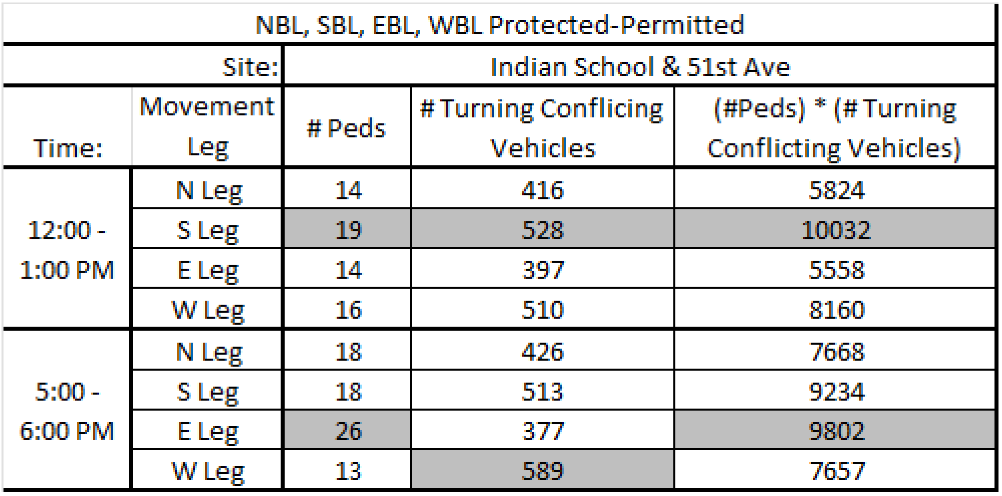


	Site:	Baseline & 51st Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicting Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	51	963	49113
	S Leg	23	812	18676
	E Leg	29	950	27550
	W Leg	38	1090	41420

Indian School & 51^{st} Ave Results

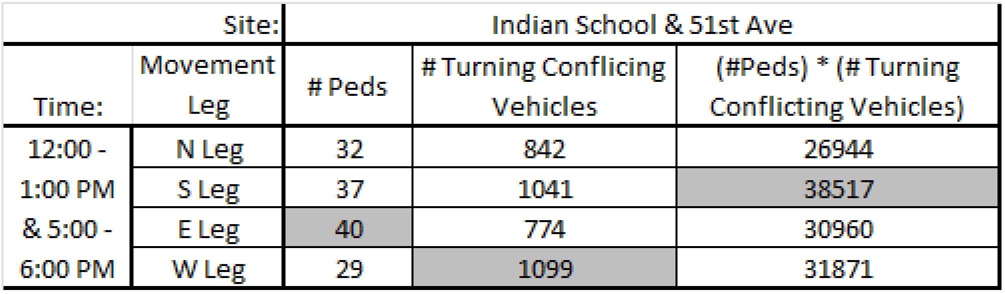
The initial result shows the data collected when the phases were in the permitted portion of the protected-permitted phases at Indian School Rd & 51^{st} Ave. The intermediate result shows the data collected over the combined period.

Initial Results for Indian School & 51^{st} Ave



NBL, SBL, EBL, WBL Protected-Permitted				
Site:		Indian School & 51st Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicing Vehicles)
12:00 - 1:00 PM	N Leg	14	416	5824
	S Leg	19	528	10032
	E Leg	14	397	5558
	W Leg	16	510	8160
5:00 - 6:00 PM	N Leg	18	426	7668
	S Leg	18	513	9234
	E Leg	26	377	9802
	W Leg	13	589	7657

Intermediate Results for Indian School & 51^{st} Ave



Site:		Indian School & 51st Ave		
Time:	Movement Leg	# Peds	# Turning Conflicing Vehicles	(#Peds) * (# Turning Conflicing Vehicles)
12:00 - 1:00 PM & 5:00 - 6:00 PM	N Leg	32	842	26944
	S Leg	37	1041	38517
	E Leg	40	774	30960
	W Leg	29	1099	31871

Appendix G: Pedestrian-Turning Vehicle Conflict Data Reduction

Instruction for Conflict Data Reduction

Any video software with a resolution of one hundredth or thousandth of a second may be used. Details regarding each column in the conflict data collection template are provided below:

Site Location (Column A): Identify site location name (e.g., Indian School Rd & 19th Ave)

Crosswalk Position (Column B): Identify crosswalk position (e.g., NE, NW, SE, or SW)

Crosswalk Length (Column C): Crosswalk length was measured in feet from the edge of a curb to the edge of the curb on opposite side through the middle of the crosswalk using Google Maps Aerial view.

Number of Lanes (Column D): Identify number of lanes of the street adjacent to the crosswalk.

Camera Placement (Column E): Enter camera placement/label (i.e., NW, SW, NE, SE, etc....) of camera that is being viewed for data collection.

Time of Day (Column F): Enter time of day of the incident. Incident should be within the study period between 7am-7pm and in the format [hh:mm].

Video ID (Column G): Enter video ID #/name that the event was recorded from.

Conflict No. (Column H): Unique ID number assigned to each conflict.

Conflict Location (Column I): Enter the lane number adjacent to the crosswalk as conflict location. Lane numbering will begin with the lane closest to the camera.

WALK Indication time Stamp (Column J): Record time when pedestrian WALK indication signal starts in the format [hh:mm:ss.00].

FDW Indication time Stamp (Column K): Record time when pedestrian flashing Don't Walk (FDW) indication signal starts in the format [hh:mm:ss.00].

DW Indication time Stamp (Column L): Record time when pedestrian Don't Walk (DW) indication signal starts in the format [hh:mm:ss.00].

Unit 1 (Column M): Enter the code of the first unit that enters the conflict zone. Use code 1 for Pedestrian, 2 for Passenger Vehicle, 3 for Heavy Vehicle, 4 for Bike, or 5 for Scooter.

Unit 1 Departure Time (Column N): Record the time when Unit 1 exits the conflict zone in the format [hh:mm:ss.00]. A section of the unit should be referenced (e.g., front bumper or tire) for consistency for vehicles.

Unit 2 (Column O): Enter the code of the second unit that enters the conflict zone. Use code 1 for Pedestrian, 2 for Passenger Vehicle, 3 for Heavy Vehicle, 4 for Bike, or 5 for Scooter.

Unit 2 Arrival Time (Column P): Record the time when Unit 2 enters the conflict zone. A section of the unit should be referenced (e.g., front bumper or tire) for consistency for vehicles.

PET Value (Column Q): Post-Encroachment Time (PET) is calculated automatically in the spreadsheet. This column determines the difference between times stamps of the Unit 2's arrival at the conflict box and Unit 1's departure from the conflict box. If Column Q is equal or less than 5 seconds, the rest of the columns (Column R to Column AQ) need to be filled, otherwise not. Data needs to collect for pedestrians (including signal violators) conflicting with turning vehicles. Do not need to collect data for conflict with through vehicles. Be careful noticing the conflicts with PET values less than 5 for the pedestrians who did not start crossing or reached the other side of the crosswalk and left the video view.

Conflict Time after WALK Signal (Column R): Calculated automatically in the spreadsheet. This column determines the difference between times stamps of the Unit 2's arrival at the conflict box and start of WALK indication signal.

Vehicle Direction (Column S): Enter code 1 for vehicle taking left turn, or 2 for vehicle taking right turn.

Pedestrian Movement Direction (Column T): Enter code 1 for pedestrian moving away from the camera, or 2 for pedestrian moving towards the camera.

Vehicle Speed Time Stamp #1 (Column U): Enter time when the unit's front wheel/bumper crosses over speed landmark 1.

Vehicle Speed Time Stamp #2 (Column V): Enter time when the unit's front wheel/bumper crosses over speed landmark 2.

Landmarks distance (Column W): Landmarks distance (Crosswalk width) was measured in feet using Google Maps Aerial view.

Elapsed Time for Speed Measurement (Column X): Calculate automatically in the spreadsheet. This column determines the time difference between vehicle speed time stamp 1 and 2.

Speed (Column Y & Z): These columns automatically calculate the speed of the unit based on the distance between two landmarks and elapsed time. Column Y determines speed in feet per second (fps), while Column Z converts fps to miles per hour (mph).

Driver Evasive action (Column AA): Enter code 0 for no evasive action taken, 1 for hard braking, 2 for hard swerving, or 3 for other evasive action taken during the observed event (include comment in column AR for 'other' evasive action).

Pedestrian Evasive action (Column AB): Enter code 0 for no evasive action taken, 1 for hard stopping, 2 for hard swerving, or 3 for other evasive action taken during the observed event (include comment in column AR for 'other' evasive action).

Driver Violation (Column AC): Enter code 0 for no violation, 1 for red light running, 2 for rolling stop, 3 for stopping inside crosswalk, or 4 for other violation observed during the event (include comment in column AR for 'other' driver violation).

Pedestrian Distraction (Column AD): Enter code 0 for no distraction, 1 for talking on cell, 2 for texting on cell, 3 for headphones, or 4 for other pedestrian distraction observed during the event (include comment in column AR for 'other' pedestrian distraction).

Pedestrian Age (Column AE): Enter code 1 for child, 2 for adult, 3 for older adult, or 4 for unknown. Use your best judgement to estimate pedestrian age.

Pedestrian Gender (Column AF): Enter code 1 for male, 2 for female, or 3 for unknown. Use your best judgement to estimate pedestrian gender.

Pedestrian Group Size (Column AG): Enter the size of the group this pedestrian belongs to. A group is defined as a set of one or more pedestrians who are crossing the street towards the same direction and waited for the WALK signal or started their crossing at the same time.

Pedestrian with Additional Mobility Device (Column AH): Enter code 0 for none, 1 for wheelchair/walking aid, 2 for stroller, 3 for device (bicycle, electric bike, skateboard, etc.) ridden, 4 for device walked, or 5 for other mobility device (include comment in column AR).

Pedestrian Starts Crossing at WALK/FDW/SDW (Columns AI, AJ & AK): Identify when pedestrian starts crossing the crosswalk. For any pedestrian, enter 'Yes' to exactly one of the three columns and 'No' to the other two. For example, if the crossing started during the WALK signal, enter 'Yes' to Column AI and 'No' to Columns AJ and AK.

Pedestrian Pushed Button/ Anyone in the Group Pushed Button? (Col AL & AM): Enter 'Yes' to Column AL if this pedestrian pushed the button, otherwise enter 'No'. Enter 'Yes' to Column AM if anyone from this group pushed the button, otherwise enter 'No'.

Pedestrian Crossing Start Time and End Time (Column AN & AO): Identify when pedestrian starts and ends crossing the crosswalk. Enter the time when the pedestrian takes their first step into the crosswalk to Column AN. Enter the time when the pedestrian reaches the curb of the other side of the crosswalk to Column AO.

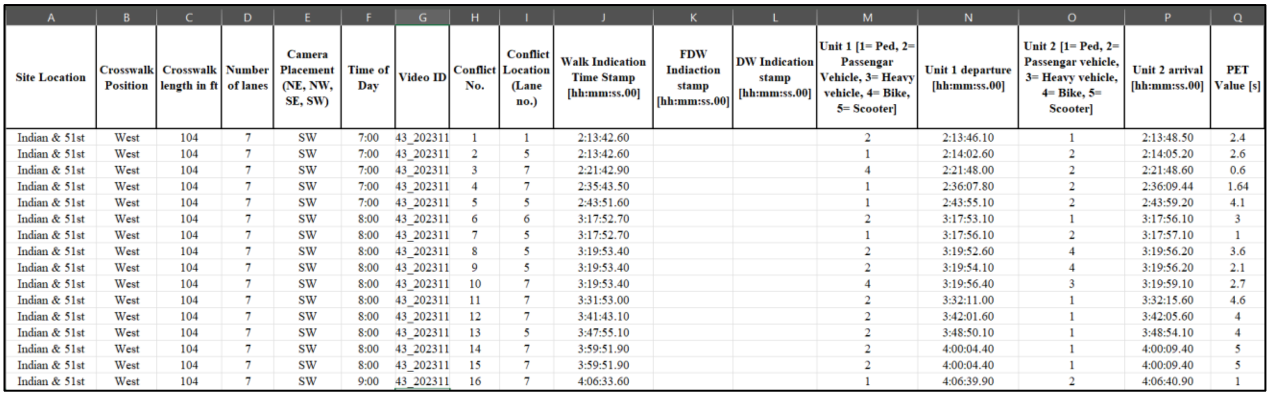
Pedestrian Crossing Time (Column AP): Calculate automatically in the spreadsheet. This column determines the time difference between pedestrian crossing start time and end time in second.

Pedestrian Walking Speed (Column AQ): This column automatically calculates the pedestrian walking speed based on crosswalk length and pedestrian crossing time in ft/sec.

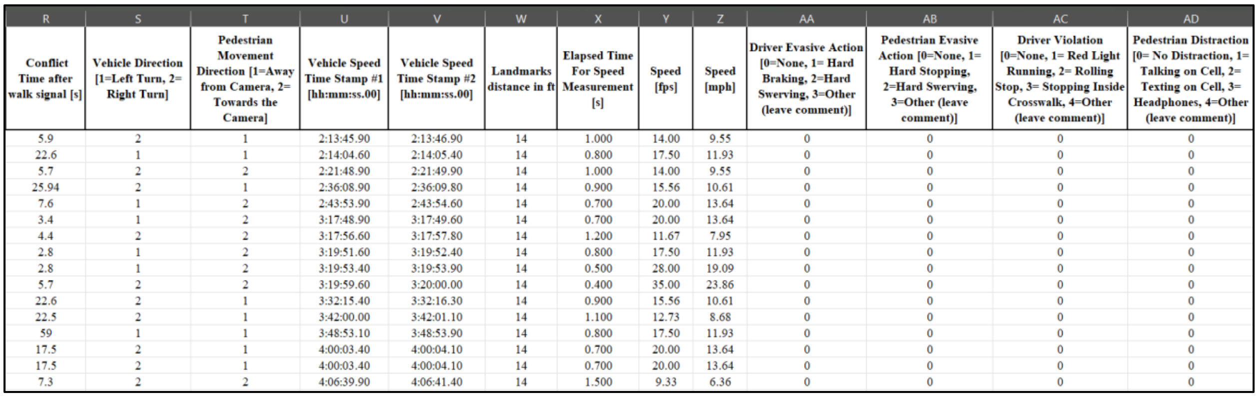
Pedestrian Crosswalk Violation? (Column AR): Enter Yes if the pedestrian was outside the crosswalk at any point during the crossing. Enter No if the pedestrian remained inside the crosswalk the entire time.

Notes (Column AS): Include any unusual observations or clarifying comments here.

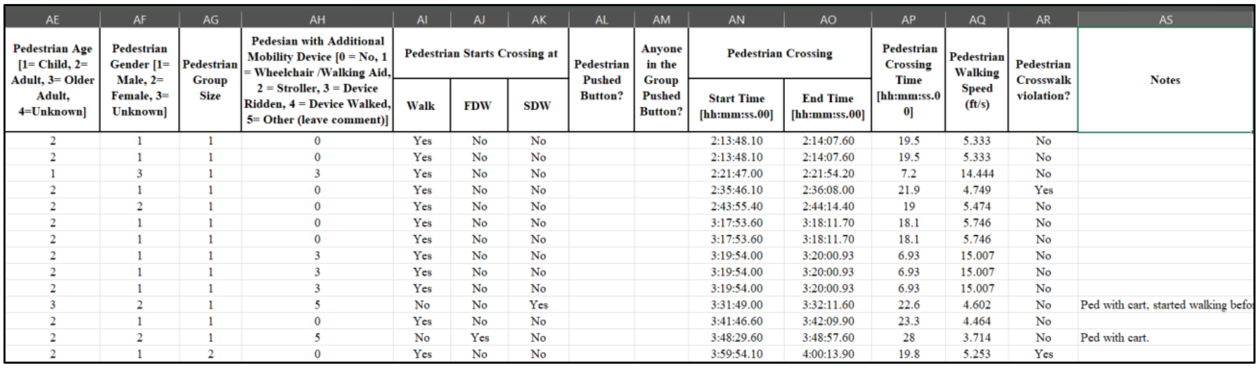
Sample Spreadsheet for Conflict Data Reduction



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Site Location	**Crosswalk Position**	**Crosswalk length in ft**	**Number of lanes**	**Camera Placement (NE, NW, SE, SW)**	**Time of Day**	**Video ID**	**Conflict No.**	**Conflict Location (Lane no.)**	**Walk Indication Time Stamp [hh:mm:ss.00]**	**FDW Indiaction stamp [hh:mm:ss.00]**	**DW Indication stamp [hh:mm:ss.00]**	**Unit 1 [1= Ped, 2= Passengar Vehicle, 3= Heavy vehicle, 4= Bike, 5= Scooter]**	**Unit 1 departure [hh:mm:ss.00]**	**Unit 2 [1= Ped, 2= Passengar vehicle, 3= Heavy vehicle, 4= Bike, 5= Scooter]**	**Unit 2 arrival [hh:mm:ss.00]**	**PET Value [s]**
Indian & 51st	West	104	7	SW	7:00	43_202311	1	1	2:13:42.60			2	2:13:46.10	1	2:13:48.50	2.4
Indian & 51st	West	104	7	SW	7:00	43_202311	2	5	2:13:42.60			1	2:14:02.60	2	2:14:05.20	2.6
Indian & 51st	West	104	7	SW	7:00	43_202311	3	7	2:21:42.90			4	2:21:48.00	2	2:21:48.60	0.6
Indian & 51st	West	104	7	SW	7:00	43_202311	4	7	2:35:43.50			1	2:36:07.80	2	2:36:09.44	1.64
Indian & 51st	West	104	7	SW	7:00	43_202311	5	5	2:43:51.60			1	2:43:55.10	2	2:43:59.20	4.1
Indian & 51st	West	104	7	SW	8:00	43_202311	6	6	3:17:52.70			2	3:17:53.10	1	3:17:56.10	3
Indian & 51st	West	104	7	SW	8:00	43_202311	7	5	3:17:52.70			1	3:17:56.10	2	3:17:57.10	1
Indian & 51st	West	104	7	SW	8:00	43_202311	8	5	3:19:53.40			2	3:19:52.60	4	3:19:56.20	3.6
Indian & 51st	West	104	7	SW	8:00	43_202311	9	5	3:19:53.40			2	3:19:54.10	4	3:19:56.20	2.1
Indian & 51st	West	104	7	SW	8:00	43_202311	10	7	3:19:53.40			4	3:19:56.40	3	3:19:59.10	2.7
Indian & 51st	West	104	7	SW	8:00	43_202311	11	7	3:31:53.00			2	3:32:11.00	1	3:32:15.60	4.6
Indian & 51st	West	104	7	SW	8:00	43_202311	12	7	3:41:43.10			2	3:42:01.60	1	3:42:05.60	4
Indian & 51st	West	104	7	SW	8:00	43_202311	13	5	3:47:55.10			2	3:48:50.10	1	3:48:54.10	4
Indian & 51st	West	104	7	SW	8:00	43_202311	14	7	3:59:51.90			2	4:00:04.40	1	4:00:09.40	5
Indian & 51st	West	104	7	SW	8:00	43_202311	15	7	3:59:51.90			2	4:00:04.40	1	4:00:09.40	5
Indian & 51st	West	104	7	SW	9:00	43_202311	16	7	4:06:33.60			1	4:06:39.90	2	4:06:40.90	1



R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
Conflict Time after walk signal [s]	**Vehicle Direction [1=Left Turn, 2= Right Turn]**	**Pedestrian Movement Direction [1=Away from Camera, 2= Towards the Camera]**	**Vehicle Speed Time Stamp #1 [hh:mm:ss.00]**	**Vehicle Speed Time Stamp #2 [hh:mm:ss.00]**	**Landmarks distance in ft**	**Elapsed Time For Speed Measurement [s]**	**Speed [fps]**	**Speed [mph]**	**Driver Evasive Action [0=None, 1= Hard Braking, 2=Hard Swerving, 3=Other (leave comment)]**	**Pedestrian Evasive Action [0=None, 1= Hard Stopping, 2=Hard Swerving, 3=Other (leave comment)]**	**Driver Violation [0=None, 1= Red Light Running, 2= Rolling Stop, 3= Stopping Inside Crosswalk, 4=Other (leave comment)]**	**Pedestrian Distraction [0= No Distraction, 1= Talking on Cell, 2= Texting on Cell, 3= Headphones, 4=Other (leave comment)]**
5.9	2	1	2:13:45.90	2:13:46.90	14	1.000	14.00	9.55	0	0	0	0
22.6	1	1	2:14:04.60	2:14:05.40	14	0.800	17.50	11.93	0	0	0	0
5.7	2	2	2:21:48.90	2:21:49.90	14	1.000	14.00	9.55	0	0	0	0
25.94	2	1	2:36:08.90	2:36:09.80	14	0.900	15.56	10.61	0	0	0	0
7.6	1	2	2:43:53.90	2:43:54.60	14	0.700	20.00	13.64	0	0	0	0
3.4	1	2	3:17:48.90	3:17:49.60	14	0.700	20.00	13.64	0	0	0	0
4.4	2	2	3:17:56.60	3:17:57.80	14	1.200	11.67	7.95	0	0	0	0
2.8	1	2	3:19:51.60	3:19:52.40	14	0.800	17.50	11.93	0	0	0	0
2.8	1	2	3:19:53.40	3:19:53.90	14	0.500	28.00	19.09	0	0	0	0
5.7	2	2	3:19:59.60	3:20:00.00	14	0.400	35.00	23.86	0	0	0	0
22.6	2	1	3:32:15.40	3:32:16.30	14	0.900	15.56	10.61	0	0	0	0
22.5	2	1	3:42:00.00	3:42:01.10	14	1.100	12.73	8.68	0	0	0	0
59	1	1	3:48:53.10	3:48:53.90	14	0.800	17.50	11.93	0	0	0	0
17.5	2	1	4:00:03.40	4:00:04.10	14	0.700	20.00	13.64	0	0	0	0
17.5	2	1	4:00:03.40	4:00:04.10	14	0.700	20.00	13.64	0	0	0	0
7.3	2	2	4:06:39.90	4:06:41.40	14	1.500	9.33	6.36	0	0	0	0



AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS
Pedestrian Age [1= Child, 2= Adult, 3= Older Adult, 4=Unknown]	**Pedestrian Gender [1= Male, 2= Female, 3= Unknown]**	**Pedestrian Group Size**	**Pedesian with Additional Mobility Device [0 = No, 1 = Wheelchair /Walking Aid, 2 = Stroller, 3 = Device Ridden, 4 = Device Walked, 5= Other (leave comment)]**	**Pedestrian Starts Crossing at**			**Pedestrian Pushed Button?**	**Anyone in the Group Pushed Button?**	**Pedestrian Crossing**		**Pedestrian Crossing Time [hh:mm:ss.00]**	**Pedestrian Walking Speed (ft/s)**	**Pedestrian Crosswalk violation?**	**Notes**
				Walk	**FDW**	**SDW**			**Start Time [hh:mm:ss.00]**	**End Time [hh:mm:ss.00]**				
2	1	1	0	Yes	No	No			2:13:48.10	2:14:07.60	19.5	5.333	No	
2	1	1	0	Yes	No	No			2:13:48.10	2:14:07.60	19.5	5.333	No	
1	3	1	3	Yes	No	No			2:21:47.00	2:21:54.20	7.2	14.444	No	
2	1	1	0	Yes	No	No			2:35:46.10	2:36:08.00	21.9	4.749	Yes	
2	2	1	0	Yes	No	No			2:43:55.40	2:44:14.40	19	5.474	No	
2	1	1	0	Yes	No	No			3:17:53.60	3:18:11.70	18.1	5.746	No	
2	1	1	0	Yes	No	No			3:17:53.60	3:18:11.70	18.1	5.746	No	
2	1	1	3	Yes	No	No			3:19:54.00	3:20:00.93	6.93	15.007	No	
2	1	1	3	Yes	No	No			3:19:54.00	3:20:00.93	6.93	15.007	No	
2	1	1	3	Yes	No	No			3:19:54.00	3:20:00.93	6.93	15.007	No	
3	2	1	5	No	No	Yes			3:31:49.00	3:32:11.60	22.6	4.602	No	Ped with cart, started walking befo
2	1	1	0	Yes	No	No			3:41:46.60	3:42:09.90	23.3	4.464	No	
2	2	1	5	No	Yes	No			3:48:29.60	3:48:57.60	28	3.714	No	Ped with cart.
2	1	2	0	Yes	No	No			3:59:54.10	4:00:13.90	19.8	5.253	Yes	

Appendix H: Pedestrian-Turning Vehicle Volume Data Reduction

Instruction for Volume Data Reduction

Details regarding each column in the Volume data collection template are provided below:

Video ID (Column A): Enter video ID that the event was recorded from.

Intersection (Column B): Identify intersection name (e.g., Indian School Rd & 19th Ave)

Crosswalk Position (Column C): Identify crosswalk position (e.g., NE, NW, SE, or SW)

Time Bin-15 mins (Column D &E): Divide video recording into 15-minute time intervals. Specify the start and end times for each time bin. (e.g., 7:00 AM-7:15 AM)

Passenger Vehicle Counts (Column F-L): Record the counts of passenger vehicles (cars, pickup trucks, vans, and SUVs) for each specified movement during the indicated time bin. For "Adjacent Right Turn" and "Crossing Right Turn," ensure to provide separate counts for green and red signal timings.

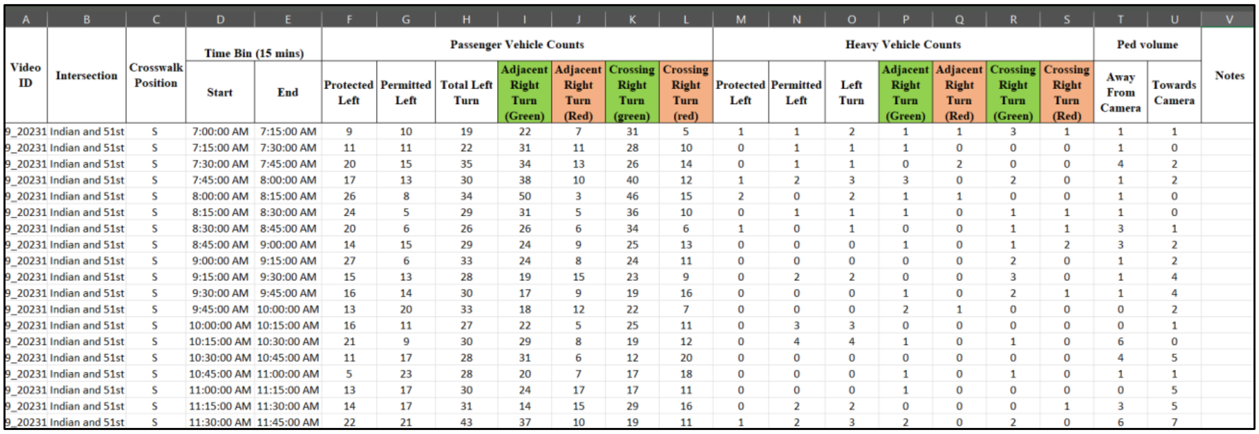
- Protected Left Turn
- Permitted Left Turn
- Total Left Turn
- Adjacent Right Turn (Green)
- Adjacent Right Turn (Red)
- Crossing Right Turn (Green)
- Crossing Right Turn (Red)

Heavy Vehicle Counts (Column M-S): Record the counts of heavy vehicles (buses, semi-trucks, package trucks, firetrucks, and RVs) for each specified movement during the indicated time bin. Single Unit trucks, Semi Unit Trucks, heavy trucks, Buses will be considered as heavy vehicles in this context.

Pedestrian Volume: Specify the pedestrian volume during the indicated time bin for pedestrian moving away from camera (Column T) and towards the camera (Column U).

Notes (Column V): Include any additional observations, comments, or notes.

Sample Spreadsheet for Volume Data Reduction



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
Video ID	Intersection	Crosswalk Position	Time Bin (15 mins)		Passenger Vehicle Counts							Heavy Vehicle Counts							Ped volume		Notes
			Start	End	Protected Left	Permitted Left	Total Left Turn	Adjacent Right Turn (Green)	Adjacent Right Turn (Red)	Crossing Right Turn (green)	Crossing Right Turn (red)	Protected Left	Permitted Left	Left Turn	Adjacent Right Turn (Green)	Adjacent Right Turn (Red)	Crossing Right Turn (Green)	Crossing Right Turn (Red)	Away From Camera	Towards Camera	
9_20231	Indian and 51st	S	7:00:00 AM	7:15:00 AM	9	10	19	22	7	31	5	1	1	2	1	1	3	1	1	1	
9_20231	Indian and 51st	S	7:15:00 AM	7:30:00 AM	11	11	22	31	11	28	10	0	1	1	1	0	0	0	1	0	
9_20231	Indian and 51st	S	7:30:00 AM	7:45:00 AM	20	15	35	34	13	26	14	0	1	1	0	2	0	0	4	2	
9_20231	Indian and 51st	S	7:45:00 AM	8:00:00 AM	17	13	30	38	10	40	12	1	2	3	3	0	2	0	1	2	
9_20231	Indian and 51st	S	8:00:00 AM	8:15:00 AM	26	8	34	50	3	46	15	2	0	2	1	1	0	0	1	0	
9_20231	Indian and 51st	S	8:15:00 AM	8:30:00 AM	24	5	29	31	5	36	10	0	1	1	1	0	1	1	1	0	
9_20231	Indian and 51st	S	8:30:00 AM	8:45:00 AM	20	6	26	26	6	34	6	1	0	1	0	0	1	1	3	1	
9_20231	Indian and 51st	S	8:45:00 AM	9:00:00 AM	14	15	29	24	9	25	13	0	0	0	1	0	1	2	3	2	
9_20231	Indian and 51st	S	9:00:00 AM	9:15:00 AM	27	6	33	24	8	24	11	0	0	0	0	0	2	0	1	2	
9_20231	Indian and 51st	S	9:15:00 AM	9:30:00 AM	15	13	28	19	15	23	9	0	2	2	0	0	3	0	1	4	
9_20231	Indian and 51st	S	9:30:00 AM	9:45:00 AM	16	14	30	17	9	19	16	0	0	0	1	0	2	1	1	4	
9_20231	Indian and 51st	S	9:45:00 AM	10:00:00 AM	13	20	33	18	12	22	7	0	0	0	2	1	0	0	0	2	
9_20231	Indian and 51st	S	10:00:00 AM	10:15:00 AM	16	11	27	22	5	25	11	0	3	3	0	0	0	0	0	1	
9_20231	Indian and 51st	S	10:15:00 AM	10:30:00 AM	21	9	30	29	8	19	12	0	4	4	1	0	1	0	6	0	
9_20231	Indian and 51st	S	10:30:00 AM	10:45:00 AM	11	17	28	31	6	12	20	0	0	0	0	0	0	0	4	5	
9_20231	Indian and 51st	S	10:45:00 AM	11:00:00 AM	5	23	28	20	7	17	18	0	0	0	1	0	1	0	1	1	
9_20231	Indian and 51st	S	11:00:00 AM	11:15:00 AM	13	17	30	24	17	17	11	0	0	0	1	0	0	0	0	5	
9_20231	Indian and 51st	S	11:15:00 AM	11:30:00 AM	14	17	31	14	15	29	16	0	2	2	0	0	0	1	3	5	
9_20231	Indian and 51st	S	11:30:00 AM	11:45:00 AM	22	21	43	37	10	19	11	1	2	3	2	0	2	0	6	7	

Appendix I: Summary of Variables in Before and After Phases for Each Site

Table I 1: Summary of variables in Before and After phases at Washington St and 3rd St intersection South (Site 1) and West (Site 2) crosswalks

Variable	Site 1				Site 2			
	Before		After LPI		Before		After LPI	
First Unit								
Pedestrian	126	83%	70	85%	248	78%	75	83%
Bicyclist	4	3%	3	4%	5	2%	0	0%
Passenger Vehicle	17	11%	8	10%	56	18%	15	17%
Heavy Vehicle	0	0%	0	0%	1	0%	0	0%
Scooter	5	3%	1	1%	8	3%	0	0%
Driver Violation								
None	139	91%	82	100%	288	91%	88	98%
Rolling Stop	0	0%	0	0%	0	0%	2	2%
Stopping Inside crosswalk	8	5%	0	0%	28	9%	0	0%
Red Light Running	0	0%	0	0%	0	0%	0	0%
Others	5	3%	0	0%	2	1%	0	0%
Driver Evasive Action								
None	143	94%	82	100%	279	88%	90	100%
Hard Braking	3	2%	0	0%	11	3%	0	0%
Other	6	4%	0	0%	28	9%	0	0%
Pedestrian Start Crossing at								
WALK	132	87%	71	87%	268	84%	80	89%
FDW	6	4%	10	12%	26	8%	9	10%
SDW	0	0%	1	1%	5	2%	1	1%
Unknown	14	9%	0	0%	19	6%	0	0%
Pedestrian Evasive Action								
None	138	91%	82	100%	301	95%	88	98%
Hard stopping	0	0%	0	0%	1	0%	2	2%
Hard swerving	2	1%	0	0%	1	0%	0	0%
Others	12	8%	0	0%	15	5%	0	0%
Pedestrian Distraction								
No Distraction	149	98%	77	94%	297	93%	88	98%
Talking on cell	0	0%	4	5%	5	2%	1	1%
Texting on cell	3	2%	0	0%	7	2%	1	1%
Headphones	0	0%	1	1%	6	2%	0	0%
Others	0	0%	0	0%	3	1%	0	0%
Pedestrian Crosswalk Violation (Yes)	32	21%	8	10%	77	24%	8	9%
Pedestrian Age								

Variable	Site 1				Site 2			
	Before		**After LPI**		**Before**		**After LPI**	
Child	1	1%	2	2%	6	2%	2	2%
Adult	145	95%	80	98%	295	93%	81	90%
Older Adult	3	2%	0	0%	7	2%	7	8%
Unknown	3	2%	0	0%	10	3%	0	0%
Pedestrian Sex								
Male	77	51%	48	59%	149	47%	49	54%
Female	68	45%	34	41%	151	47%	37	41%
Unknown	7	5%	0	0%	18	6%	4	4%
Pedestrian with Additional Mobility Device								
None	145	95%	72	88%	311	98%	84	93%
Device Ridden	0	0%	2	2%	0	0%	2	2%
Device Walked	6	4%	8	10%	4	1%	0	0%
Walking Aid	0	0%	0	0%	1	0%	1	1%
Stroller	0	0%	0	0%	2	1%	2	2%
Others	1	1%	0	0%	0	0%	1	1%
Mean Pedestrian Group Size	2.0	1.4	1.8	1.4	2.2	1.7	1.8	1.3

Table I 2: Summary of variables in Before and After phases at Indian School Rd and 51st Ave intersection South (Site 3) and West (Site 4) crosswalks

Variable	Site 3				Site 4			
	Before		After LPI		Before		After LPI	
First Unit								
Pedestrian	155	57%	173	51%	100	53%	142	68%
Bicyclist	33	12%	22	7%	21	11%	9	4%
Passenger Vehicle	82	30%	137	41%	67	35%	59	28%
Heavy Vehicle	4	1%	2	1%	1	1%	0	0%
Scooter	0	0%	2	1%	0	0%	0	0%
Driver Violation								
None	254	93%	247	74%	170	90%	203	97%
Rolling Stop	3	1%	56	17%	8	4%	1	0%
Stopping Inside Crosswalk	14	5%	28	8%	2	1%	2	1%
Red Light Running	0	0%	1	0%	3	2%	4	2%
Others	3	1%	4	1%	6	3%	0	0%
Driver Evasive Action								
None	273	100%	328	98%	189	100%	208	99%
Hard Braking	1	0%	8	2%	0	0%	2	1%
Other	0	0%	0	0%	0	0%	0	0%
Pedestrian Start Crossing at								
WALK	206	75%	244	73%	151	80%	0	0%
FDW	23	8%	61	18%	9	5%	0	0%
SDW	32	12%	11	3%	25	13%	0	0%
Unknown	13	5%	20	6%	4	2%	210	100%
Pedestrian Evasive Action								
None	261	95%	301	90%	187	99%	209	100%
Hard stopping	10	4%	0	0%	2	1%	0	0%
Hard swerving	1	0%	18	5%	0	0%	1	0%
Others	2	1%	17	5%	0	0%	0	0%
Pedestrian Distraction								
No Distraction	257	94%	322	96%	179	95%	207	99%
Talking on Cell	3	1%	10	3%	1	1%	0	0%

Variable	**Site 3**				**Site 4**			
	Before		**After LPI**		**Before**		**After LPI**	
Texting on Cell	4	1%	1	0%	5	3%	0	0%
Headphones	0	0%	1	0%	3	2%	3	1%
Others	10	4%	2	1%	1	1%	0	0%
Pedestrian Crosswalk Violation (Yes)	51	19%	121	36%	38	20%	50	24%
Pedestrian Age		0%		0%		0%		0%
Child	18	7%	9	3%	9	5%	1	0%
Adult	229	84%	313	93%	163	86%	198	94%
Older Adult	19	7%	8	2%	16	8%	11	5%
Unknown	8	3%	6	2%	1	1%	0	0%
Pedestrian Sex								
Male	193	70%	216	64%	128	68%	127	60%
Female	72	26%	89	26%	41	22%	59	28%
Unknown	9	3%	31	9%	20	11%	24	11%
Pedestrian with Additional Mobility Device								
None	203	74%	302	90%	123	65%	173	82%
Device Ridden	48	18%	0	0%	42	22%	21	10%
Device Walked	8	3%	18	5%	10	5%	7	3%
Walking Aid	1	0%	3	1%	3	2%	6	3%
Stroller	5	2%	4	1%	5	3%	3	1%
Others	9	3%	9	3%	6	3%	0	0%
Mean Pedestrian Group Size	1.7	1.0	1.8	1.5	1.3	0.5	1.5	1.1

Table I 3: Summary of variables in Before and After phases at Indian School Rd and 19th Ave intersection North (Site 5) and West (Site 6) crosswalks

Variable	Site 5				Site 6			
	Before		After LPI		Before		After LPI	
First Unit								
Pedestrian	115	67%	90	57%	165	69%	117	63%
Bicyclist	5	3%	16	10%	14	6%	13	7%
Passenger Vehicle	49	29%	52	33%	55	23%	53	29%
Heavy Vehicle	1	1%	0	0%	3	1%	0	0%
Scooter	1	1%	0	0%	2	1%	2	1%
Driver Violation								
None	149	87%	144	91%	219	92%	175	95%
Rolling Stop	10	6%	1	1%	6	3%	4	2%
Stopping Inside Crosswalk	7	4%	5	3%	8	3%	2	1%
Red Light Running	5	3%	8	5%	6	3%	4	2%
Others	0	0%	0	0%	0	0%	0	0%
Driver Evasive Action								
None	168	98%	155	98%	231	97%	185	100%
Hard Braking	3	2%	3	2%	6	3%	0	0%
Other	0	0%	0	0%	2	1%	0	0%
Pedestrian Start Crossing at								
WALK	112	65%	82	52%	174	73%	129	70%
FDW	18	11%	10	6%	36	15%	6	3%
SDW	40	23%	66	42%	29	12%	49	26%
Unknown	1	1%	0	0%	0	0%	1	1%
Pedestrian Evasive Action								
None	168	98%	152	96%	234	98%	185	100%
Hard stopping	2	1%	6	4%	2	1%	0	0%
Hard swerving	0	0%	0	0%	2	1%	0	0%
Others	1	1%	0	0%	1	0%	0	0%
Pedestrian Distraction								
No Distraction	149	87%	153	97%	227	95%	180	97%
Talking on Cell	1	1%	2	1%	0	0%	0	0%
Texting on Cell	14	8%	3	2%	8	3%	3	2%
Headphones	5	3%	0	0%	1	0%	1	1%
Others	2	1%	0	0%	3	1%	1	1%
Pedestrian Crosswalk Violation (Yes)	66	39%	78	49%	98	41%	58	31%
Pedestrian Age								
Child	6	4%	0	0%	9	4%	2	1%

Variable	**Site 5**				**Site 6**			
	Before		**After LPI**		**Before**		**After LPI**	
Adult	155	91%	145	92%	216	90%	182	98%
Older Adult	8	5%	13	8%	11	5%	1	1%
Unknown	2	1%	0	0%	3	1%	0	0%
Pedestrian Sex								
Male	114	67%	111	70%	127	53%	122	66%
Female	46	27%	39	25%	68	28%	51	28%
Unknown	11	6%	8	5%	44	18%	12	6%
Pedestrian with Additional Mobility Device								
None	155	91%	128	81%	219	92%	147	79%
Device Ridden	3	2%	25	16%	8	3%	31	17%
Device Walked	6	4%	5	3%	3	1%	3	2%
Walking Aid	4	2%	0	0%	3	1%	3	2%
Stroller	0	0%	0	0%	6	3%	1	1%
Others	3	2%	0	0%	0	0%	0	0%
Mean Pedestrian Group Size	1.7	1.4	1.4	0.6	1.7	1.3	1.5	0.8

Table I 4: Summary of variables in Before and After phases at W Baseline Rd and 51st Ave intersection North (Site 7) crosswalk

Variable	Site 7			
	Before		**After LPI**	
First Unit				
Pedestrian	120	75%	104	77%
Bicyclist	4	3%	4	3%
Passenger Vehicle	34	21%	21	16%
Heavy Vehicle	1	1%	2	1%
Scooter	0	0%	4	3%
Driver Violation				
None	152	96%	125	93%
Rolling Stop	0	0%	4	3%
Stopping Inside Crosswalk	7	4%	6	4%
Red Light Running	0	0%	0	0%
Others	0	0%	0	0%
Driver Evasive Action				
None	159	100%	135	100%
Hard Braking	0	0%	0	0%
Other	0	0%	0	0%
Pedestrian Start Crossing at				
WALK	96	60%	72	53%
FDW	18	11%	30	22%
SDW	45	28%	33	24%
Unknown	0	0%	1	1%
Pedestrian Evasive Action				
None	159	100%	127	94%
Hard stopping	0	0%	0	0%
Hard swerving	0	0%	0	0%
Others	0	0%	8	6%
Pedestrian Distraction				
No Distraction	156	98%	131	97%
Talking on Cell	0	0%	0	0%
Texting on Cell	1	1%	2	1%
Headphones	1	1%	0	0%
Others	1	1%	2	1%
Pedestrian Crosswalk Violation (Yes)	29	18%	38	28%
Pedestrian Age				
Child	1	1%	7	5%
Adult	151	95%	123	91%
Older Adult	7	4%	5	4%
Unknown	0	0%	0	0%

Variable	Site 7			
	Before		**After LPI**	
Pedestrian Sex				
Male	111	70%	93	69%
Female	48	30%	36	27%
Unknown	0	0%	6	4%
Pedestrian with Additional Mobility Device				
None	135	85%	115	85%
Device Ridden	7	4%	4	3%
Device Walked	5	3%	2	1%
Walking Aid	6	4%	3	2%
Stroller	6	4%	11	8%
Others	0	0%	0	0%
Mean Pedestrian Group Size	1.5	0.7	2.1	1.2

Table I 5: Summary of variables in Before and After phases at W Baseline Rd and 51st Ave intersection West (Site 8) crosswalk

Variable	Site 8					
	Before		**After LPI**		**After NRTOR**	
First Unit						
Pedestrian	138	72%	94	68%	95	68%
Bicyclist	7	4%	8	6%	5	4%
Passenger Vehicle	45	23%	34	25%	34	25%
Heavy Vehicle	0	0%	0	0%	2	1%
Scooter	2	1%	2	1%	3	2%
Driver Violation						
No Violation	191	100%	134	97%	116	84%
Red Light Running	0	0%	0	0%	0	0%
NRTOR violation	-	-	-	-	23	17%
Stopping Inside Crosswalk	1	1%	4	3%	0	0%
Rolling Stop	0	0%	0	0%	6	4%
Others	0	0%	0	0%	0	0%
Driver Evasive Action						
None	191	100%	138	100%	139	100%
Hard Braking	0	0%	0	0%	0	0%
Other	1	1%	0	0%	0	0%
Pedestrian Start Crossing at						
WALK	170	89%	94	68%	78	56%
FDW	8	4%	23	17%	22	16%
SDW	14	7%	21	15%	39	28%
Unknown	0	0%	0	0%	0	0%
Pedestrian Evasive Action						
None	192	100%	138	100%	133	96%
Hard stopping	0	0%	0	0%	0	0%
Hard swerving	0	0%	0	0%	0	0%
Others	0	0%	0	0%	6	4%
Pedestrian Distraction						
No Distraction	186	97%	137	99%	131	94%
Talking on Cell	1	1%	0	0%	1	1%
Texting on Cell	0	0%	1	1%	2	1%
Headphones	4	2%	0	0%	0	0%
Others	2	1%	0	0%	5	4%
Pedestrian Crosswalk Violation (Yes)	35	18%	35	25%	8	6%
Pedestrian Age						

Child	5	3%	3	2%	7	5%
Adult	186	97%	133	96%	124	89%
Older Adult	1	1%	2	1%	8	6%
Unknown	0	0%	0	0%	0	0%
Pedestrian Sex						0%
Male	139	72%	87	63%	84	60%
Female	53	28%	49	36%	50	36%
Unknown	0	0%	2	1%	5	4%
Pedestrian with Additional Mobility Device						
None	172	90%	128	93%	114	82%
Device Ridden	10	5%	0	0%	4	3%
Device Walked	4	2%	10	7%	11	8%
Walking Aid	3	2%	0	0%	3	2%
Stroller	3	2%	0	0%	7	5%
Others	0	0%	0	0%	0	0%
Mean Pedestrian Group Size	1.6	80%	1.8	1.1	1.7	80%