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Behavioral Investigation of Temporary and Permanent Pedestrian Infrastructure

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16. Abstract (Limit: 250 words)

Agencies may treat pedestrian crossing sites initially with temporary treatments (i.e., removable flexible delineators or bollards) to test efficacy, but the pedestrian safety effects of temporary infrastructure are not well understood. This study tested the impact of temporary and permanent pedestrian infrastructure such as curb extensions/bump-outs and pedestrian medians/refuges as it relates to pedestrian and driver behavior. Twelve intersections in Minneapolis and Saint Paul, MN, comprising a mixture of intersection traffic control types and pedestrian infrastructure were examined before and after installation of the infrastructure. Staged pedestrian crossings by research staff at crosswalks examined driver stopping behavior and analyzed video data from installed traffic cameras to examine natural pedestrian behavior. A computer algorithm processed the video data to estimate vehicle speeds at the sites. For signalized intersections, the use of flexible delineators as a curb extension led to a reduced likelihood of drivers stopping for pedestrians during staged crossings. Little to no effect was found for permanent curb extensions at signalized intersections, perhaps due to the role that increased physical separation and visual complexity plays in the likelihood of drivers stopping for pedestrians. For unsignalized intersections, both temporary and permanent curb extensions were found to have similar and mixed effects for pedestrian safety when considering average driver speed, stopping likelihood, and pedestrian behavior. Both permanent and temporary medians had generally positive effects for the pedestrian safety measures, especially for average driver speed. Future research should closely examine the relative pedestrian safety impacts of temporary and permanent refuges at signalized intersections.

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Behavioral Investigation of Temporary and Permanent Pedestrian Infrastructure

Final Report

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Executive Summary

Pedestrian injuries and fatalities remain an ongoing problem in Minnesota (MnDPS, 2022), leading to significant personal, societal, and financial costs each year. Identifying effective mitigation strategies to improve safety and reduce risks to pedestrians is vital to personal and public health. Pedestrian infrastructure is generally effective at improving pedestrian safety. To test efficacy, agencies may initially treat sites with temporary treatments (e.g., removable bollards), which are also relatively less expensive than more permanent installations. But unlike with more permanent infrastructure, pedestrian and driver behavior at temporary infrastructure relative to permanent infrastructure is less known, as well as how temporary treatments interact with driver factors such as speed and likelihood of stopping for crossing pedestrians. The research literature review on permanent pedestrian infrastructure found that refuge/median islands appear to have the most replicable benefits across the board for most safety metrics, except for driver stopping rates, which has mixed results. Curb extensions or bump-outs appear to be effective by means of both speed reduction and improvement in pedestrian visibility and in the reduction of the pedestrian risk exposure to the roadway but appear to have little effect on stopping rates.

This study was conducted to test the effect of temporary and permanent pedestrian infrastructure such as curb extensions/bump-outs and pedestrian refuge islands/medians on pedestrian and driver behavior. The focus was on how pedestrian and driver behavior changed and affected safety and risk. The present study was mostly reliant on the city of Minneapolis' Vision Zero's 2023-2024 pedestrian safety plan, but sites were selected with the cooperation of the city of Minneapolis and the city of Saint Paul. Twelve intersections in Minneapolis and Saint Paul, MN, comprising a mixture of intersection traffic control types and pedestrian infrastructure were examined before and after installation of the infrastructure. The following site and implementation types were selected: bollard bump-out (i.e., curb extension) at signalized sites with and without a hardened centerline, concrete bump-out at a signalized site, bollard bump-out at an unsignalized site, concrete bump-out at an unsignalized site, bollard refuge/median at signalized site, bollard refuge/median at an unsignalized site, and a concrete refuge at an unsignalized site. The only site type that was not available for pre- and post-installation measurement due to logistical issues was a concrete refuge/median at a signalized site. Staged crossings by the research team at crosswalks examined driver stopping behavior. Video data from installed traffic cameras was analyzed to examine naturalistic pedestrian behavior. A computer algorithm processed the video data to estimate vehicle speeds at the sites.

Staged crossings by the research team focused on right-turning drivers at signalized sites and drivers going straight on unsignalized sites, as these two maneuvers are most likely to generate legal conflict points with crossing pedestrians at these site types. At signalized sites, the focus was more on drivers turning right, than drivers turning left, because it is easier to attribute stopping behavior to the presence of the pedestrian with the driver is turning right, whereas the driver turning left may be stopping for oncoming traffic and not the pedestrian. For unsignalized sites, the focus was on drivers going straight and not on turning drivers, because drivers turning are already slowing down to make a turn, whereas drivers going straight must decide to stop for the pedestrian, before slowing down to stop.

For camera data, 1 week of pre-installation video data and up to 2 weeks of post-installation video data for the pedestrian infrastructure was captured at the sites. After pedestrian infrastructure installation, a delay of 1 week was employed before installing cameras, to partially mitigate any novelty effects. The cameras recorded video data continuously after it was in place, barring technical issues. The traffic data cameras were installed by Quality Counts LLC (https://www.qualitycounts.net/), who then transferred the video files to the University of Minnesota (UMN) research team. Coders scoring the videos focused on two-hour blocks per site around times of the day with higher likelihoods of pedestrian and vehicle traffic, including morning rush hour (7:00 AM to 9:00 AM), lunch (11:00 AM to 1:00 PM), and afternoon rush hour (4:00 PM to 6:00 PM). Elements coded include the time of the crossing, where the pedestrian waited, whether they ceded the right-of-way, whether pedestrians crossed unsafely by forcing drivers to stop, whether drivers stopped for the pedestrian, and other relevant variables.

For speed data analysis, the camera data processing by the computer algorithm went frame-by-frame (i.e., single-frame processing approach). The method for determining vehicle speeds from traffic camera data is described in significant detail elsewhere (Katariya et al., 2024; Katariya et al., 2025). The speed estimation focused on computing speed averaged over one second at a specific location in the camera image that generally corresponded to where a pedestrian could be crossing at the site. To support and validate the speed assessment from the camera footage by the computer algorithm, in-person speed data measurement was conducted for some of the 2024 study sites. This involved selecting two easily visible landmarks at a site and recording the time it took free-flowing vehicles to traverse the distance between the two landmarks for a given direction of travel.

There was an observed reduction in the rate of right-turning drivers stopping for pedestrians at the signalized intersections with temporary curb extensions installed, which may represent the influence of visual clutter (Edquist et al., 2012) and distraction, as drivers may be focusing on navigating the turn and avoiding the flexible delineators, reducing the odds of the driver observing the crossing pedestrian. As this effect emerged when considering two different signalized intersections (Pillsbury & 31st was excluded from that analysis because of the low rate of conflicts), and the association of right-turn stopping and pedestrian crashes (Houssain et al., 2019), this may represent the primary safety concern of this infrastructure type. A similar but weak marginal effect occurred for the permanent curb extensions at the signalized intersections after controlling for the effects of the time of day. One potential explanation for this finding is that the increased physical separation could play a minor contributing role in stopping likelihood as increased distance may reduce the driver's perceived risk (i.e., less likelihood of a pedestrian-involved crash) and lead to riskier behavior.

There appeared to be several reliable positive benefits of the quick-build temporary infrastructure as well. These included (1) improved driver stopping rates for pedestrians with temporary refuges at unsignalized intersections, (2) reduced average speeds of drivers in free-flowing traffic for temporary refuges at both signalized and unsignalized intersections, and (3) some mixed evidence for reduced average speeds for drivers approaching temporary curb extensions at signalized and unsignalized intersections. The effects of permanent infrastructure appeared to be either neutral or positive across the board.

Chapter 1: Introduction

A number of factors other than exposure contribute to pedestrian and bicycle crash risk, and roadway features such as undivided roadways, work zones, lack of sidewalks, lack of on-street parking, and decreased shoulder width are all associated with a greater risk for non-motorized crashes (Turner et al., 2017). Given the role that infrastructure plays in affecting crash risk, the National Transportation Safety Board has highlighted infrastructure design as a significant crash countermeasure for urban planners and engineers, while noting better data was needed (NTSB, 2018). Known crash modification factors for pedestrians can be found elsewhere (see https://www.cmfclearinghouse.org). Furthermore, identifying pedestrian crash risk factors and how to mitigate these factors are key components of the Highway Safety Improvement Program (HSIP; https://www.dot.state.mn.us/trafficeng/safety/hsip.html). This chapter provides a summary description and initial assessment of the literature on pedestrian infrastructure and its impact on pedestrian safety.

1.1 The Use and Value of Pedestrian Infrastructure

Although the data was analyzed over a decade ago, Minneapolis pedestrians had predictable patterns of infrastructure use, and there is likely some generalization of these use patterns to other urban centers (Hankey et al., 2012). Arterial and collector roads had significantly higher pedestrian traffic, particularly those associated with retail corridors and other significant destinations. This is because said infrastructure provides the greatest efficiency of access. Furthermore, pedestrian volumes were significantly large at the central business district and bodies of water and declined by 15% per kilometer from said district and 11% per kilometer from bodies of water.

Zandieh and colleagues (2016) examined 173 older pedestrians (65+) and their relationship with the built environment with a mixed-method approach employing GPS, survey instruments, and interviews. This is valuable because older pedestrians have worse outcomes when involved in a motor vehicle crash but also significantly benefit from walking as a way of maintaining health and well-being (Tournier et al., 2016). The study authors identified regional areas of high and low socio-economic deprivation to use as a factor in their analyses (i.e. high and low deprivation areas). Older participants in both types of deprivation areas perceived problems with poor pavement conditions and maintenance, as well as uneven pavements, as fear of falling is an issue and many older participants have foot ailments that make walking on uneven ground painful. Both types of older pedestrians also preferred quietness, perceived safety, and aesthetics, which increased the likelihood of walking. However, older pedestrians from high socioeconomic deprivation areas were significantly affected by the presence or lack thereof of public amenities (e.g., benches, user friendly public toilets) and poor air quality (e.g., excessive vehicle exhaust). Most relevant for the purpose of this review, older pedestrians from high deprivation areas were less likely to walk in the context of high traffic volume roads, high speeds on quieter streets, few crossings or traffic signals, and no traffic islands (e.g., pedestrian refuges).

Nag and colleagues (2020) examined the relationship between the physical environment, preferences, and self-reported use in an urban and suburban location. Participants did not report greater preference or satisfaction for improvements in footpath continuity (clear available walking route), but this did lead to more use. When improvements to continuity were combined with buffers between pedestrians and vehicle traffic or combined with removal of obstructions to improve ease of walking, this led to both higher preferences or satisfaction and more use. This suggests that barriers such as raised medians, islands, and curb extensions should lead to improvements in these metrics.

The value of pedestrian infrastructure may not be immediately obvious to members of the public, who recently made their opinions known on recent pedestrian safety initiatives in both Saint Paul and Minneapolis since 2018. For example, Figure 1.1 shows commentary by a citizen on the implementation costs on a typical temporary pedestrian infrastructure component (i.e., a delineator).

Figure 1.1 Commentary placed on a delineator at Nicollet & 26th St in Minneapolis, MN, taken in 2023. Note says "Wasting our tax money here; $1,200 each."

However, it is worth noting that the willingness of users to pay for facilities or infrastructure is higher on a per trip basis for pedestrians and pedestrian infrastructure than for bicyclists and bicycle infrastructure, when shown how the infrastructure provides significant return on investment, although this effect was observed in a rural location (Laird et al., 2013). Although the observed effect is limited in scope, the potential marketability of pedestrian infrastructure (with demonstrated value) is significant given that there are slightly more pedestrians than bicyclists. For example, in Minneapolis, the commuting percentage is 7% for walking and 5% for biking (out of the total work commuting percentage) (Minneapolis, 2023).

Volker and Handy (2021) examined this question of whether investments in pedestrian and bicycle infrastructure led to worse or better economic outcomes. Most common complaints on pedestrian and bicycle infrastructure come from local businesses and motorists expressing concern that said infrastructure will limit revenue due to reduced traffic efficiency or parking. The paper reviews 23 studies examining either the degree of consumer spending or other quantifications of economic impact to local businesses pre and post installation of pedestrian or bicycle facilities. The only potential negative economic impact observed was for automobile-centric businesses and bicycle facilities. Besides that, pedestrian or bicycle infrastructure either had a positive effect or no effect on economic impact, including those circumstances in which vehicle parking or travel lanes were reduced to provide space for these facilities.

The primary demonstrable value of pedestrian infrastructure is safety, as pedestrians must share the road with motor vehicles that can pose a significant risk. Therefore, the rest of the literature review considers the risk to pedestrians and how risks are affected by infrastructure. Pedestrian and bicycle infrastructure can vary in price, although a current assessment of cost is beyond the scope of this review. An older assessment of cost was performed by Bushell and colleagues (2013). We should note, however, that pedestrian infrastructure maintenance in winter conditions and ADA compliance is important in this respect, and should follow guidelines established elsewhere (Veneziano et al., 2023).

1.2 Pedestrian Safety Infrastructure Research Surveys

The following section covers research surveying or reviewing the available literature on the impact of pedestrian safety infrastructure. Descriptions of specific studies directly and empirically testing research questions on pedestrian safety infrastructure are provided in a later section.

Gitelman and colleagues (2012) conducted an international analysis of pedestrian safety infrastructure measures available at the time. They focused on the following safety categories: Crash or accident reduction, conflict reduction, and speed reduction.

For *crash reduction*, they found evidence that the following infrastructure components improved safety: Sidewalks, pedestrian fences along medians, improved lighting, curb extensions, pedestrian refuge islands, pedestrian overpasses and underpasses, raised medians, changing two ways to one way on collector roads, converting a junction to a roundabout, general traffic calming measures, speed humps, raised pedestrian crossings, a Woonerf (shared space), a pedestrian zone, an exclusive green phase for pedestrians for all crossing directions at signalized locations, and introducing traffic signals (e.g., Pelican or Puffin crossings) at either a junction or midblock (Gitelman et al., 2012).

For *conflict reduction*, they found evidence that the following infrastructure components improved safety: Pedestrian refuge islands, improving lighting, overhead flashing beacons, warning signs nearby crosswalks, advanced stop markings (particularly on multi-lane roads), in-pavement lights at crosswalk activated by pedestrians, signs with animated eyes activated by pedestrians, other types of enhanced lighting for the crosswalk activated by pedestrians, leading pedestrian intervals, moving eyes signage to warn pedestrians of turning vehicles at shared green phase, and countdown signals for the clearance phase (Gitelman et al., 2012). See the MUTCD guidelines for the design of animated eyes in MUTCD 2023 11th Ed, Chapter 4I.02.12.

For *speed reduction*, they found evidence that the following infrastructure components improved safety: Pedestrian refuge islands, in-pavement lights at crosswalk activated by pedestrians, reducing roadway widths or roadway narrowing, raised medians (between travel directions), general traffic calming measures, speed humps, raised pedestrian crossings, and a Woonerf (shared space) (Gitelman et al., 2012).

Based on their survey of the research, Gitelman and colleagues (2012) made the following recommendations. In the case of multi-lane streets with unsignalized crosswalks, especially those experiencing high traffic volumes, they advise implementing traffic calming strategies in areas with significant pedestrian activity. These strategies may encompass measures such as speed bumps, lane narrowing, lane reduction, and narrowing the road for parking and bus stops. Other methods may involve the installation of a raised crosswalk, a raised intersection, or converting an intersection into a single-lane roundabout for traffic calming purposes. Furthermore, steps to enhance crosswalk visibility are valuable on these roads, including eliminating visibility obstructions, extending sidewalks, improving lighting, adding high-mounted traffic signs with reflective properties, and implementing a pedestrian warning system with in-road warning lights. For unsignalized crosswalks on a two-way two-lane street, suitable options include incorporating a refuge island within the crosswalk area, constructing a raised median along the relevant section of the street, or transforming an intersection into a single-lane roundabout. For signalized intersections, the goal would be to minimize the instances where pedestrians and turning vehicles share the right-of-way, and decrease the number of pedestrian crossings when the signal is red. Potential measures include the elimination of shared green signals for pedestrians and turning vehicles, increase the leading pedestrian interval time, stop green waves (e.g., green light synchronization) for vehicles during off-peak hours, or adjust the traffic signal programming to prioritize pedestrian flow (Gitelman et al., 2012).

Zegeer and Bushell (2012) performed a similar international analysis, focusing generally on pedestrian crash trends and considering countermeasures. Their first major observation was based on an old analysis in 1993 indicating the relative importance of impact speed on fatality and injury rate of pedestrians. At 20 mph impact speed, under 10% of the crashes were fatal, and over 20% of the crashes had no injuries reported. For 30 mph impact speed, fatal crash percentage for pedestrians increased to over 40%, whereas the percentage of uninjured crashes was closer to 5%. At 40 mph, over 80% of pedestrian-involved crashes were fatal, and there were practically no observations of uninjured crashes (Zegeer & Bushell, 2012).

They outline several broad risk factors that contribute to pedestrian crash likelihood and severity, including social and policy factors, driver factors, vehicle factors, roadway factors, and pedestrian factors. High vehicle speeds and volumes, for example, are vehicle/roadway factors that significantly contribute to risk and severity of pedestrian crashes. They then specify some of these risk factors for signalized and unsignalized crossings. For signalized crossings, risk factors include higher pedestrian and traffic volumes, greater ratio of average daily traffic for vehicles on the minor road compared to the major road, number of lanes, and the presence of bus stops and schools within 300 meters of the intersection. For unsignalized crossings, increased pedestrian and vehicle traffic volumes, number of lanes (exposure), and no raised median or no refuge island.

For countermeasures at signalized intersections, the authors recommend narrowing the roadway, ensuring sidewalks and raised medians are installed, and introducing pedestrian overpasses or underpasses if possible. For higher volume (12,000+ vehicles a day) unsignalized locations, they recommend raised medians, signals (pedestrian/traffic), improved lighting (particularly for nighttime), refuge islands, lane reduction (4 to 3 or 3 to 2), or conversion to a roundabout if possible. More generally, they recommend considering the visibility or conspicuity of pedestrians, particularly at night (Zegeer & Bushell, 2012).

Blackburn and colleagues (2018) outlined in a similar approach to Gitelman and colleagues (2012) what safety issues were addressed by a given pedestrian crash countermeasure, with a focus on uncontrolled crossings. The types of infrastructure that could have a temporary or permanent counterpart as explored in this current research project, specifically curb extensions and refuge islands, presumably help address numerous issues (Blackburn et al., 2018). These include pedestrian vehicle conflicts, excessive vehicle speeds, pedestrian visibility/conspicuity, and separation from traffic. However, Blackburn and colleagues (2018) indicate that they predict these measures will not address drivers yielding to pedestrians, which the current project further evaluates.

Stoker and colleagues (2015) found the following types of pedestrians to exhibit the most risk in terms of risk of crash or severity: Young children, young adults between 15-21 years of age, males, older pedestrians, pedestrians of lower socio-economic status, visually impaired pedestrians, and intoxicated or distracted pedestrians. The presented findings here are constricted to the relatively wealthy socio-economic context of the United States, other findings are presented in the referenced document for countries with different cultures and socio-economic contexts.

Stoker and colleagues (2015) generally concur with the previous findings (Zegeer & Bushell, 2012) that traffic exposure, traffic volumes, higher traffic speeds, and pedestrian visibility are the most significant contributors to pedestrian risk. Pedestrian infrastructure that demonstrably reduces exposure to vehicle traffic includes sidewalks, footpaths or walking trails, overpasses, and underpasses. Infrastructure clearly reducing traffic volume includes chicanes, road diets, half closures, diagonal diverters, and median barriers. Reported infrastructure clearly reducing vehicle speeds was extracted from Vanderschuren and Jobanputra (2009). These are split between measures implementable on arterials and local roads. Effective measures that reduce vehicle speed on arterials include raised crosswalks, textured pavements (which increase friction), rumble strips, roundabouts, chokers, road diets, perceptual designs intended to take advantage of how humans perceive speed and distance to encourage safer driver behavior (e.g., Denton, 1980), warning signs, half closures (barrier creating a one-way street for a short distance), diagonal diverters (diagonal barriers across an intersection), lateral shifts (which briefly shifts the direction of an otherwise straight street to slow traffic), median barriers, and gateway treatments. Effective measures that reduce vehicle speed on local roads include speed humps, speed tables, raised crosswalks and intersections, textured pavements, speed cushions (speed tables/humps that include wheel cutouts to allow large vehicles to pass unaffected), rumble strips, traffic circles and roundabouts, chicanes (series of curves), chokers, road diets, perceptual designs, warning signs, half closures, diagonal diverts, and lateral shifts.

Mead, Zegeer, and Bushell (2014) evaluated pedestrian roadway infrastructure in general. They note that marked crosswalks at uncontrolled locations may increase the likelihood of pedestrian crashes at undivided multilane roads of significant average daily traffic (e.g., over 15,000 vehicles a day), although their findings indicate that there is a positive benefit of marked crosswalks relative to unmarked crosswalks for these locations for traffic volumes between 5,000 and 10,000 ADT. Their general recommendation is that marked crosswalks should not be used without additional enhancements for roadways of significant speeds, volume, and lane counts.

Mead and colleagues (2014) specifically discuss curb extensions and refuge islands. For curb extensions, which are suitable at both signalized and unsignalized locations, the summarized results are somewhat mixed according to their review, with one study finding no effects of the installation (although this could have been due to local traffic conditions) and another study finding that the curb extension improved driver stopping rate for pedestrians at the crossing compared to a corner at the same intersection that was not treated. The positive effect was attributed to the increased visibility of the pedestrian.

For refuge islands, Mead and colleagues (2014) also indicated some mixed (yet mostly positive) benefits in terms of various safety metrics (conflict rate/count, percentage of drivers stopping, crash rate, etc.), with the best outcomes going to raised median islands relative to painted median islands. This suggests potential positive benefits of introducing a clear barrier or buffer to traffic by means of quick-build temporary infrastructure.

1.3 Pedestrian Infrastructure Risk Assessment

The following section considers two studies that have used findings in the known pedestrian safety research literature to develop models to predict or index the degree of risk posed to pedestrians by the characteristics of a crossing. These models are useful because they can help infer what aspects or elements of a crossing could be addressed to improve safety for pedestrians, and what the relative safety contribution each infrastructure element provides.

Zegeer and colleagues (2006) constructed a pedestrian safety index based on two preliminary models utilizing the known factors that increased pedestrian risk at the time of publication. One model assessed safety ratings, while the other measured behavioral outcomes (e.g., avoidance and conflicts). The ratings model found significant effects with the presence of stop signs and signals on the main street was associated with improved safety ratings, although signals interacted with traffic volume, whereas the number of through lanes and the 85th percentile speed were associated with reduced safety ratings. The behavioral model found that the presence of signals on the main street, and the presence of a refuge island was associated with fewer avoidance maneuvers and conflict, whereas the number of through lanes were associated with more avoidance maneuvers and conflict. This resulted in a pedestrian safety index model, in which the following variables were used to provide a safety index: Signal (traffic/pedestrian) present (Y/N), stop sign present (Y/N), commercial area (Y/N) (i.e., retail area, restaurants), number of through lanes on crossing in both directions, 85th percentile speed in mph, and the main street traffic volume measured with ADT in the thousands. Traffic signals could be considered positive, unless it was a high traffic volume signalized location, in which case the safety value of the signal for pedestrians decreases. While not included in their final model, it is worth noting that the use of a pedestrian refuge was associated with positive safety ratings. Furthermore, this sort of index could provide a control measure for any assessment of the relative contribution of pedestrian infrastructure.

Nesoff and colleagues (2018) extended this idea with their Inventory for Pedestrian Safety Infrastructure (IPSI), which allows for coding sites using Google Street Views. While the detailed validation process is beyond the scope of this review, the actual inventory items include roadway features, midblock features, and intersection features, which all presumably contribute to the relative risk to pedestrians.

The scored general roadway features include whether it is a one-way or two-way street, count of lanes, whether there is a posted speed limit sign nearby and what the posted speed limit is, the presence of lamp posts or streetlights, the presence of on-street parking, alley streets, sidewalks and their maintenance quality, the presence of islands/medians, speed bumps/humps, pedestrian overpasses/underpasses/bridge, a fence to prevent street crossing, bus stops, and whether there is an on-ramp or exit ramp present (Nesoff et al., 2018).

The scored midblock features include count of marked crosswalks, count of crosswalks with flashing lights or reflectors embedded in in the pavement, count of pedestrian crossing signs, and a count of pedestrian crossing signals. The scored intersection features include whether the intersection is a traffic circle or roundabout, the count of intersecting streets (e.g., 4 corners mean 2 intersecting streets), count of marked crosswalks with walk signal, stop light, or stop sign, count of marked crosswalks without walk signal, stop light, or stop sign, count of crosswalks with flashing lights or reflectors embedded in in the pavement, count of streets with traffic or stop lights, count of stop/yield/crossing signs, count of pedestrians signals, and how many streets have advance stop lines placed back from the crosswalk (Nesoff et al., 2018).

1.4 Empirical Studies

This section covers relevant individual studies that directly measure the effectiveness of various infrastructures on pedestrian safety.

Kamyab and colleagues (2003) provided an early assessment of speed reduction techniques on Minnesota roadways using temporary pedestrian safety infrastructure. Specifically, they evaluated the speed reduction effectiveness of removable pedestrian islands, paired with a pedestrian crossing sign, and dynamic sign messaging showing the word “slow” to speeding drivers. The devices worked at Twin Lakes but failed to work in Bemidji, presumably because of the location of the sign in the latter location.

Karkee (2005) examined several different countermeasures pre and post installation in Las Vegas, Nevada, for both AM and PM peak traffic periods, at different sites in a manner like the current project. Of relevance here, the “turning traffic must yield to pedestrians” sign was effective at getting drivers to yield when turning, and the high visibility crosswalk, warning signs, and advance yield markings at midblock locations appeared to also be effective at improving driver and pedestrian behaviors. Pulugurtha and colleagues (2012) followed up this study in the same location (Las Vegas) at eight different sites with a similar methodology, testing high visibility crosswalks, pedestrian refuges, pedestrian channelization, and Danish offsets. Pedestrian channelization is often seen in work zones or other locations requiring safe pedestrian travel, and employs physical barriers to separate pedestrians and traffic. Danish offsets or staggered crosswalks are crosswalks with median islands on multilane roads that offset the crosswalk so that the crossing pedestrian must turn in the median and face the direction of oncoming traffic before crossing the second half of the crosswalk. High visibility crosswalks and pedestrian refuges were observed to help pedestrian behaviors as measured by whether pedestrians looked for vehicles, and improved driver yielding to the crossing pedestrians. These installations did not appear to affect yielding distance.

In the context of stopping for pedestrians, Bella and Silvesri (2015) employ Fuller’s (1984) driver threat avoidance model, a precursor to Fuller’s more recent modeling work in driver control theory (Fuller, 2011). To summarize, the model states that driver behavior is focused on both time efficiency and risks or threats on the road, and when a “discriminative stimulus” (e.g., a risk) such as a pedestrian is detected by a driver, drivers engage in either an anticipatory avoidance response (e.g., braking to slow down) or a non-avoidance response (e.g., does not intend to yield). In terms of reinforcement/punishment conditioning, drivers psychologically experience reward when pedestrians do not contest the right-of-way when drivers perform a non-avoidance response, and experience punishment when their yielding (anticipatory avoidance response) results in time delay. There are a number of factors that govern the likelihood of drivers selecting one response option or the other, but one key factor is the time to arrive at the crossing when the driver detects the pedestrian/stimulus. Bella and Silvesri (2015) indicate that the greatest conflict occurs when the driver can arrive at the crossing between 1 and 4 seconds, which is enough time to generate a conflict if there is a pedestrian that intends to cross, and often depends on the willingness of the driver to stop, among other factors. However, if the driver observes the pedestrians earlier than 4 seconds, the driver presumably knows they cannot cross before the pedestrian if the pedestrian were to attempt to cross and is more likely to slow down. Therefore, increasing visibility with longer sight distances is important for pedestrian safety at crossings.

With the threat avoidance model in mind, Bella and Silvesri (2015) conducted a simulated driving experiment examining driver speed and other metrics such as stopping distance when approaching zebra crossings with simulated pedestrians present or absent. These simulations also considered other infrastructure and their relative effectiveness when combined with zebra crossings: Curb extensions, parking restrictions, and advanced stop/yield markings. The best performance was achieved when zebra crossings were combined with curb extensions, both in reduced speed and initial braking distance as well as yielding rate, and this performance data was corroborated with questionnaire data from the participants indicating greater willingness to stop and better simulated pedestrian visibility. See Figure 4 for an illustration of the better visibility afforded by curb extensions.

Lin and colleagues (2019) examined pedestrian crash data to examine rate and severity because of demographics, road environment, and land use type, with a focus on low-income regions, given that pedestrian behavior is more prevalent and riskier in those regions. For higher rates of pedestrian crashes, the significant factors were greater proportion of older adults, reduced car ownership, higher traffic signal density, higher number of bus stops, higher proportion of high-speed roads, and greater densities of discount stores, fast-food restaurants, and convenience stores. For greater pedestrian crash severity, the primary variable is a dark or poorly lit environment, although the number of impaired pedestrians and aggressive drivers also contributed to the likelihood of greater injury severity. There were also a significant number of engineering and roadway feature related outcomes (see Table 6 in Lin et al., 2019). Besides poorly lit environments, a significant number of crashes and fatalities occur outside of intersections, closer to bus stops, and higher-speed roads, therefore Lin and colleagues (2019) recommend (1) implementing adequate and uniform lighting and placement of said lighting for pedestrians crossing, (2) treatments at non-intersection locations such as signals (HAWKs, RRFBs), high visibility crosswalks, and median islands, (3) bus stop improvements such as relocation , and (4) speed reduction treatments (e.g., traffic calming on local roads). Finally, they emphasize the need for site visits and road safety audits instead of solely relying on historical crash data.

Craig and colleagues (2019) revisited Mead and colleagues (2014) cautionary note on installing crosswalk markings at either high speed or high-volume roads, particularly those that are multilane, by measuring driver stopping rates to staged pedestrians at an unsignalized crossing on Maryland Avenue in Saint Paul, Minnesota. The speed limit on Maryland Avenue was 30 mph, and the average daily traffic was over 21,000 vehicles (MnDOT, 2019a). The road was a two-lane road with a turn lane, which falls into recommending or cautioning use of crosswalk markings without other enhancements depending on whether one classifies the road as two-lane or three-lane (see Figure 3). During the road construction process to install a road diet (see MnDOT, 2019a), the transverse crosswalk markings at the location were removed. The research team performed staged crossings before and after the markings were removed, and measured driver stopping rates and stopping distances. They found that the presence of markings predicted stopping rate and distance, with the removal of markings being associated with fewer drivers stopping and closer stopping distances for drivers that did stop (i.e., under 10 feet to the pedestrian). This also suggests that the presence of crosswalk markings helps drivers form an expectancy or provides a cue that they should be looking for pedestrians, making the resulting pedestrian more detectable if present (Craig et al., 2019). Craig and colleagues (2023) followed up this line of research in Minneapolis, Minnesota. In this follow-up study, the research team performed staged crossings at several crosswalk sites in Minneapolis, with the sites initially not being marked, and were then painted a few weeks later with continental markings. Although distance was not analyzed in the follow-up study, the study was able to replicate the observed greater driver stopping rate associated with markings present.

Morris and colleagues (2019) implemented a multifaceted intervention program to improve driver stopping rates in Saint Paul, Minnesota, employing both education, outreach, and two levels of police enforcement that occurred in waves. A major component of the program included in-street engineering in the form of R1-6 signs on multiple sites with different traffic characteristics and lane counts. These thin and durable signs have an illustrated stop sign and indicate that state law requires stopping for pedestrians. R1-6 signs can be considered a form of temporary or quick build pedestrian safety infrastructure as they provide the function of warning signs and traffic calming depending on where they are installed. Single placement signs (usually on the median) were very effective at improving driver stopping rates to staged pedestrians at study sites except for the highest traffic volume multilane sites. Stopping rates at the latter sites were improved with a combination of police enforcement and multiple R1-6 signs placed in a “gateway” configuration (both the median and the curb).

Budzynski and colleagues (2021) studied the influence of various pedestrian safety infrastructure on pedestrian and driver behavior in Poland, which is of interest here because Poland driving regulations do not require drivers to give way to pedestrians, meaning significant improvements in driver behavior will not be confounded with legal consequences, unlike in Minnesota. In general, stopping rates were not much impacted by infrastructure, with an overall stopping rate of about 20% when pedestrians were waiting to cross at measured sites. However, driver speed appeared to be affected by the presence of infrastructure. Drivers slowed down the most when pedestrians were present at a roundabout, whereas drivers slowed down more at locations where a refuge island was present compared to locations where an island was not present irrespective of the presence of a pedestrian.

1.5 Literature Review Conclusion

This introduction reviewed the use and value of pedestrian infrastructure, summarized research surveys that came out within the last 15 years and covered specific empirical studies that may not have been considered in the research surveys. Some general use takeaways are: (1) traffic volume, average speed, and lane number are important factors for risk, (2) older pedestrians, children, and individuals of lower socioeconomic status are particularly vulnerable, (3a) maintenance (e.g., no cracks in sidewalks, no potholes, no faded striping., etc.) and (3b) physical barriers between vehicle traffic and pedestrians are particularly valuable for use, and (4) there may be a higher willingness to support improved pedestrian infrastructure if its value is communicated and said infrastructure either has neutral or positive economic benefit for the local community.

Some safety-specific takeaways are: (1) focusing on speed reduction, visibility, and pedestrian-vehicle separation appear to be the most effective approaches to take, (2) refuge islands appear to have the most replicable benefits across the board for most safety metrics, with the possible exception of driver stopping rates, which has mixed results, and (3) curb extensions appear to be effective by means of both speed reduction and improvement in pedestrian visibility. It is worth noting that the relationship between driver stopping rates and pedestrian crash rates is unclear, with increased stopping rates potentially leading to a greater risk of multiple threat conflict (but see Morris, et al., 2020), whereas higher driver stopping rates have also been associated with reduced pedestrian crash rates at uncontrolled crossings (Schneider et al., 2017). There could be a potential tradeoff between frequency and severity of crashes, a promising future research topic.

Of particular importance are Mead and colleagues (2014) observations that painted median islands do not perform as well as raised median islands, that is, the presence of a barrier appears to be critical. These barriers can include low objects such as a curb, or taller objects such as delineators and walls, if a physical boundary is established between pedestrians and vehicle traffic that could present a disruption if drivers attempt to cross the boundary. This suggests that the use of temporary or quick build infrastructure that incorporates some form of a barrier should be as effective as permanent installations using barriers. This is reminiscent of research done with bike lanes, as both separated and buffered bike lanes are perceived as safer and more comfortable to use compared to their non-buffered non-separated counterparts (Sanders & Judelman, 2018), and buffered bike lanes using actual barriers, even those using plastic delineators, were perceived as more comfortable to bicyclists, particularly those concerned with safety (McNeil et al., 2015). Drivers give more space to bicyclists on wide painted buffer bicycle lanes compared to no bicycle lanes or regular painted bicycle lanes, but they give even more space to bicyclists in protected bike lanes (Nolan et al., 2021). Given this indication of the importance of physical barriers over driver cues such as signs and paint, the current project indirectly considers whether this barrier hypothesis has support in measuring the relative effectiveness of temporary pedestrian safety infrastructure using delineators.

1.6 Research Questions and Project Timeline

Pedestrian injuries and fatalities remain an ongoing problem in Minnesota (MnDPS, 2022), leading to significant personal, societal, and financial costs each year. Identifying effective mitigation strategies to improve safety and reduce risks to pedestrians is vital to personal and public health.

Pedestrian infrastructure is generally effective at improving pedestrian safety. Agencies may initially treat sites with temporary treatments (e.g., removable bollards, see Figure 1.2) to test efficacy, which are also relatively less expensive than more permanent installations. But unlike with more permanent infrastructure, pedestrian behavior at temporary infrastructure relative to permanent infrastructure is less known, as is how temporary treatments interact with driver factors such as speed and likelihood of stopping for crossing pedestrians.

This study was conducted to test the impact of temporary and permanent pedestrian infrastructure such as curb extensions/bump-outs and pedestrian refuge islands/medians on pedestrian and driver behavior. The focus was on how pedestrian and driver behavior changed and affected safety and risk. The project tasks and timeline are presented in Table 1.1**.** The study was mostly reliant on the city of Minneapolis' Vision Zero's 2023-2024 pedestrian safety plan and traffic calming efforts by the city of Saint Paul.

Figure 1.2 Image of a flexible delineator or bollard in yellow plastic with retroreflective markings/tape at the top of the post. Similar delineators are made in white and orange colors.

Table 1.1 Project tasks and timeline

Task and Task Number (#)	Task Completion Date	Corresponding Final Technical Report Chapter
(1) Initial Memo on Benefits	**October 31st 2023**	**Chapter 5: Conclusion and Recommendations**
(2) Research Update	**October 31st 2023**	**Chapter 1: Introduction**
(3) Site Selection Phase One	**August 31st, 2023**	**Chapter 2: Site Selection and Data Collection**
(4) Field Data Collection Phase One	**February 28th, 2024**	**Chapter 2: Site Selection and Data Collection**
(5) Preliminary Data Analysis	**May 31st 2024**	**Chapter 3: Staged Crossing Analysis, Chapter 4: Traffic Camera Footage Analysis**
(6) Site Selection Phase Two	**May 31st, 2024**	**Chapter 2: Site Selection and Data Collection**
(7) Field Data Collection Phase Two	**April 30th, 2025**	**Chapter 2: Site Selection and Data Collection**
(8) Speed Data Analysis	**June 30th, 2025**	**Chapter 3: Staged Crossing Analysis, Chapter 4: Traffic Camera Footage Analysis**
(9) Data Analysis	**June 30th, 2025**	**Chapter 3: Staged Crossing Analysis, Chapter 4: Traffic Camera Footage Analysis**
(10) Final Memo	**August 31st, 2025**	**Chapter 5: Conclusion and Recommendations**
(12) Draft Final Report	**October 31st, 2025**	**--**
(13) Final Publishable Report	**December 31st, 2025**	**--**

The research plan comprised the following features for site selection and infrastructure implementation.

Select sites (intersections) in two year-long phases

1. **2023**
2. **2024**

Sites should be one of two infrastructure designs

1. **Curb extension/bump-out** (hardened centerline optional)
2. **Refuge island/median**

Infrastructure designs should use one of two materials/methods

1. **Flexible delineators (bollards)**
2. **Concrete**

Study sites would (ideally) be balanced between two types

1. **Signalized** (traffic signal controlled)
2. **Unsignalized** (not controlled by a traffic signal)

An adequate measurement sample should occur

(1) **Before/pre-**installation of the infrastructure
(2) **After/post-**installation of the infrastructure

Measurement samples would ideally involve multiple methods

(1) **In-person scoring** (capture driver-pedestrian interactions)
(2) **Camera footage** (capture naturalistic pedestrian behavior and driver speeds)

Following this approach, the following site and implementation types were selected:

- Bollard bump-out at signalized sites with and without a hardened centerline,
- Concrete bump-out at a signalized site,
- Bollard bump-out at an unsignalized site,
- Concrete bump-out at an unsignalized site,
- Bollard refuge/median at signalized site,
- Bollard refuge/median at an unsignalized site, and
- A concrete refuge at an unsignalized site.

The only site type that was not available for pre- and post-installation measurement due to logistical issues was a concrete refuge/median at a signalized site.

The site selection and data collection process for these sites are described in the following chapters.

Chapter 2: Site Selection and Data Collection

The final sites selected are provided in Table 2.1 and the data collection timeline is provided in Table 2.2.

Table 2.1 Selected sites

Study Period	Location	Type	City	Installation Infrastructure
Phase 1 (2023)	Nicollet & 26th W	Signalized	Minneapolis	Temporary Pedestrian Refuge
Phase 1 (2023)	Bloomington & 24th	Signalized	Minneapolis	Temporary Curb Extension + Hardened Centerline
Phase 1 (2023)	31st & Pillsbury	Signalized	Minneapolis	Temporary Curb Extension
Phase 1 (2023)	33rd & Lyndale N	Unsignalized	Minneapolis	Temporary Curb Extension
Phase 1 (2023)	34th & Lyndale N	Unsignalized	Minneapolis	Permanent Pedestrian Refuge
Phase 1 (2023)	36th & Pillsbury	Unsignalized	Minneapolis	Temporary Curb Extension
Phase 2 (2024)	N 12th St & Hennepin Ave	Signalized	Minneapolis	Permanent Curb Extension
Phase 2 (2024)	Maple St S & Hennepin Ave	Signalized	Minneapolis	Permanent Curb Extension
Phase 2 (2024)	Cedar Ave S & E 38th St	Signalized	Minneapolis	Temporary Curb Extension
Phase 2 (2024)	Longfellow Ave & E 38th St	Unsignalized	Minneapolis	Temporary Pedestrian Refuge + Temp Curb Extension
Phase 2 (2024)	22nd Ave S & E 35th St	Unsignalized	Minneapolis	Permanent Pedestrian Refuge
Phase 2 (2024)	N Milton St & Thomas Ave W	Unsignalized	Saint Paul	Temporary Curb Extension
Phase 2 (2024)	N Avon St & Thomas Ave W	Unsignalized	Saint Paul	Permanent Curb Extension on one side of crosswalk

Table 2.2 Data collection timeline

Location	Pre-Install Crossing Dates	Pre-Install Camera Dates	Installation Date	Post-Install Crossing Dates	Post-Install Camera Dates
Nicollet & 26th W	July 28th to August 8th 2023	July 28th to August 3rd 2023	August 9th, 2023	August 10th to November 21st 2023	August 14th 2023 to August 29th 2023
Bloomington & 24th	July 31st to August 17th 2023	August 10th to August 17th 2023	September 20th 2023	September 21st to November 21st 2023	October 9th to October 18th 2023
31st & Pillsbury	July 31st to August 17th 2023	August 1st to August 8th 2023	August 31st 2023	August 31st to November 13th 2023	October 3rd to October 18th 2023
33rd & Lyndale N	July 31st to August 17th 2023	August 1st to August 8th 2023	November 20th 2023	April 23rd, to May 23rd 2024	May 6th to May 20th 2024
34th & Lyndale N	July 31st to August 17th 2023	August 1st to August 7th 2023	November 20th 2023	April 23rd, to May 23rd 2024	May 6th to May 20th 2024
36th & Pillsbury	August 3rd to August 17th 2023	August 1st to August 8th 2023	August 31st 2023	August 31st to November 21st 2023	October 3rd to October 18th 2024
12th St & Hennepin	July 5th to August 13th, 2024	July 10th to July 18th, 2024	November 21st, 2024	June 27th to September 12th, 2025	April 8th to April 15th, 2025
Maple & Hennepin	July 5th to August 15th, 2024	July 10th to July 18th, 2024	November 21st, 2024	July 3rd to September 12th, 2025	April 8th to April 15th, 2025
Cedar & 38th	September 27th to October 15th, 2024	September 30th to October 14th, 2024	November 6th, 2024	November 15th to November 24th, 2024	November 12th to November 25th, 2024
Longfellow & 38th	September 27th to October 23rd, 2024	September 30th to October 14th, 2024	November 6th, 2024	November 6th to November 21st, 2024	November 7th to November 20th, 2024
22nd & 35th	July 25th to August 23rd, 2024	---	October 7th, 2024	October 23rd to November 21st, 2024	November 7th to November 14th, 2025
Milton & Thomas	May 23rd to July 2nd, 2024	June 25th to July 3rd, 2024	October 21st, 2024	October 24th to November 22nd, 2024	November 7th to November 20th, 2024
Avon & Thomas	May 23rd to June 6th, 2024	May 28th to June 5th, 2024	November 21st, 2024	March 28th to May 8th, 2025	April 8th to April 15th, 2025

Images of the selected sites are presented in **Appendix A** and **Appendix B**.

2.1 Site Selection

2.1.1 2023 Site Selection

The research team at the Human Factors Safety Laboratory received a preliminary list in early July 2023 of planned pedestrian safety installations along 4 of the 7 corridors as part of Minneapolis' Vision Zero safety initiative. These initial corridors included north Lyndale, Nicollet, Bloomington, and 35th St. Further information came mid-July 2023 for 31st St and 36th St. A list of 11 preliminary sites, incorporating a mix of signalized and unsignalized locations and installation plans, was distributed to the MnDOT TAP on July 13th, 2023. The two primary issues raised by the TAP in reference to the preliminary list were: (1) the need to select sites with temporary and permanent pedestrian refuges/medians, which were missing from the initial list, and (2) the consideration of research questions which could be answered with the judicious selection of some of the sites.

In response to the first issue, two new sites were added to address the TAP concern, as one site is planned for a temporary pedestrian refuge installation, and the other is planned for a permanent pedestrian refuge installation (see Table 2.1; 33rd & Lyndale; 34th & Lyndale).

For the second issue, several potential research questions were raised by the TAP. These included: "Differences of impacts between installation on one-way vs two-way streets? Differences between wrap around bump-outs vs bump-outs on a single leg? Difference between bump-outs on collector/arterial vs on neighborhood street? Differences between hardened centerlines and ped refuge island?"

However, the sites in the initial list that could potentially answer the offered questions were not selected. These include 35th & Longfellow (unsignalized site with wraparound curb extension), which was dropped because of the aforementioned community pressure to rapidly install the infrastructure at the 35th St corridor; 31st & Lyndale (signalized site with hardened centerlines), dropped because of its proximity to planned road construction along Bryant Avenue in the summer and fall of 2023; and Nicollet & 27th (unsignalized t-intersection with a temporary curb extension on a neighborhood street), which was dropped because the installation is at a stop sign, which is a confounding factor.

Given time pressure and the need to effectively coordinate with both the city and the traffic data collection company (for camera data), the research team quickly finalized their list of 6 sites, with 3 of the sites being signalized, and 3 being unsignalized, with a mix of temporary and permanent pedestrian refuges, temporary curb extensions, and hardened centerlines. The only installation type not assessed during 2023 were permanent curb extensions, which were assessed in the following year (2024).

2.1.2 2024 Site Selection

In late March 2024, the research team received a preliminary shortlist of two planned pedestrian safety installations in Minneapolis, MN with concrete medians. These sites were originally W 36th St/Pleasant Ave and Lyndale Ave N/45th Ave N. In mid-April, these sites were reassigned to E 35th St/22nd Ave S and N 14th Ave/Emerson Ave N. In late May, Minneapolis communicated that more sites were being considered. The city indicated that a signalized location with a temporary curb extension would be available after some internal discussion and shared a number of concrete curb extension sites and a smaller number of concrete pedestrian refuge sites.

In early May 2024, the research team received a list of three candidate sites in Saint Paul, MN, with concrete curb extensions and partial bollard curb extensions. These sites were along Thomas Avenue (west). Of those three sites, one site (Victoria St N & Thomas Ave W) was excluded from further consideration. The planned curb extensions for this site would be placed at stop signs. This placement would prevent unimpeded traffic flow along the direction of the curb extension installations. The other two sites (N Avon St & Thomas Ave W, N Milton St & Thomas Ave W) remained on the candidate list.

Given time pressure and the need to effectively coordinate with both the city and the traffic data collection company (for camera data), the research team compiled an initial list of sites. The research team provided alternative options to the initial list, and included E 35th & 22nd Ave S, an unsignalized permanent median refuge in Minneapolis. E 35th & 22nd Ave S was of particular interest to the research team because it provided a better comparison to the temporary pedestrian refuge at the unsignalized site of 33rd & Lyndale Ave North. The previous year's (2023) permanent pedestrian refuge site at 34th & Lyndale Ave North included small curves in the roadway to promote speed reduction similar to a chicane along with the pedestrian refuge, which was not mirrored in the installation at 33rd & Lyndale Ave North. The installation at E 35th & 22nd Ave S did not include these additional curves, it was a useful comparison site. Because the primary focus at E 35th & 22nd Ave S was on speed reduction and driver stopping rate, not on natural pedestrian behavior, and given the time and budget limitations for collecting and analyzing video footage, the research teams planned to conduct data collection at the E 35th & 22nd Ave S site only with in-person field work. By using staged crossings and spot speed methodologies using stopwatches, the research team assumed they could reliably collect the safety outcomes of interest without using cameras for this site. After discussion with the TAP and the Technical Liaison, the final list of sites was selected, as presented in Table 2.1.

2.2 Data Collection

As a reminder, data collection followed the general experimental design, restated here.

- Two field methods for data collection (staged crossings by research team, camera)
  - Staged and natural crossings at selected crosswalks at the sites to better capture driver-pedestrian interactions
  - Video recordings via cameras placed at the sites to capture natural pedestrian behavior
- Two types of sites (signalized intersections, unsignalized intersections)
  - Signalized intersections focused on legal conflicts between pedestrians and drivers, when pedestrians have the right-of-way and drivers turning right must stop for those pedestrians
  - Unsignalized intersections focused on free-flowing non-turning traffic, as pedestrians safely initiate their right-of-way by stepping into the crosswalk
- Two infrastructure designs (pedestrian refuge/median, curb extension)

    - During scoring videos for curb extension sites, coders examined whether pedestrians waited on the curb, or in the street if part of the street was enclosed by flexible delineators
    - During scoring videos for the pedestrian refuge sites, coders examined whether pedestrians utilized the pedestrian refuge (e.g., waited in the median)
- Two builds for those designs (permanent, temporary/quick build)

Data collection and planning for each site was contingent on communication with the City of Minneapolis, the City of Saint Paul, and their coordination with their own teams and contracted crews. Because implementation of the planned infrastructure did not happen all at once, the time period for pre-installation staged crossing and camera data, installation, and post-installation staged crossing and camera data were different for each site.

2.2.1 Data Collection Methods

Data collection methods in this project included staged crossings, scoring video recordings with installed traffic cameras, the use of computer algorithms to determine driver speeds from traffic camera video recordings, and an in-person method to determine driver speed.

2.2.1.1 Staged Crossing Method

Staged crossings focused on right-turning drivers at signalized sites and drivers going straight on unsignalized sites, as these two maneuvers are most likely to generate legal conflict points with crossing pedestrians at these site types. At signalized sites, the focus is more on drivers turning right, than drivers turning left, because it is easier to attribute stopping behavior to the presence of the pedestrian when the driver turns right, whereas the driver turning left may be stopping for oncoming traffic and not the pedestrian. For unsignalized sites, the focus is on drivers going straight and not on turning drivers, because drivers turning are already slowing down to make a turn, whereas drivers going straight must decide to stop for the pedestrian, before slowing down to stop. The staged crossing methodology utilized the methods employed in previous research, described below (Craig et al., 2019; 2023; Morris et al., 2019; 2020; Van Houten et al., 2021).

Site visits happened in pairs, with one team member as a staged crossing pedestrian, and the other being an observer/coder, and the two switching roles midway through the site visit to share the exposure risk, specifically 10 crossings out of 20 total crossings. The crossing method involved following an established protocol in which the crosser neared the crosswalk as drivers approached, while allowing time for vehicles to see and respond to a pedestrian crossing. The staged crosser initiated the crossing by putting one foot in the street of the marked crosswalk and waiting for an indication of yielding or stopping by the approaching driver.

For signalized sites with right-turning drivers, this attempt occurred once the green light and walk signal were initiated and the driver utilized the turn signal to indicate they intended to turn right, while providing for adequate time for the driver to notice the pedestrian and stop. For drivers turning at signalized sites at the far side of the crossing, they were counted as failing to stop if they turned while the staged pedestrian was halfway across the street in the first direction of travel. For these far-side interactions at signalized crosswalks, because stopping compliance at traffic signals is typically very high (Morris et al., 2023) the focus was less on creating a legal conflict and more on driver courtesy.

For unsignalized sites, the staged crossers utilized a predefined "dilemma zone" to guide when they should initiate the crossing to allow adequate time for drivers to see and react to crossing pedestrians. This adheres to state-wide traffic laws instructing pedestrians to cross safely and not cross when drivers would not have adequate time to stop. This dilemma zone is defined by a modification of the signal timing formula to determine phase change periods (e.g., yellow lights) (ITE, 2009). See Van Houten and colleagues (2013) for more details on the dilemma zone. This zone is typically 141 feet from the crosswalk on roads with a 30-mph speed limit at zero grade and was measured by a measuring wheel and marked with orange paint. A second team member, as a coder, would observe the driver/staged pedestrian interaction, and score the results of the interaction on a coding sheet on paper or a corresponding entry form on a tablet.

For staged crossings, sites were visited at least twice a week, if possible, between the hours of 9:00 AM and 4:00 PM, avoiding inclement weather such as rain or snow. Staged crossing site visits typically lasted between 20 to 30 minutes depending on traffic conditions such as volume and the timing of the signals for the walk cycles.

2.2.1.2 Staged Crossing Training

Staged crossing staff were trained by senior research staff in order to appropriately and consistently apply the staged crossing methodology and accurately record the results of the crossings. The initial training occurred at two sites on the University of Minnesota - Twin Cities campus in Minneapolis, MN, USA, with one site being a signalized intersection at Harvard & Beacon, and the other at a nearby unsignalized crosswalk a block north of the intersection on Harvard St. Given the slow speeds of the vehicles and the significant pedestrian presence due to the location of students, faculty, and staff at the university, this represents a very simple introduction to the crossing methodology for both site types. This initial introduction was followed up by two sessions of on-the-job training with senior research staff to ensure adequate proficiency with both crossing and observational coding. Once training was completed, the coding staff were allowed to begin coding without supervision.

2.2.1.3 Camera and Video Recording Method

For camera data, the intent was to capture 1 week of pre-installation video data and up to 2 weeks of post-installation video data for the pedestrian infrastructure at the sites, for both temporary and permanent infrastructure types. After pedestrian infrastructure installation, a delay of one week was employed before installing cameras, to partially mitigate any novelty effects. Novelty effects refer to sudden changes in the behavior of drivers who were familiar with the intersection and were not expecting the new infrastructure. These effects are temporary as drivers become more familiar with the installation. Only one week of post-installation data collection was collected for 12th St & Hennepin Ave, Maple St & Hennepin Ave, and Avon St N & Thomas Ave W, because this data collection occurred in Spring 2025, with months of exposure to the installations (November 2024 to April 2025), ensuring that novelty was not a major factor. The cameras recorded video data continuously after it was in place, barring technical issues. The traffic data cameras were installed by Quality Counts LLC (https://www.qualitycounts.net/), who then transferred the video files to the Human Factors Safety Laboratory.

Scoring the videos from the cameras utilized an online Qualtrics survey and log sheet. Coders would access and download the video they were assigned, either on Dropbox or Google Shared Drive. Coders scoring the videos focused on two-hour blocks per site around times of the day with higher likelihood of pedestrian and vehicle traffic, including morning rush hour (7:00 AM to 9:00 AM), lunch (11:00 AM to 1:00 PM), and afternoon rush hour (4:00 PM to 6:00 PM). Video coders would enter in the time (Date and Hour/Minutes/Seconds) and then begin coding as they observed a pedestrian initiating a crossing at the site. Elements coded include the time of the crossing, where the pedestrian waited, whether they ceded the right-of-way, whether pedestrians crossed unsafely and forced drivers to stop, whether drivers stopped for the pedestrian, and other relevant variables. Coding specified whether the pedestrian was crossing from one side of the street (i.e., Location A) to the other side of the street (Location B), or vice-versa (Location B to Location A). This is important because some intersections with curb extensions have asymmetric installations, where only one side of the street received the relevant treatment. One example is N 12th St & Hennepin Ave, where only the south corner of the intersection received a concrete curb extension, whereas the west corner did not receive any treatment.

2.2.1.4 Speed Data Assessment from Cameras

Camera data processing went frame-by-frame (i.e., single-frame processing approach), and frame rates in the collected video varied between 10 and 25 frames per second (fps) with most of the video being collected in 10 fps.

The method for determining vehicle speeds from traffic camera data is described in significant detail elsewhere (Katariya et al., 2024; Katariya et al., 2025). We provide a general summary.

1. *Region of interest*. The region of interest is specified in the image frame and the rest of the image is filtered out.
2. *Object detection*. An object detection model (YOLO v81; Jocher, Chaurasia, & Qiu, 2023) trained on a traffic vehicle dataset (BDD10K; Yu et al., 2020) identifies and classifies objects in the region of interest for a given image frame.
3. *Object tracker*. Over successive image frames, classified objects are assigned identifiers and tracked positionally, supported by the ByteTrack algorithm (Zhang et al., 2022). After an object has been tracked, its identifier and bounding box are sent to a speed estimation module.
4. *Speed estimation part 1: Perspective transformation.* A perspective transformation maps pixel coordinates from the image frame onto “real-world” dimensions with known coordinates for precise motion tracking and speed estimation. These calculations are accomplished using a homography matrix.
5. *Speed estimation part 2: Speed computation.* Once mapped to real-world coordinates, the object displacement over multiple frames is used to calculate changes in object position over time. Because distances are known from the real-world coordinates, and time is known based on the rate of video capture (i.e., frames per second), the speed of the object can be computed.

6. *Data filtering.* Certain aspects of the processing pipeline were filtered based on the research question. Vehicle type was limited to cars, trucks, and buses (classified by BDD10K). Stationary vehicles were removed. Vehicles were discarded if they were moving in directions that were not specified as of interest by the UMN research team. Finally, for the present analysis, vehicles moving closely behind another vehicle were discarded from the analysis to keep the focus on free-flowing traffic. This boundary was defined as within 40 pixels in a given image frame. See Figure 2.1.

Figure 2.1 Filtering of vehicles following too closely (red circles), while free-flowing traffic (green circles) are considered for speed analysis.

The speed estimation focused on computing speed averaged over one second at a specific location in the camera image that generally corresponded to where a pedestrian may be crossing at the site. An example of the speed assessment line is presented in Figure 2.2.

Figure 2.2 Speed averaged over one second is measured at the indicated red lines. The line generally aligns with the pedestrian crossing path.

2.2.1.5 In-Person Speed Data Collection

To support and validate the speed assessment from the camera footage by the UNCC team, the Human Factors Safety Laboratory at UMN team conducted in-person speed data measurement for some of the 2024 study sites. This involved selecting two easily visible landmarks at a site and recording the time it takes free-flowing vehicles to traverse the distance between the two landmarks for a given direction of travel. The goal was to collect 100+ vehicles at specified direction per site per study period (pre/post), following FHWA guidelines (2012) for spot speed studies, which are used to set speed limits.

2.3 Implementation Notes

2.3.1 2023 Pre-Installation Notes

Nicollet & 26th. Given the immediate deadline on the site Nicollet & 26th W (installation was scheduled for August 3rd, 2023, and occurred on August 9th, 2023), the research team began collecting pre-installation data for this site as soon as they could. This may have resulted in fewer data points for this location relative to others in terms of pre-installation data.

Pillsbury & 31st. Turning rates were extremely slow at this site for the relevant staged crosswalk that would be most affected by the temporary curb extension.

Pillsbury & 36th. This is an unsignalized site that originally didn't have crosswalk markings. Crosswalk markings were striped at this location on August 2nd, 2023, and staged crossings began shortly thereafter. The new crosswalk markings were continental style.

2.3.2 2023 Post-Installation Notes

The pedestrian refuge installations along Lyndale (33rd & 34th) were originally projected to be completed in mid-October of 2023, requiring a significant amount of time due to road closures and construction along that corridor. However, the project completion was delayed and finally completed on November 20th, 2023. Given the late timing, and the continued traffic disruption due to continued road maintenance nearby, post-installation data collection for those locations was postponed to the Spring of 2024.

Bloomington & 24th. Installation of the temporary curb extension (August 31st) occurred before the hardened centerline (September 20th).

Pillsbury & 31st. As indicated in the pre-installation notes, this site had very small turning volumes at the relevant crosswalk during staged crossings.

Lyndale & 33rd. The road was closed on August 20th, 2023, for construction of pedestrian safety infrastructure along the north Lyndale corridor and did not reopen until November 20th, 2023. The post-installation data collection was postponed to the Spring of 2024 due to late installation.

Lyndale & 34th. The road was closed on August 20th, 2023, for construction and installation of the permanent pedestrian refuge, and did not reopen until November 20th, 2023. *Lyndale & 33rd.* The post-installation data collection was postponed to the Spring of 2024 due to late installation.

Examples of the temporary pedestrian infrastructure (curb extension, hardened centerline, pedestrian refuge) are provided in Figure 2.3 **and** Figure 2.4.

Figure 2.3 An example of a temporary curb extension and hardened centerline, located at Bloomington & 24th.

Figure 2.4 An example of a temporary pedestrian refuge or median, located at Nicollet & 26th.

Figure 2.3 outlines the number of site visits or observation sessions for each site. For signalized sites, these comprised about 20 walk signal cycles per session, and for unsignalized sites, each session comprised of 20 crossings. Some visits or sessions were cut short due to external factors such as precipitation or high levels of traffic (e.g., afternoon rush hour).

Table 2.3 Data collection count of sessions by site in 2023.

Site	Site Type	Pre-Installation Sessions	Post-Installation Sessions	Total Sessions
Bloomington & 24th	Signalized	7	16	23
Nicollet & 26th	Signalized	4	23	27
Pillsbury & 31st	Signalized	8	10	18
Pillsbury & 36th	Unsignalized	7	19	26
Lyndale & 33rd	Unsignalized	7	N/A	7
Lyndale & 34th	Unsignalized	9	N/A	9
Total		**42**	**68**	**110**

2.3.3 2024 Implementation Notes

Examples of the temporary pedestrian infrastructure (curb extension, pedestrian refuge/median) are provided in Figure 2.5 and Figure 2.6. A curb extension or bump-outs widens (i.e., extends) the curb or sidewalk zone into the street, presumably improving visibility between pedestrians and drivers, reducing the amount of pedestrian exposure to traffic while crossing the street, and potentially slowing vehicle turning speeds (City of Minneapolis, 2021, Chapter 3.7D). The pedestrian median provides some element of protection to crossing pedestrians, with either pavement markings, raised islands, and other means to separate motorized traffic and pedestrians, which reduces pedestrian crashes (FHWA, 2021).

Figure 2.5 An example of a temporary curb extension, located at Milton St & Thomas Ave (left) and Cedar Ave S & E 38th St (right).

Figure 2.6 An example of a temporary pedestrian refuge, located at Longfellow Ave & E 38th St.

Examples of the permanent pedestrian infrastructure (curb extension, refuge) are provided in Figure 2.7 and Figure 2.8.

Figure 2.7 An example of a permanent curb extensions, located at N 12th St & Hennepin Ave (left), and N Avon St & Thomas Ave (right).

Figure 2.8 An example of a permanent pedestrian refuge, located at 22nd Ave S & E 35th St.

2.3.4 2024 Post-Installation Notes

Hennepin Ave & N 12th St. Installation of permanent curb extension with bus stop completed late November 2024. Camera data were not collected until April 2025, due to concerns with winter weather affecting the crossing data.

Hennepin Ave & Maple St S. Installation of permanent curb extension completed late November 2024. Camera data were not collected until April 2025, due to concerns with winter weather affecting the crossing data.

N Avon St & Thomas Ave. Installation of permanent curb extension completed late November 2024. Staged crossings and camera data were not collected until April 2025, due to concerns with winter weather affecting the crossing data.

Table 2.4**,** presented below, outlines the count of data collection sessions over the measurement period by site. A data collection session is a site visit to collect staged crossing data, with the goal of collecting up to 20 crossings per visit. These 20 crossings could be by the staged crossers, natural pedestrians, or a combination. Occasionally, fewer than 20 crossings would be recorded due to data collection issues (e.g., temporary construction suddenly disrupting normal traffic patterns).

Table 2.4 Data collection count of sessions by site in 2024.

Site	Site Type	Pre-Installation Sessions	Post-Installation Sessions	Total Sessions
Hennepin Ave & N 12th St	Signalized	12	7	19
Hennepin Ave & Maple St S	Signalized	9	7	16
Cedar Ave S & E 38th St	Signalized	4	6	10
Longfellow Ave & E 38th St	Unsignalized	4	5	9
22nd Ave S & E 35th St	Unsignalized	8	6	14
N Milton St & Thomas Ave W	Unsignalized	10	6	16
N Avon St & Thomas Ave W	Unsignalized	10	6	16
	Total	**57**	**43**	**100**

2.3.5 2024 In-Person Speed Data Collection Notes

In-person speed data was also collected for four of the seven sites. Initial assessment of signalized speed data found that it was difficult to collect free-flowing traffic data that is appropriate for spot speed study methodology (Forbes et al., 2012). Therefore, the measurements focused on unsignalized sites. The goal was to support and validate the measurements collected by the speed study analysis conducted by the UNCC team. There were 268 vehicle speeds measured for 22nd Ave S & E 35th St, 237 vehicle speeds measured for Longfellow Ave & E 38th St, and 115 vehicle speeds measured for N Milton St & Thomas Ave W. In-person speed data collection for N Avon St & Thomas Ave W was also completed at the end of April 2025.

Chapter 3: Staged Crossing Analysis

The staged crossing analysis focuses on drivers stopping for pedestrians. The strength of the relationship between the rates of drivers stopping for pedestrians and pedestrian crash rates has not been the topic of significant study.

3.1 Stopping Rates and Pedestrian Crashes

For low-speed intersections, one study found that sites in Wisconsin that had two or more pedestrian crashes were associated with a reduced rate of driver stopping for crossing pedestrians of 6.4% (Schneider et al., 2017). More explicitly stated, low-speed uncontrolled intersections with no reported pedestrian crashes had higher stopping rates compared to sites with 2 or more pedestrian crashes in a 5-year period (Schneider et al., 2018). Although this model won't directly transfer to signalized intersections, we can extrapolate a potential relationship between higher driver stopping rates and a reduced likelihood for at least 2 pedestrian crashes at a given location, particularly if the rates change by more than 6.4% after an installation.

For high-speed intersections, defined as locations with a posted speed limit greater than 45 mph, one study found an association between drivers failing to stop for pedestrians and higher crash rates for sites in Louisiana (Houssain et al., 2024). This failure to stop and pedestrian crash likelihood relationship held in the following situations: (1) single stop intersections with one direction of traffic not controlled, like our "unsignalized" intersections, (2) right-turn maneuvers, irrespective of traffic control type present, and (3) residential locations in general (Houssain et al., 2024). This analysis was done for high-speed traffic corridors and our study sites only examined lower speed sites (e.g., 30 mph or lower), but this finding highlights the importance of examining stopping rates for drivers at our unsignalized intersections, as well as the stopping rates of right-turning drivers at our signalized intersections, as there is a plausible relationship between the stopping rates and pedestrian crash rates for these scenarios.

3.2 Descriptive Statistics

The following represents the number of cycles or crossings and the percentage of drivers stopping for pedestrians for both signalized sites (Table 3.1 and Table 3.2) and unsignalized sites (Table 3.3 and Table 3.4). In this section, the data is not analyzed to determine if there is a statistically significant difference between the pre-installation and post-installation percentages. These analyses are presented in the inferential statistics section of this report.

3.2.1 Signalized Sites

Table 3.1 Crossing (Walk Cycle) Count for Signalized Sites.

Study Period	Site	Pre-Installation Crossings	Post-Installation Crossings	Total Crossings
Phase 1 (2023)	Bloomington & 24th	120	320	440
Phase 1 (2023)	Nicollet & 26th	80	450	530
Phase 1 (2023)	Pillsbury & 31st	152	180	332
Phase 2 (2024)	Cedar & 38th	80	89	169
Phase 2 (2024)	Maple & Hennepin	150	130	280
Phase 2 (2024)	12th & Hennepin	200	150	350
	Total	**782**	**1319**	**2101**

Table 3.2 Stopping Percentage by Signalized Site.

Site Location	Installation Type	Pre-Installation	Post-Installation
Pillsbury & 31st	Temporary Curb Extension	--	--
Bloomington & 24th	Temporary Curb Extension	87.25%	72.43%
Nicollet & 26th	Temporary Ped Refuge	70.76%	80.23%
Cedar & 38th	Temporary Curb Extension	83.30%	84.19%
Maple & Hennepin	Permanent Curb Extension	87.17%	92.0%
12th & Hennepin	Permanent Curb Extension	88.14%	86.14%

3.2.2 Unsignalized Sites

Table 3.3 Crossing Count for Unsignalized Sites.

Study Period	Site	Pre-Installation Crossings	Post-Installation Crossings	Total Crossings
Phase 1 (2023)	Pillsbury & 36th	140	360	500
Phase 1 (2023)	Lyndale & 33rd	133	200	333
Phase 1 (2023)	Lyndale & 34th	178	180	358
Phase 2 (2024)	Longfellow & 38th	100	90	190
Phase 2 (2024)	22nd & 35th	140	120	260
Phase 2 (2024)	Milton & Thomas	188	109	297
Phase 2 (2024)	Avon & Thomas	200	120	320
	Total	1079	1179	2258

Table 3.4 Stopping Percentage by Unsignalized Site.

Site Location	Installation Type	Pre-Installation	Post-Installation
Pillsbury & 36th	Temporary Curb Extension	33.58%	31.05%
Lyndale & 33rd	Temporary Ped Refuge	13.32%	17.00%
Lyndale & 34th	Permanent Ped Refuge	6.35%	10.41%
Longfellow & 38th	Temporary Ped Refuge	8.40%	20.96%
22nd & 35th	Permanent Ped Refuge	17.74%	34.08%
Avon & Thomas	Permanent Curb Extension	37.13%	50.06%
Milton & Thomas	Temporary Curb Extension	23.92%	26.96%

3.3 Inferential Statistics

This section provides details on the statistical analysis of the staged crossing data, with a focus on stopping percentages.

3.3.1 Definitions for Inferential Statistics Analysis

The following definitions are included to better understand the statistical analyses in the following sections.

- Generalized Linear Model (GLM): This is a statistical analysis that generalizes linear regression by allowing predictors to be mapped onto the responses in different ways (link function) and allowing the specification of the probability distribution (i.e., the natural pattern of data).

- Generalized Estimating Equation (GEE): These are estimations of generalized linear models for repeated measures data, using variables to help estimate the unmeasured correlations within data.

- Akaike's Information Criterion (AIC): A selection criterion for determining which statistical model to use, with a focus on selecting the more parsimonious, generalizable model. Smaller values indicate more parsimonious, better “fitting” statistical models.

- Quasi Likelihood under Independence Model Criterion (QIC): A modification of the AIC model selection criterion approach for statistical model parsimony applied to generalized estimating equations (GEE). Smaller values indicate better “fitting” statistical models.

- Gamma probability distribution: A hypothetical distribution of continuous data that is always positive and skewed.

- Normal probability distribution: A hypothetical distribution of continuous data that is always “bell-shaped”, with a single peak and symmetrical tails (i.e., normal curve or Gaussian distribution).

- Log-link function: This function transforms the outcome variable by applying an exponent to the outcome variable for a unit increase in a given predictor variable.

- Identity link function: This function allows the linear model to directly predict the outcome variable without transformation.

- Chi-Square statistic (X^2): A test that compares observed data to expected data, to test if there is a relationship between two variables. Larger values indicate that a relationship is present.

- Beta weight (B): A regression coefficient that specifies the amount that the dependent variable increases or decreases for a unit increase in the given independent variable.

- Degrees of freedom (df): The number of values that can vary in the calculation of a particular statistic (e.g., chi-square, t-statistic, etc.).

- p-value: This indicates the likelihood of finding the observed results if the null hypothesis (e.g., no relationship or effect) is true.

- Estimated marginal means (emm): These are means estimated by the statistical model, indicating averages of response variables.

- Odds Ratio (OR): A ratio of the odds of an event happening when a second event has occurred and the odds of that same event happening when the second event has not occurred.

3.3.2 Details of Inferential Statistics Analysis

In the following analysis on stopping percentages, we establish the site performance prior to the installation of the infrastructure as the reference category to which the post-installation measurements are compared. We also provide the odds ratio (OR) against the reference category of pre-installation. The primary metric is stopping percentage, as that provides a measure of relative rate of stopping and incorporates total vehicle conflicts in the denominator. The analysis for staged crossing stopping rates used a generalized linear model (GLM) with a gamma probability distribution and log-link function. The time period of installation (pre/post) was used as the independent variable. The Akaike's Information Criterion (AIC) is used to report model fit, with smaller values being indicative of better model fit.

Right-turn failures to stop for pedestrians are associated with pedestrian crashes, but the strength of the association is not clear (Hossain et al., 2024), so we do not use a critical threshold for signalized right-turn stopping rates.

For unsignalized sites, we consider a critical threshold. As the percentage change of 6.4% was associated with a significant difference in pedestrian crash rates for unsignalized low-speed intersections (Schneider et al., 2017; Schneider et al., 2018), we use that as a general threshold for practical significance as a potential impact of installation effects on pedestrian crash likelihood.

3.4 Signalized Sites Inferential Analysis

3.4.1 Primary Signalized Sites Analyses

The analyses presented in Table 3.5 indicate separate generalized linear models (GLMs) with installation period (pre/post) used as independent variables. The results of each are presented in each row of the table, with statistically significant differences highlighted in the right-most column. On a site-by-site basis, there appeared to be no effect of installation.

Table 3.5 Stopping Rate Assessment for Signalized Sites

Type	Material	Site	AIC	B (SE)	*P*	OR	Estimated Marginal Means		Significant Difference
							Pre-Installation	Post-Installation	
Curb Extension	Permanent	12th & Hennepin	164.3	-.02 (.07)	.734	.98	88.11%	86.14%	No
		Maple & Hennepin	126.5	.06 (.08)	.483	1.06	87.17%	92.09%	No
	Temporary	31st & Pillsbury	42.4	-.18 (.31)	.557	.83	100%	83.33%	No
		Bloomington & 24th	210.8	-.19 (.13)	.163	.83	87.25%	72.43%	No
		Cedar & 38th	95.9	-.03 (.17)	.855	.97	85.42%	82.78%	No
Refuge	Temporary	Nicollet & 26th	214.3	.13 (.08)	.114	1.13	70.76%	80.23%	No

Note. There were no permanent refuge signalized sites included in the study.

3.4.2 Secondary Signalized Sites Analyses

Because crossing conflicts between staged pedestrians and right-turning drivers were relatively infrequent at signalized intersections compared to staged crossings at unsignalized intersections, potential effects may not be easily observable, and the analyses may lack statistical power. To account for this, two follow-up analyses combining the data from different sites were conducted using generalized estimating equations (GEE). Accounting for secondary variables becomes more important with a wider range of sampling periods, so both analyses controlled for the hour time-block during staged crossing site visits to manage time-of-day effects. Instead of AIC, model fit was accounted for with the Quasi Likelihood under Independence Model Criterion (QIC), with lower scores indicating better model fit. Both analyses used a gamma probability distribution, with log link function. The subject effect of site location (e.g., Bloomington & 24th, Cedar & 38th) was included in the model. Pillsbury & 31st was excluded from both analyses due to low pedestrian-driver conflict rates as only four driver stopping percentage rates are reported over the course of 19 site visits.

The first GEE analysis examined only the signalized temporary curb extension sites of Bloomington & 24th and Cedar & 38th, with an independent variable of period (pre-installation, post-installation), with time-block accounted for in the model. The results are presented in Table 3.6. The second GEE analysis also included 12th & Hennepin, Maple & Hennepin, and Nicollet & 26th and included an interaction term of Installation Period (Pre/Post) × Design (Curb Extension / Refuge) × Type (Temporary / Permanent) along with time-block. The results of this single analysis are presented in Table 3.7.

Table 3.6 Integrated Stopping Rate Assessment for Signalized Temporary Curb Extension Sites

Type	Material	QIC	B (SE)	*p*	OR	Estimated Marginal Means		Significant Difference
						Pre-Installation	Post-Installation	
Curb Extension	Temporary	4.91	-.15 (.06)	**.019**	.87	86.75%	75.01%	**Yes**

Note. The estimated marginal means will be different between Tables due to different variables entered into the statistical model.

Table 3.7 Integrated Stopping Rate Assessment for Signalized Installation Sites

Variable	X^2 (*df*)	QIC	*p*	Estimated Marginal Means		Significant Difference
Estimated Time Block	.06 (1)	7.26	.803			
Installation Period	.01 (1)	7.26	.914			
Installation Design	19.77 (1)	7.26	**< .001**			**Yes**
Installation Type	17.42 (1)	7.26	**< .001**			**Yes**
Installation Period × Design × Type	73.03 (2)	7.26	**< .001**			**Yes**
Condition				***Pre-Installation***	***Post-Installation***	
Temporary Curb Extension			**< .001**	**86.60%**	**75.08%**	**Yes**
Temporary Refuge			**.009**	**70.86%**	**80.09%**	**Yes**
Permanent Curb Extension			1.000	87.85%	88.98%	No

Note. The estimated marginal means will be different between Tables due to different variables entered into the model. The pairwise comparisons employ Bonferroni corrections for multiple comparisons.

The results indicate that when taken altogether, there appears to be a decline in drivers stopping for pedestrians after the temporary curb extensions are put in place. The odds ratio (reported as Exp(B) in the GEE analysis) of a driver stopping for a pedestrian is .767 after a temporary curb extension is installed, representing a decline in stopping likelihood ($p < .001$). No change in likelihood would be an odds ratio of 1.0. It is worth noting that in this analysis, there is a smaller but statistically significant decline in stopping likelihood after a permanent curb extension is installed at a signal (OR = .896, p = .001). This effect is small, and it doesn't show up in the estimated marginal means presented in Table 3.7.

3.5 Unsignalized Sites Inferential Analysis

The analyses presented in Table 3.8 indicate separate generalized linear models (GLMs) with installation period (pre/post) used as independent variables. The results of each are presented in each row of the table, with statistically significant differences highlighted in the right-most column. On a site-by-site basis, there appeared to be moderate effect of installation period for some of the pedestrian refuge/median unsignalized sites, particularly 35th & 22nd and 38th & Longfellow, exceeding the 6.4% stopping rate change threshold that may indicate a reduction in pedestrian crash risk.

Table 3.8 Stopping Rate Assessment for Unsignalized Sites

Type	Material	Site	AIC	B (SE)	*P*	OR	Estimated Marginal Means		Significant and Exceeds 6.4% Threshold
							Pre-Installation	Post-Installation	
Curb Extension	Permanent	Avon & Thomas	136.6	.18 (.18)	.336	1.19	39.13%	46.74%	No
	Temporary	36th & Pillsbury	199.1	-.12 (.13)	.348	.89	34..71%	30.72%	No
		Milton & Thomas	129.3	.04 (.26)	.893	1.04	24.73%	25.6%	No
Refuge	Permanent	34th & Lyndale	104.4	.68 (.29)	.018	1.97	5.86	11.56%	No
		35th & 22nd	102.4	.84 (.26)	.001	2.33	15.67%	36.50%	**Yes**
	Temporary	33rd & Lyndale	114.7	.27 (.20)	.190	1.30	13.12%	17.10%	No
		38th & Longfellow	67.1	.99 (.26)	**< .001**	2.68	7.99%	21.38%	**Yes**

Chapter 4: Traffic Camera Footage Analysis

The following analyses focus on the camera data that was either scored by hand to examine pedestrian behavior or analyzed by computer algorithms to determine driver speeds.

4.1 Natural Pedestrian Behaviors

Pedestrians will frequently commit pedestrian crossing violations, such as crossing outside the pedestrian crosswalk boundaries or crossing against the signal (Cinnamon, Schuurman, & Hameed, 2011), although it is worth noting that crossing outside the markings is not illegal in Minnesota unless the adjacent intersections are signalized. Pedestrians are recorded as being at fault in a significant number of pedestrian crashes, presumably due to crossing when they do not have the right-of-way and fail to yield to a driver (Ulfarsson, Kim, & Booth, 2010), cross at an illegal point (Kemnitzer et al., 2019; Okafor et al., 2023; Ulfarsson, Kim, & Booth, 2010), or when they dart into the road (Kemnitzer et al., 2019; Okafor et al., 2023). Okafor and colleagues (2023) found that pedestrians failing to yield to drivers led to an 11.25% increase in the likelihood of an evident or severe injury, with that increase growing to 16.20% for older adults (65+ years).

Given that the present scored camera data only provides an assessment of crossing against the signal for signalized sites and forcing the stop for unsignalized sites (i.e., stepping out when there isn't adequate time for a driver to voluntarily stop), these two metrics will be examined to consider any changes in pedestrian severe injury risk based on observed pedestrian behavior changes due to installations.

4.1.1 Signalized Sites Video Scoring

The crossings scored by the coders are shown in the following figures depicting multiple study sites:

- Figure 4.1: Pillsbury & 31st (left) and Bloomington & 24th (right)
- Figure 4.2: Cedar & 38th
- Figure 4.3: 12th & Hennepin (left) and Maple & Hennepin (right

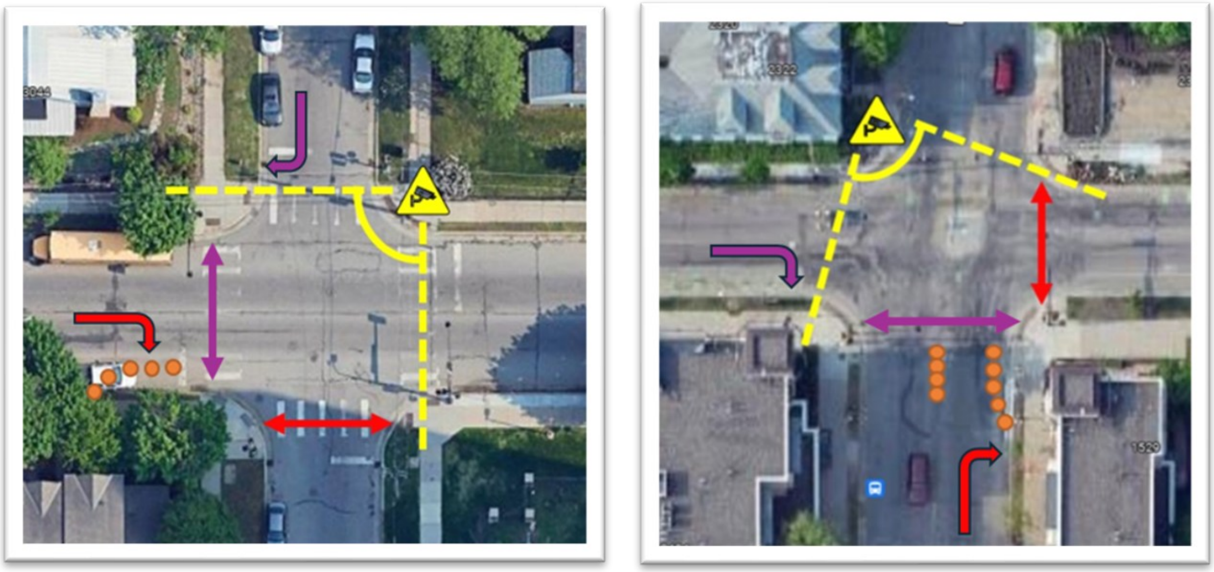

Figure 4.1 Staged coding and camera coding details on Pillsbury & 31st (left) and Bloomington & 24th (right). The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers turning on the curved red arrow. The camera data focused on coding natural pedestrians crossing on the violet double arrow and the stopping rate of drivers turning on the curved violet arrow. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

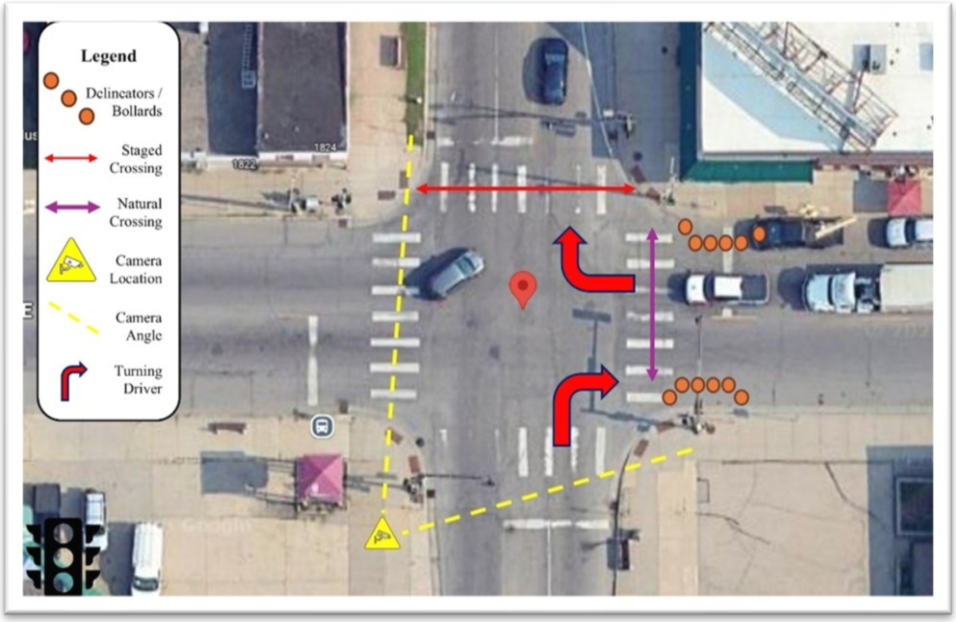

Figure 4.2 Staged coding and camera coding details on Cedar & 38th. The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers turning on the curved red arrow. The camera data focused on coding natural pedestrians crossing on the violet double arrow. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

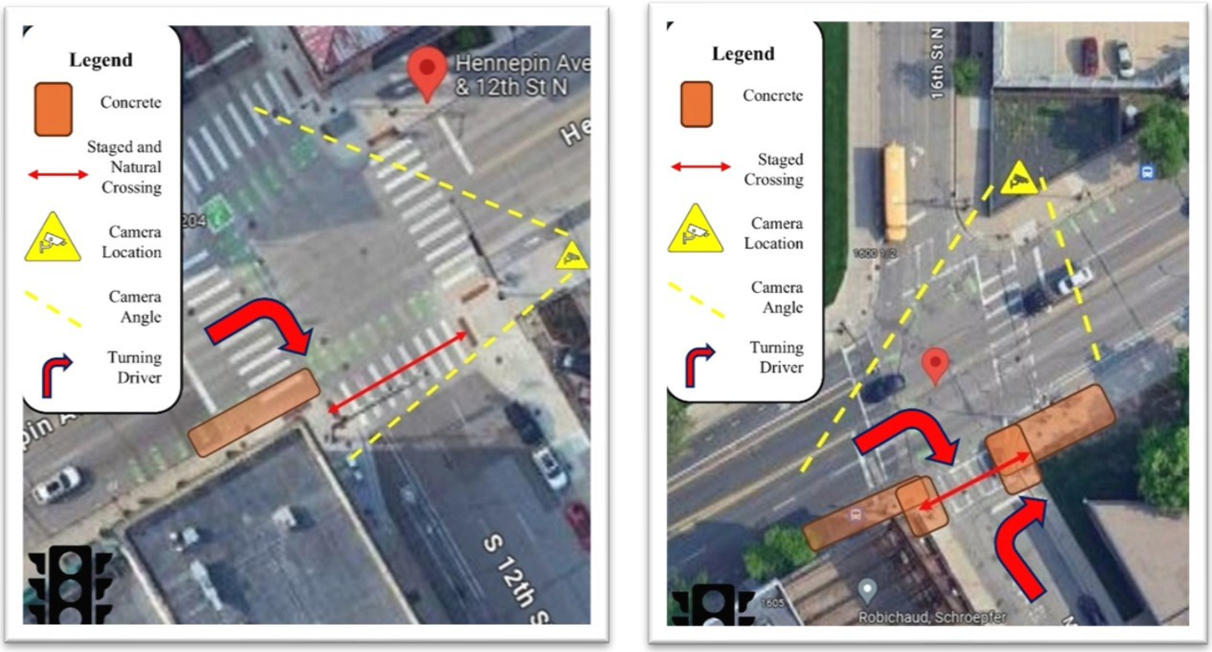

Figure 4.3 Camera coding details on 12th & Hennepin (left) and Maple & Hennepin (right). The camera data focused on coding natural pedestrians crossing on the red double arrow and the stopping rate of drivers turning on the curved red arrow. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

These crossing directions were different relative to the staged crossing data because the primary use of the camera data was to measure *pedestrian interaction with the infrastructure* to see if they would be more likely to violate the crossing cycle, which is not plausible when assessing the red arrow crossings in Figure 4.1. This is only an issue for curb extension installations for the signalized intersections, as driver-infrastructure interactions and pedestrian-infrastructure interactions are consistent across unsignalized sites, and the pedestrian refuge on the signalized site (Nicollet & 26th).

The coding for Nicollet & 26th was relatively like the staged crossings, as interactions between pedestrians and infrastructure was consistent with the same crossing directions performed by the staged crossing team, see Figure 4.4.

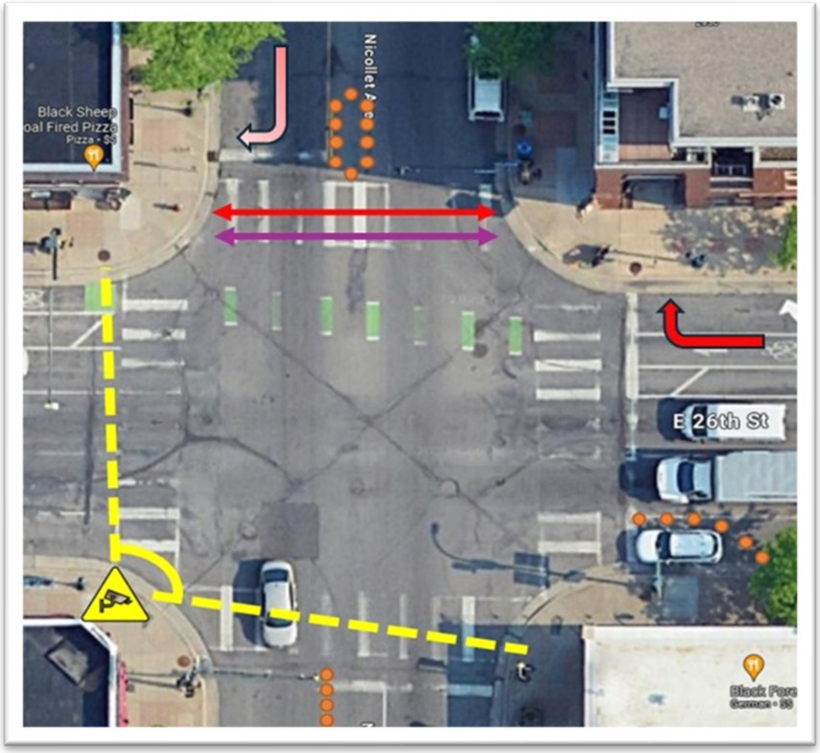

Figure 4.4 Coded crossing for Nicollet & 26th (temporary pedestrian refuge site. The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers turning on the curved red arrow. The camera data focused on coding natural pedestrians crossing on the violet double arrow and the stopping rate of drivers turning on the curved red arrow, and the curved light red arrow. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

4.1.1.1 Signalized Sites Descriptive Statistics

The following table (Table 4.1) presents the descriptive results for pedestrians not following the WALK signal on the signalized sites.

Table 4.1 Rate of Pedestrian Crossing Violations for Signalized Sites

Site Location	**Pre-Installation**	**Post-Installation**
Pillsbury & 31st	9.13%	14.69%
Bloomington & 24th	18.53%	14.98%
Cedar & 38th	10.28%	2.53%
12th & Hennepin	11.39%	7.47%
Maple & Hennepin	28.75%	24.68%
Nicollet & 26th	7.88%	11.90%

Notes. Averages represent either pedestrians crossing from the side of the intersection with the infrastructure, or both sides of the intersection if the infrastructure is present in both sides or the middle of the street.

4.1.2 Unsignalized Sites Video Scoring

The analyses for the camera data for the unsignalized sites used a similar approach to the analyses for the signalized camera data, focusing on pedestrians forcing the stop. Reviews of the videos focused on *two-hour blocks* to account for the maximum likelihood of pedestrian and driver volume. These are presented in the following figures.

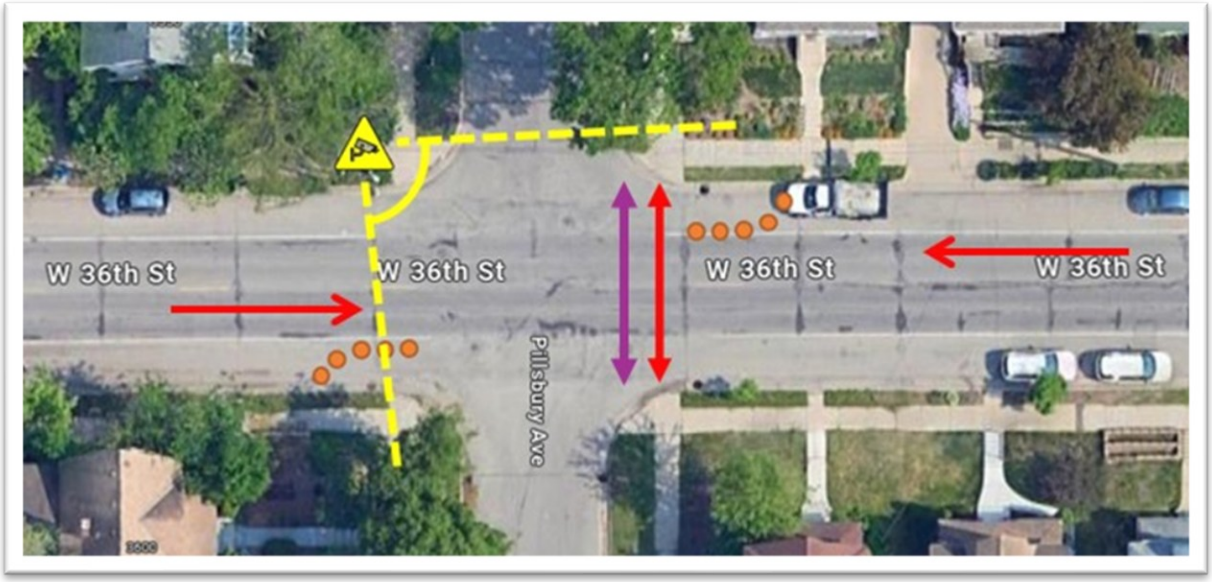

Figure 4.5 Coded crossing for Pillsbury & 36th (temporary curb extension unsignalized site). The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers on the two single straight red arrows. The camera data focused on coding natural pedestrians crossing on the violet double arrow and the stopping rate of drivers proceeding on the two single straight red arrows. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

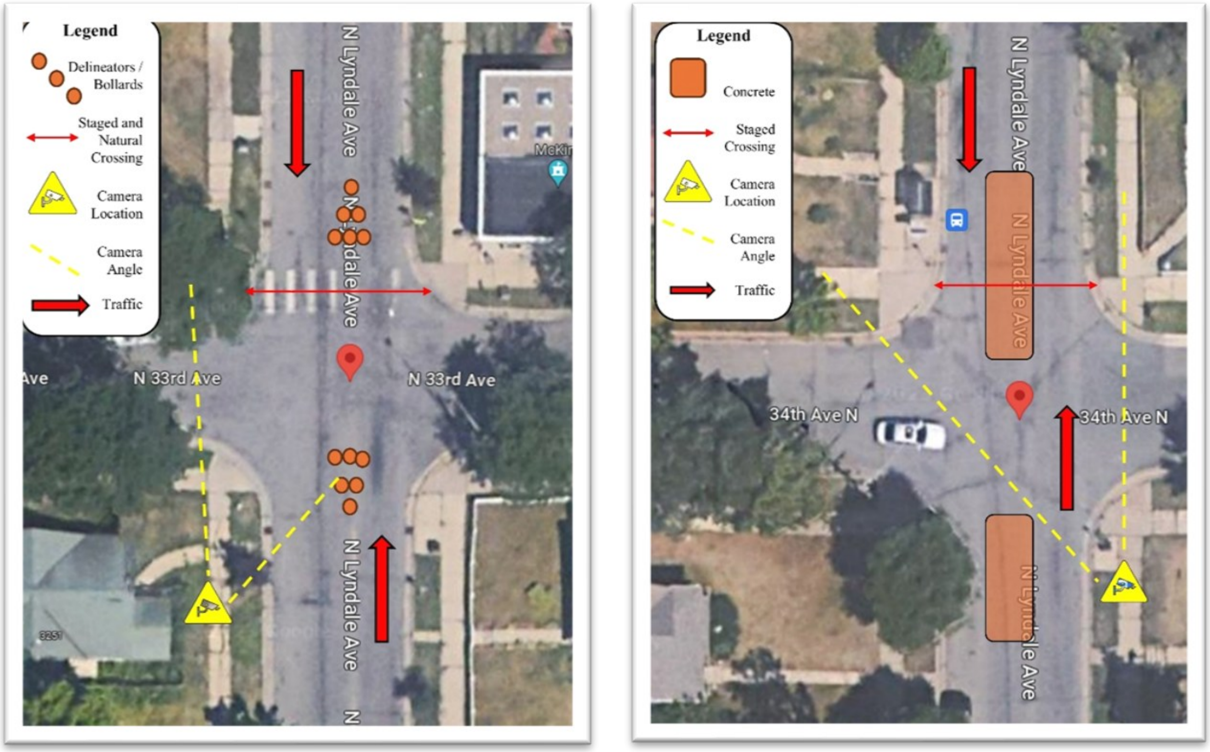

Figure 4.6 Coded crossing for Lyndale & 33rd (left) and Lyndale & 34th (right) The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers on the two single straight red arrows. The camera data focused on coding natural pedestrians crossing on the red double arrow and the stopping rate of drivers proceeding on the two single straight red arrows. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

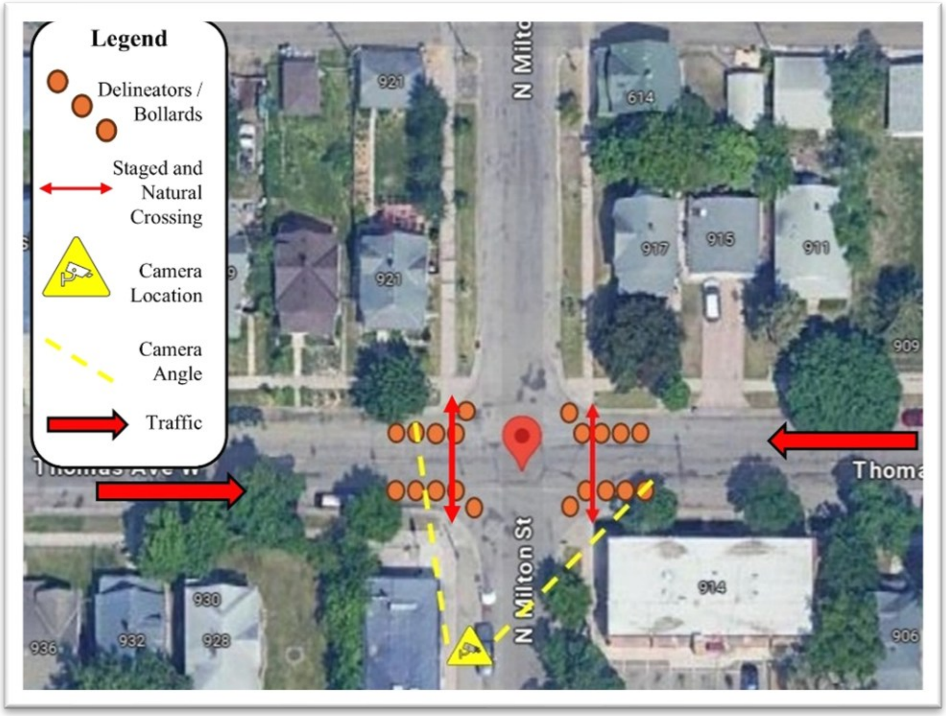

Figure 4.7 Coded crossing for Milton & Thomas. The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers on the two single straight red arrows. The camera data focused on coding natural pedestrians crossing on the red double arrow and the stopping rate of drivers proceeding on the two single straight red arrows. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

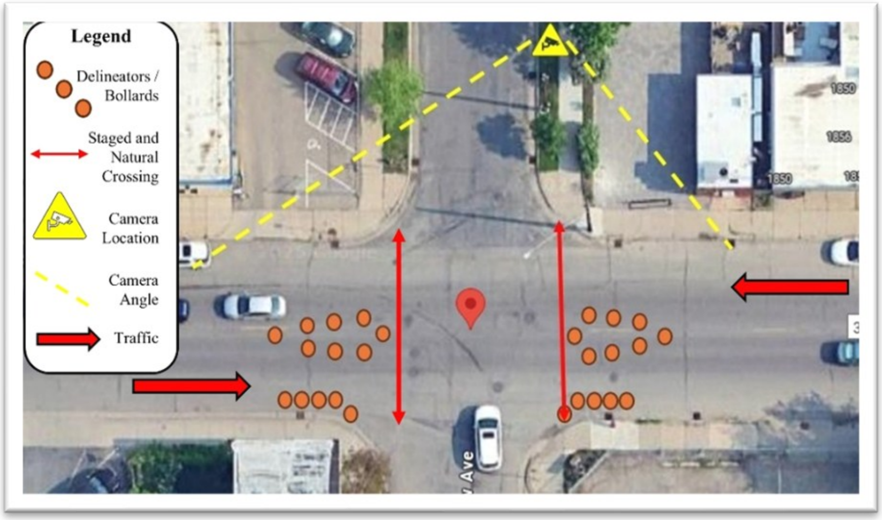

Figure 4.8 Coded crossing for Longfellow & 38th. The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers on the two single straight red arrows. The camera data focused on coding natural pedestrians crossing on the red double arrow and the stopping rate of drivers proceeding on the two single straight red arrows. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

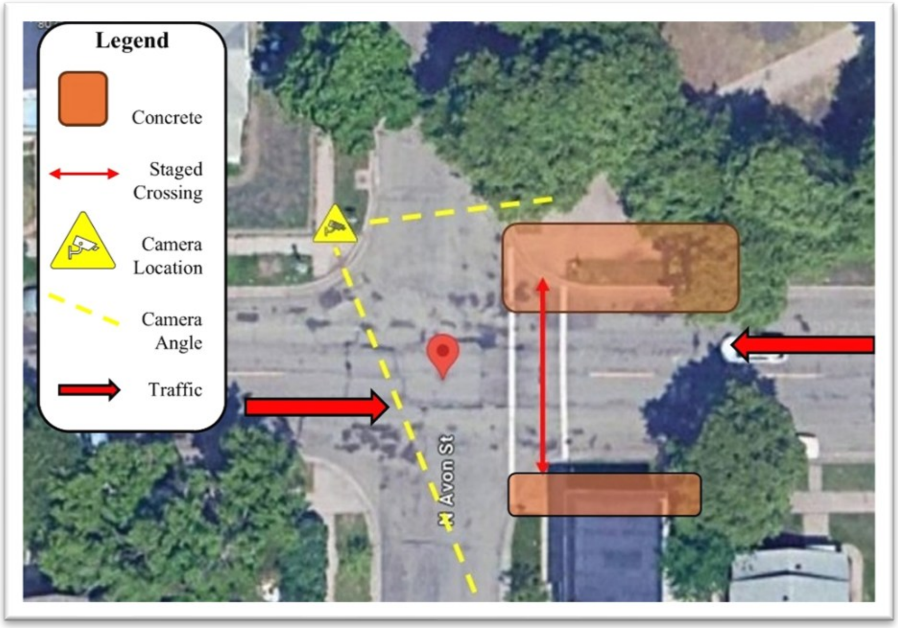

Figure 4.9 Coded crossing for Avon & Thomas. The staged crossing data captured staged pedestrians crossing the street along the red double arrow and the stopping rate of drivers on the two single straight red arrows. The camera data focused on coding natural pedestrians crossing on the red double arrow and the stopping rate of drivers proceeding on the two single straight red arrows. The yellow dashed lines indicate the angle of camera capture, and the orange dots indicate the post-installation bollard placements.

4.1.2.1 Unsignalized Sites Descriptive Statistics

The following table (Table 4.2) presents the descriptive results for pedestrians forcing the stop on the unsignalized sites.

Table 4.2 Percentage of Pedestrian Forcing the Stop for Unsignalized Sites

Site Location	Pre-Installation	Post-Installation
Pillsbury & 36th	1.96%	3.90%
Lyndale & 33rd	7.14%	2.71%
Lyndale & 34th	4.76%	4.88%
Longfellow & 38th	2.53%	7.05%
Milton & Thomas	0.00%	1.67%
Avon & Thomas	8.89%	2.09%

4.1.3 Natural Pedestrian Behavior Inferential Statistics

This analysis was focused on the count of pedestrian violations of the right-of-way. This occurred at an unsignalized site when a pedestrian stepped out onto the crosswalk in front of an approaching vehicle without giving the driver sufficient time to initiate stopping prior to the pedestrian entering the crosswalk. For signalized sites, this occurred when pedestrians crossed against the Don’t Walk signal.

Because these violations were a relatively infrequent occurrence, it was difficult to analyze each site separately. Therefore, we adopted an integrated GEE approach like the analysis of right-turn stopping rates for temporary curb extensions in **Table 3.6**.

Here, the dependent variables are a count of pedestrians forcing the stop at an unsignalized site (presented in **Table 4.4**) and a count of pedestrians crossing against the signal (presented in **Table 4.3**). The GEE analyses all used negative-binomial distributions and log-link function, with site location and date of video entered as subject factors.

Each analysis included the correlates of time-block, estimated vehicle count, and "no event" pedestrian crossings as a proxy for pedestrian volume. The installation period (pre/post) was the independent variable of interest.

4.1.4 Signalized Sites Analysis

Table 4.3 Integrated Pedestrian Violation Count Assessment for Signalized Sites

Type	Material	QIC	B (SE)	*p*	OR	Estimated Marginal Means	
						Pre-Installation	Post-Installation
Curb Extension	Temporary	325.3	.09 (.16)	.577	1.09	1.11	1.22
	Permanent	93.1	-.16 (.15)	.281	.85	3.52	3.01
Refuge	Temporary	99.1	1.18 (.22)	**< .001**	1.06	1.26	4.11

Note. Because these analyses focus on count, the OR (odds ratio) indicates the likelihood of a pedestrian violation event.

4.1.5 Unsignalized Sites Analysis

Table 4.4 Integrated Pedestrian Violation Count Assessment for Unsignalized Sites

Type	Material	QIC	B (SE)	*p*	OR	Estimated Marginal Means	
						Pre-Installation	Post-Installation
Curb Extension	Temporary	58.2	-.77 (.52)	.142	.47	.05	.02
	Permanent	17.1	-2.3 (1.3)	.082	.10	.02	.00
Refuge	Temporary	62.2	.80 (.63)	.203	2.23	.03	.06
	Permanent	29.6	.41 (1.01)	.688	1.50	.02	.03

Note. Because these analyses focus on count, the OR (odds ratio) indicates the likelihood of a pedestrian violation event.

4.2 Driver Speed

The introduction of neighborhood slow zones in New York City (NYC), NY, found that road casualties declined about 8.74% in these slow zones relative to other similar areas in NYC, and this resulted in benefits of approximately $9 to $15 per resident as a function of reducing productivity losses because of injury and death (Jiao et al., 2019). Given this, we can anticipate a relationship between higher vehicle speeds and pedestrian death and injury.

Hussain and colleagues (2019) conducted a 15-study meta-analysis to examine fatality risk to pedestrians. They found that the odds of a pedestrian fatality grow by 11% (Odds Ratio (OR) = 1.1) and the odds of a severe injury increase by 9% (OR = 1.09) for every increase of 1 km/h for impact speed. On average, the risk of a fatality to a pedestrian was about 5% at 30 km/h (~18.641 mph), 13% at 40 km/h (~24.855 mph), and 29% at 50 km/h (~31.069 mph) impact speeds. Rosen & Sanders (2009) found that the fatality risk of a pedestrian crash at 50 km/h (~31.069 mph) impact speed was twice as high as a crash at 40 km/h (~24.855 mph), and at least five times greater than a crash at 30 km/h (~18.641 mph). They also provided two fatality risk functions based on their study of pedestrians being struck by the front of passenger vehicles. The first function does not account for pedestrian characteristics [Eq 1], while the second function accounts for age [Eq 2], although this only applies for pedestrians aged 15 and older.

$$P(v) = \frac{1}{1+\exp\,(6.9-(0.09*v))} \tag{1}$$

$$P(v, age) = \frac{1}{1+\exp(9.1-(0.095*\,v)-(0.040*age))} \tag{2}$$

Impact speed, *v*, is measured in km/h. *Age* is pedestrian age in years, with a minimum of 15 years for this fatality risk function (Rosen & Sanders, 2009).

Tefft (2013) examined the risk of fatalities or severe injuries based on impact speed for collisions in the United States in the years 2007 through 2009. The risk of a fatality was 10% at 24.1 mph and 25% at 32.5 mph, while the risk of a severe injury was 10% at 17.1 mph and 25% at 24.9 mph (Tefft, 2013). Jurewicz and colleagues (2016) reviewed research examining the link between mass, speeds, collision types, and the likelihood of fatalities and severe injuries. While the typical threshold of impact collision speed is about 30 km/h (~18.641 mph), they identified the key threshold as 20 km/h (~12.427 mph) for impact speeds in collisions with pedestrians. This threshold was determined by establishing the boundary of a severe injury likelihood of 10% for Vision Zero purposes. Finally, an older study examining the risk of injury to children found that sites with average speeds over 40 km/h (~24.855 mph) had a higher rate of injury or death for child pedestrians, although there were no corresponding increases in risk with greater average speeds (Roberts et al., 1995). This makes the threshold of 25 mph or 24.855 mph an important one to consider in terms of safety.

4.2.1 Speed Descriptive Statistics

The descriptive statistics focuses on vehicles categorized as “pass through” by the computer algorithm, meaning that they are at proceeding through the intersection at the speed of at least 10 miles per hour or more. This will ensure that the speed measurements do not assess drivers reacting to the traffic signal to stop. Table 4.5 contain descriptive statistics for signalized sites and Table 4.6 contain descriptive statistics for unsignalized sites.

Table 4.5 Signalized site descriptive statistics for speed.

Site	Pre-Installation Average Speed (mph)	Post-Installation Average Speed (mph)	Pre-Installation 85th Percentile Speed (mph)	Post-Installation 85th Percentile Speed (mph)
12th & Hennepin	22.79	20.11	27.41	23.05
Bloomington & 24th	18.28	19.14	20.22	20.76
31st & Pillsbury	18.42	20.44	21.59	35.01
Cedar & 38th	18.94	16.03	23.18	17.75
Maple & Hennepin	21.34	18.88	24.27	21.82
Nicollet & 26th	18.50	16.81	21.39	19.04

Table 4.6 Unsignalized site descriptive statistics for speed.

Site	Pre-Installation Average Speed (mph)	Post-Installation Average Speed (mph)	Pre-Installation 85th Percentile Speed (mph)	Post-Installation 85th Percentile Speed (mph)
22nd & 35th	27.37	26.81	30.19	--
33rd & Lyndale	26.10	23.04	29.16	25.47
34th & Lyndale	25.47	19.47	27.86	21.88
Avon & Thomas	20.38	19.90	26.39	26.43
Milton & Thomas	20.52	23.31	23.81	25.85
38th & Longfellow	22.08	19.48	26.40	24.27
36th & Pillsbury	26.33	22.57	28.61	24.88

4.2.2 Speed Inferential Statistics

Given that high driver speed is associated with a higher likelihood of pedestrian fatality and higher injury severities, and that the introduction of low-speed zones as been demonstrated to be cost effective (Jiao et al., 2019), we examine speed changes as a function of intervention type.

The analyses to examine average speed as a function of installation period used generalized estimating equations (GEE). The average speed considered vehicles categorized as “Pass Through” by the computer algorithm on the camera, travelling on a straight trajectory. Pass Through vehicles were defined as those that found to remain at or above approximately 10 mph throughout the measurement period. The GEE analyses used a gamma probability distribution, with log link function. The subject effect of date of the site visit was included in the model. The independent variables of installation period (pre/post) and whether the video data was capturing vehicles on a weekday (M-F) or the weekend (Saturday/Sunday). Estimated time-block was included as a correlate.

As new installations go in, the expectation is that drivers should slow down on average. If an analysis found that there was no effect of installation period, or if drivers were faster on average in the post-installation period, a second analysis would decompose the GEE by traffic direction to more closely examine the effects of the installation, if more than one direction of traffic was assessed. The probability of a pedestrian fatality given a collision at the given average speeds are reported. These probabilities were calculated using Equation 1, converting mph into km/h (Rosen & Sanders, 2009). Changes in probabilities of fatality and severe injury are also calculated, if a significant effect of installation period is found, based on Hussain and colleagues (2019).

Average speed assessment for signalized curb extension sites are presented in Table 4.7, average speed assessment for unsignalized curb extension sites are presented in Table 4.8, and average speed assessment for unsignalized refuges are presented in Table 4.9. These analyses only examine the video data.

The measurements of driver speeds at 35th & 22nd were only fully assessed with in-person measurement. Because the number of vehicle samples and site visits were not as extensive with this method compared to the use of traffic cameras, the analysis was different. The analysis for in-person vehicle speeds used a generalized linear model (GLM) with a normal probability distribution and an identity function, with period of installation (pre/post) as the independent variable. This analysis is presented in Table 4.10.

4.2.2.1 Signalized Sites with Curb Extensions

Table 4.7 Average Speed Assessment for Signalized Curb Extension Sites from Cameras

Material	**Site**	**Traffic Direction**	**QIC**	**B (SE)**	***P***	**OR**	**Estimated Marginal Means (Ped Fatality Probability in %)**		**Estimated Change of Relative Odds in % for Significant Effects**	
							Pre-Install	Post-Install	Fatality	Severe Injury
Permanent	12th & Hennepin	Eastbound	37.5	-.12 (.03)	**< .001**	.88	22.71 mph (2.63%)	20.08 mph (1.81%)	-46.56%	-38.09%
	Maple & Hennepin	Eastbound	43.8	-.12 (.04)	**.002**	.89	21.19 mph (2.12%)	18.81 mph (1.51%)	-42.13%	-34.47%
Temporary	31st & Pillsbury	Eastbound	12.4	.18 (.01)	**< .001**	1.19	19.38 mph (1.64%)	23.15 mph (2.80%)	+66.74%	+12.02%
	Bloomington & 24th	Northbound	5.5	.04 (.00)	**< .001**	1.04	18.28 mph (1.41 %)	19.11 mph (1.58%)	+14.69%	+12.02%
	Cedar & 38th	Both	67.0	-.16 (.03)	**< .001**	.85	18.58 mph (1.46%)	15.83 mph (.99%)	-48.68%	-39.83%

Notes. Ped Fatality Probability based on Rosen & Sanders (2009). Estimated Change of Relative Odds in Percentages based on Houssain et al., (2019).

4.2.2.2 Unsignalized Sites with Curb Extensions

Table 4.8 Average Speed Assessment for Unsignalized Curb Extension Sites from Cameras

Material	**Site**	**Traffic Direction**	**QIC**	**B (SE)**	***p***	**OR**	**Estimated Marginal Means (Ped Fatality Probability in %)**		**Estimated Change of Relative Odds in % for Significant Effects**	
							Pre-Install	Post-Install	Fatality	Severe Injury
Permanent	Avon & Thomas	Both	48.2	-.02	.125	.98	--	--	--	--
		Eastbound	29.3	-.08	**< .001**	.92	16.36 mph (1.07%)	15.12 mph (.89%)	-21.95%	-17.96%
		Westbound	18.5	.01 (.02)	.952	1.00	24.83 mph (3.54%)	24.86 mph (3.56%)	--	--
Temporary	36th & Pillsbury	Eastbound	60.1	-.15 (.03)	**< .001**	.86	26.24 mph (4.31%)	22.55 mph (2.57%)	-65.32%	-53.45%
	Milton & Thomas	Eastbound	30.3	.04 (.03)	.214	1.04	22.91 mph (2.71%)	23.75 mph (3.05%)	--	--

Notes. Ped Fatality Probability based on Rosen & Sanders (2009). Estimated Change of Relative Odds in Percentages based on Houssain et al., (2019).

4.2.2.3 Unsignalized Sites with Refuges/Medians

Table 4.9 Average Speed Assessment for Unsignalized Refuge Sites from Cameras

Material	**Site**	**Traffic Direction**	**QIC**	**B (SE)**	***p***	**OR**	**Estimated Marginal Means (Ped Fatality Probability in %)**		**Estimated Change of Relative Odds in % for Significant Effects**	
							Pre-Install	Post-Install	Fatality	Severe Injury
Permanent	34th & Lyndale	Both	37.9	-.27 (.01)	< .001	.77	25.63 mph (3.96%)	19.61 mph (1.70%)	-106.57%	-87.19%
Temporary	33rd & Lyndale	Both	94.3	-.12 (.02)	< .001	.88	26.32 mph (4.36%)	23.26 mph (2.84%)	-54.17%	-44.32%
	38th & Longfellow	Both	81.2	-.13 (.02)	< .001	.88	21.85 mph (2.33%)	19.25 mph (1.61%)	-46.03%	-37.66%

Note. The site of 35th & 22nd used in-person speed assessment instead of camera data, as there was no available pre-installation camera footage for that location. This assessment did not include measurements where the two observers disagreed on more than two seconds for a given vehicle to traverse the start and end measurement points. Ped Fatality Probability based on Rosen & Sanders (2009). Estimated Change of Relative Odds in Percentages based on Houssain et al., (2019).

Table 4.10 Average In-Person Speed Assessment for 22nd Ave S & E 35th St

Material and Design	Site	Traffic Direction	AIC	B (SE)	*p*	OR	Estimated Marginal Means (Ped Fatality Probability in %)		Estimated Change of Relative Odds in % for Significant Effects	
							Pre-Install	Post-Install	Fatality	Severe Injury
Permanent Refuge	35th & 22nd	Westbound	1440.3	-1.00 (.45)	.027	.37	27.65 mph (5.24%)	26.67 mph (4.58%)	-17.35%	-14.19%

Because the GLM analysis presented in Table 4.10 had a very poor model fit, with a large AIC value, we transformed the speed data with a natural log transformation to better approximate a normal distribution. Repeating the GLM analysis on the natural log transformed data led to a better model fit (AIC = -299.5). The results of that analysis also found a significant effect of installation period, with post-installation natural log speeds as less on average compared to pre-installation natural log speeds, B (SE) = -.04 (.02), *p* = .019, OR = .96.

4.3 Secondary Considerations

The site of Pillsbury & 31st may have had issues with on-street parking. The before and after pictures of Pillsbury & 31st in Figure 4.10 **and** Figure 4.11 may indicate a major difference in parked vehicles which could affect the Base Free Flow Speed (BFFS) due to changes in lane width and may partly explain the increase in vehicle speed (FHWA, 2022). Estimates of available lane width with a car present in that location, and the leading flexible delineator in the curb extension were comparable (~13.68 ft and ~13.86 ft) (see Figure 4.12 and Figure 4.13), so the determination of whether this approach applies in this situation is: (1) whether substantial on-street parking (pre-installation) counts as “reduced lane width” and (2) less substantial on-street parking (post-installation) counts as “more lane width”. I Furthermore, traffic speeds increased in general for this location, including the direction of travel that should not be affected by the curb extension (westbound), suggesting that other external factors may play a role in this average speed increase at this location.

Figure 4.10 Still frames from the first (left) and last (right) days of pre-installation camera footage at Pillsbury & 31st. Note the position of the two lead parked cars on the left side of the intersection.

Figure 4.11 The first day of post-installation camera data at Pillsbury & 31st. Note the absence of the parked cars, replaced by the bollard curb extension.

Figure 4.12 Overhead picture of Pillsbury & 31st, with a distance estimation of the lane width from a vehicle parked on the street to the middle of the street. Images and estimation taken from Google Maps ©.

Figure 4.13 Overhead picture of Pillsbury & 31st, with a distance estimation of the lane width from the approximate location of the leading bollard in the temporary curb extension to the middle of the street. Images and estimation taken from Google Maps ©.

Chapter 5: Conclusion and Recommendations

5.1 Costs

5.1.1 Permanent Pedestrian Safety Infrastructure

Pedestrian infrastructure using concrete and other long-lasting and resilient materials such as curb extensions and median refuges differ in cost depending on site conditions, as well as whether drainage systems must be factored into the installation. An older 2013 assessment of costs indicated that curb extensions cost on average about $13,000 each, resulting in approximately $100,000 required for a full retrofit of a four-leg intersection. However, as noted, the price of a curb extension can vary significantly, with a maximum observed cost of approximately $40,000 for a single curb extension. There are similar costs for median islands, with an average median island costing about $13,000, and costing at maximum about $40,000 (Bushell et al., 2013). In 2025 dollars, $13,000 in 2013 is about $18,000, and $40,000 in 2013 is about $55,000.

5.1.2 Temporary Pedestrian Safety Infrastructure

Current flexible delineators cost between $30 and $100 each, depending on height, material, and other features, consistent with a 2019 survey of costs by MnDOT (2019b). There are also installation costs to be considered; for example, the average hourly earnings in Minnesota in 2025 were about $40 (BLS, 2025). While not specified, curb extensions using flexible delineators usually require a minimum of 4 to 6 delineators per extension and at least 6 delineators for a refuge section on one side of the intersection (see Figure 5.1). Most intersections have two refuge sections, leading to a minimum of 12 delineators. Both extensions and refuges may also require paint and reflective tape, the former of which may cost about $20 and the latter of which costs approximately $700 for 6 inches of tape width (MnDOT, 2019b). Finally, it is worth noting that “temporary” can imply a wide range of installation durations, from a couple of days to weeks, months, and even seasonable applications. For longer installation periods, more durable and usually more costly materials may be needed.

Figure 5.1 Temporary refuge section with bollards and paint.

5.1.3 Pedestrian Crashes

Fatal pedestrian crashes cost at least $68M in medical costs and work loss costs (CDC, 2020), and this is likely a conservative estimate. The comprehensive costs of pedestrian non-fatality crashes is $230,000 for incapacitating injury crashes and $58,700 for non-incapacitating evident injury crashes (Michigan Crash Facts, 2012), based on a 2012 analysis by the National Safety Council. These are older assessments, so the current value of these losses could be significantly higher. In 2025 dollars, $135,000 in 2004 is about $230,000 (Miller et al., 2004), $230,000 in 2012 is about $323,000 (Michigan Crash Facts, 2012), and $58,000 in 2012 is about $81,000 (Michigan Crash Facts, 2012).

5.2 Considerations

On-street parking appears to have mixed effects on pedestrian safety. For example, significant on-street parking can be of higher risk for crashes with child pedestrians (Roberts et al., 1995), but other locations with significant on-street parking can have comparatively very low severe and fatal crash rates (Marshall, Garick, & Hansen, 2008). A critical review by Biswas and colleagues (2017) noted that high-speed streets with an average free flow speed of 35 mph or more are adversely affected by the presence of on-street parking, leading to higher rates of pedestrian crashes, whereas low-speed streets with an average free flow speed of less than 35 mph show a safety benefit of on-street parking, with a reduction in the rate of severe and minor injury crashes (although the parking should be parallel and not angled).

One final note is the plausible role of visual complexity. While the complexity of the road environment likely has an impact on driver performance and cognition, the contribution of visual complexity is understudied. In a driving simulation study, Edquist and colleagues (2011) found that participants rated driving through simulated on-street parking in an urban environment as more mentally taxing and tended to drive through those locations more slowly on average (~30 mph) relative to similar urban locations without on-street parking (~34 mph). An arterial route (non-urban) with no parking was rated as less mentally demanding and led to the highest average speeds relative to all the urban locations that presumably had more visual clutter (Edquist et al., 2011). This may have safety implications for pedestrian safety infrastructure that introduces significant visual clutter into the driving environment.

5.3 Unsafe Effects

The reduced rate of drivers stopping for pedestrians at the signalized intersections with temporary curb extensions installed may represent the influence of visual clutter (Edquist et al., 2012) and distraction, as drivers may be focusing on navigating the turn and avoiding the flexible delineators, which could reduce the odds of the driver observing and stopping for the crossing pedestrian. Because this effect emerged when considering two different signalized intersections (Pillsbury & 31st was excluded from that analysis because of the low rate of conflicts), and due to the association of right-turn stopping and pedestrian crashes (Houssain et al., 2019), this may represent the primary safety concern of this infrastructure type.

It is worth noting that a smaller, marginal effect occurred for the permanent curb extensions at the signalized intersections after controlling for the effects of the time of day (**Table 3.7** and the paragraph following that table), suggesting that the increased physical separation may play a minor role in stopping likelihood as increased physical separation may reduce the driver's perceived risk and lead to riskier behavior. However, because the effect of the temporary curb extensions are relatively salient in comparison to those of permanent curb extensions, the visual complexity explanation may play a stronger role in affecting the driver's likelihood of violating a pedestrian's right-of-way.

The increased number of pedestrian violation counts at Nicollet & 26th is also a concern because these sorts of violations are associated with higher rates of pedestrian crashes (Okafor et al., 2023). However, these measurements occurred during a period of significant local construction (early August 2023), and this finding was only present on a single site, so this observation warrants a cautionary note and indicates that further investigation is needed to determine whether this is a generalizable effect.

5.4 Positive Safety Effects

There appeared to be several reliable positive benefits of the quick-build temporary infrastructure. These included (1) improved driver stopping rates for pedestrians with temporary refuges at unsignalized intersections, (2) reduced average speeds of drivers in free-flowing traffic for temporary refuges at both signalized and unsignalized intersections, and (3) some mixed evidence for reduced average speeds for drivers approaching temporary curb extensions at signalized and unsignalized intersections. The effects of permanent infrastructure appear to be either neutral or positive across the board.

5.5 Recommendations

The general safety benefits of pedestrian safety infrastructure are difficult to disentangle from the characteristics of the sites, including on-street parking, volume of pedestrians crossing, vehicle traffic volume, and types of drivers and pedestrians. However, given the negative and positive benefits described in the previous section, the following items for implementation of the research findings are recommended.

It is also worth noting that there are some trade-offs for use of flexible delineators, as these temporary installations would require regular maintenance, as well as special care for winter maintenance as the equipment may be affected by significant winter weather.

5.5.1 Temporary Curb Extensions at Signalized Intersections

- If considering the use of temporary curb extensions, their use is cautioned at signalized intersections from a safety perspective, as the present results suggest that their presence may affect the likelihood of drivers stopping for a crossing pedestrian, and their impact on average driver speeds is mixed.

- There may be an advantage for reducing unwanted overtaking or lane-changing behavior, but that was not considered in detail here.
    - The effect is similar but much smaller (marginal) for permanent curb extensions at intersections with traffic signals.
        - This implies that the visual complexity or distractibility of the flexible delineators may play a notable role for drivers at signalized intersections. One option to consider is testing the safety tradeoffs of bollards of different heights. Bollards are often at 36 inches in height. Would they have a similar effect at 24 inches or 12 inches for signalized intersections when used as curb extensions?
    - If the location has generally low-speed traffic (i.e., less than 35 mph) and has significant on-street parking, and it is anticipated that the addition of temporary curb extensions and other bollard treatments would reduce the level of on-street parking. This may have positive or negative safety effects depending on other roadway characteristics.

5.5.2 Temporary Curb Extensions at Unsignalized Intersections

- Temporary curb extensions at unsignalized intersections appear to be neutral or mixed on their impact on driver stopping or pedestrian violations.
- The effects are mixed or inconsistent for average driver speeds. However, if curb extensions are used for other reasons, such as improving sight distances for pedestrians at the crosswalk, this could be justified.
- There do not appear to be any superior benefits of permanent curb extensions relative to temporary curb extensions for our safety measures.
    - Avon & Thomas (permanent) and 36th & Pillsbury (temporary) both had significant reductions in average driver speed after installation, at least in the eastbound directions.
- If the primary concern is pedestrian walking space or walkability, the permanent curb extension may be preferred.

5.5.3 Temporary Refuges

- The temporary refuge appears to have generally positive effects for pedestrian safety and could be considered as an option for reducing driver speeds for both signalized and unsignalized intersections, and for improving the likelihood of drivers stopping for crossing pedestrians at unsignalized locations.
    - If the prospective installation site is signalized, has a significant pedestrian volume, and pedestrians crossing against the signal is a major concern for the location, the

preliminary finding suggests some caution in installing the temporary refuge. However, this finding needs to be tested with more sites to be confident in this implementation recommendation.

- The effects of the refuge material (temporary/permanent) appear to be roughly comparable, although this is difficult to definitively establish. The effects at Lyndale & 34th (permanent refuge) were elevated by changing the geometry of the roads to slow the approaching drivers, and the effects at 35th & 22nd (permanent refuge) were measured in-person instead of with the camera algorithm, so while an effect of installation was shown, the measurements were relatively imprecise for that site.
- The current design of the temporary refuges as tested in this study do not appear to be pedestrian friendly, as the design focuses on emphasizing physical separation of vehicle traffic and the median, without any explicit accommodation for pedestrian crossings. This may be because for these locations, the installations were primarily implemented as medians instead of refuge islands, with the emphasis on physically separating traffic in opposite directions of travel instead of separating crossing pedestrians from traffic.
    - This is highlighted in the left and middle diagrams in Figure 5.2**.** A more pedestrian friendly layout of flexible delineators is presented in the right diagram on Figure 5.2**,** which better communicates physical separation between the crossing pedestrian in the median and vehicle traffic. A similar approach is presented in Figure 5.3, which has been used in MnDOT District 1. Installation guidelines for this style of median island can be found in MnDOT's *Demonstration Project Implementation Guide* (MnDOT, 2019b, pg. 23).

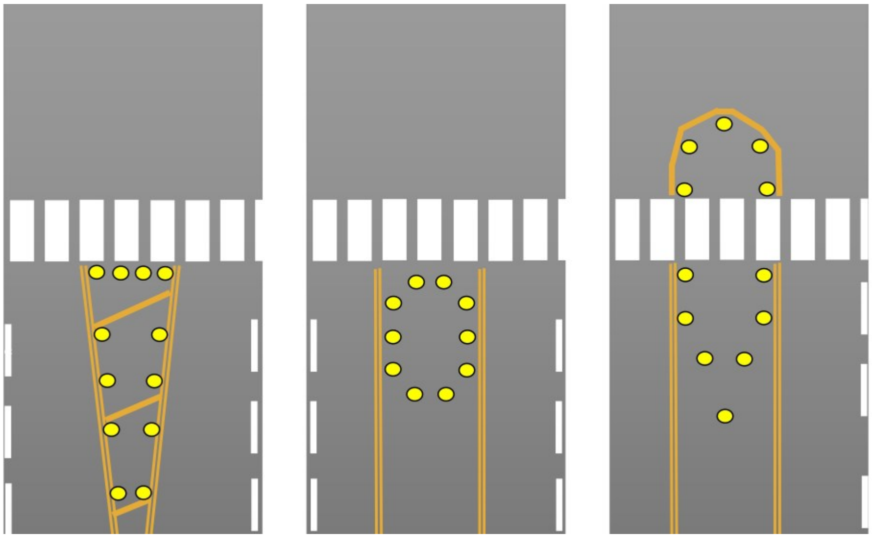

Figure 5.2 Renderings of temporary or quick-build median refuges. The left and middle diagrams reflect examples of median refuges used in the current study, at 33rd & Lyndale and Nicollet & 26th respectively. The diagram on the right is a hypothetical refuge intended to better represent a pedestrian island, communicating physical separation between the pedestrian and vehicle traffic.

Figure 5.3 An example of a quick-build or temporary pedestrian refuge island installed in MnDOT District 1. Image provided by MnDOT.

References

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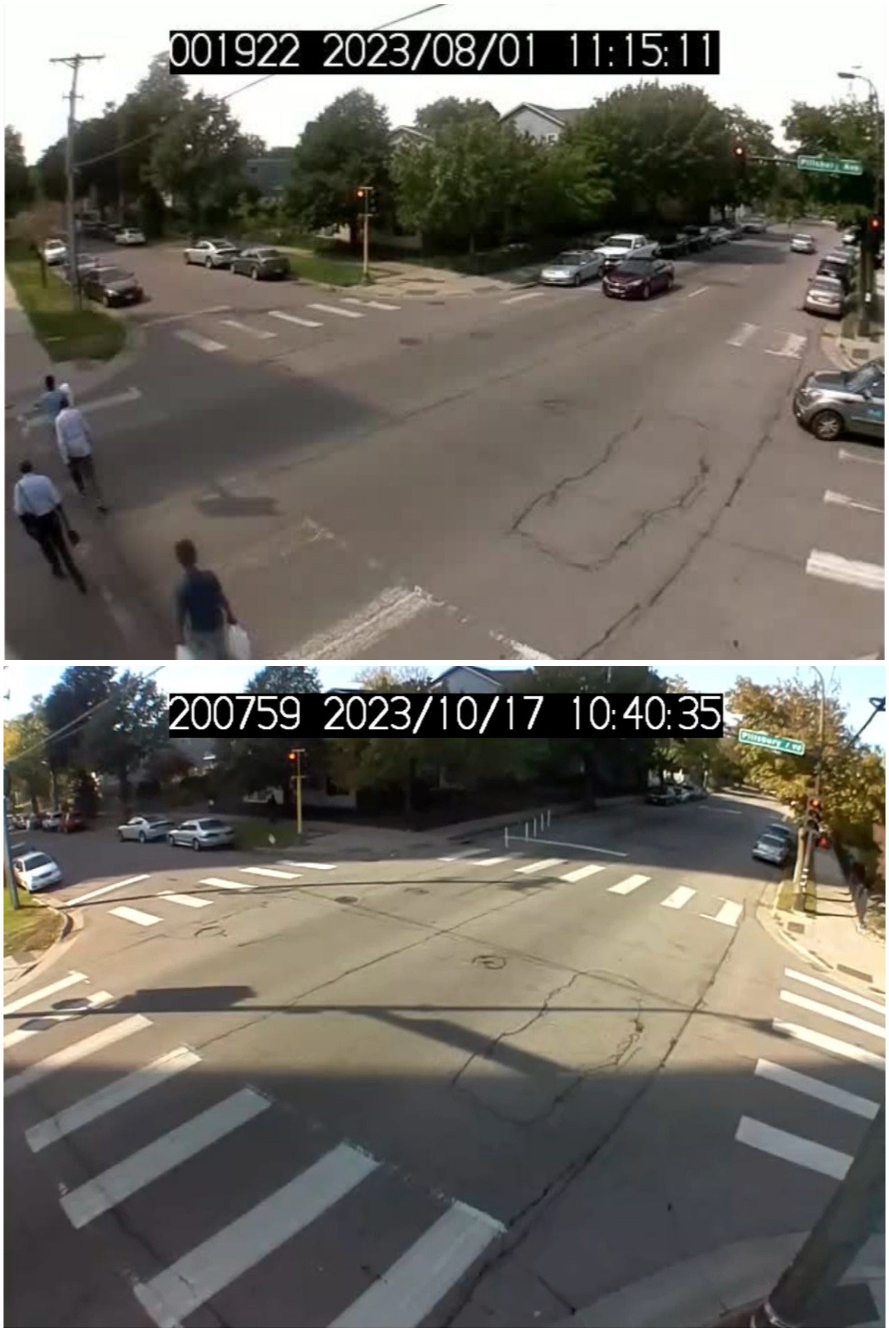
Appendix A

Signalized Site Images



Images of **31st & Pillsbury**, pre-installation (top image) and post-installation (bottom image).

Images of **Bloomington & 24th**, pre-installation (top image) and post-installation (bottom image).

Images of **Nicollet & 26th**, pre-installation (top image) and post-installation (bottom image).

Images of **12th & Hennepin**, pre-installation (top image) and post-installation (bottom image). The added curb extension is difficult to see underneath the shadow cast by the building.

Images of **Cedar & 38th**, pre-installation (top image) and post-installation (bottom image).

Images of **Maple & Hennepin**, pre-installation (top image) and post-installation (bottom image).

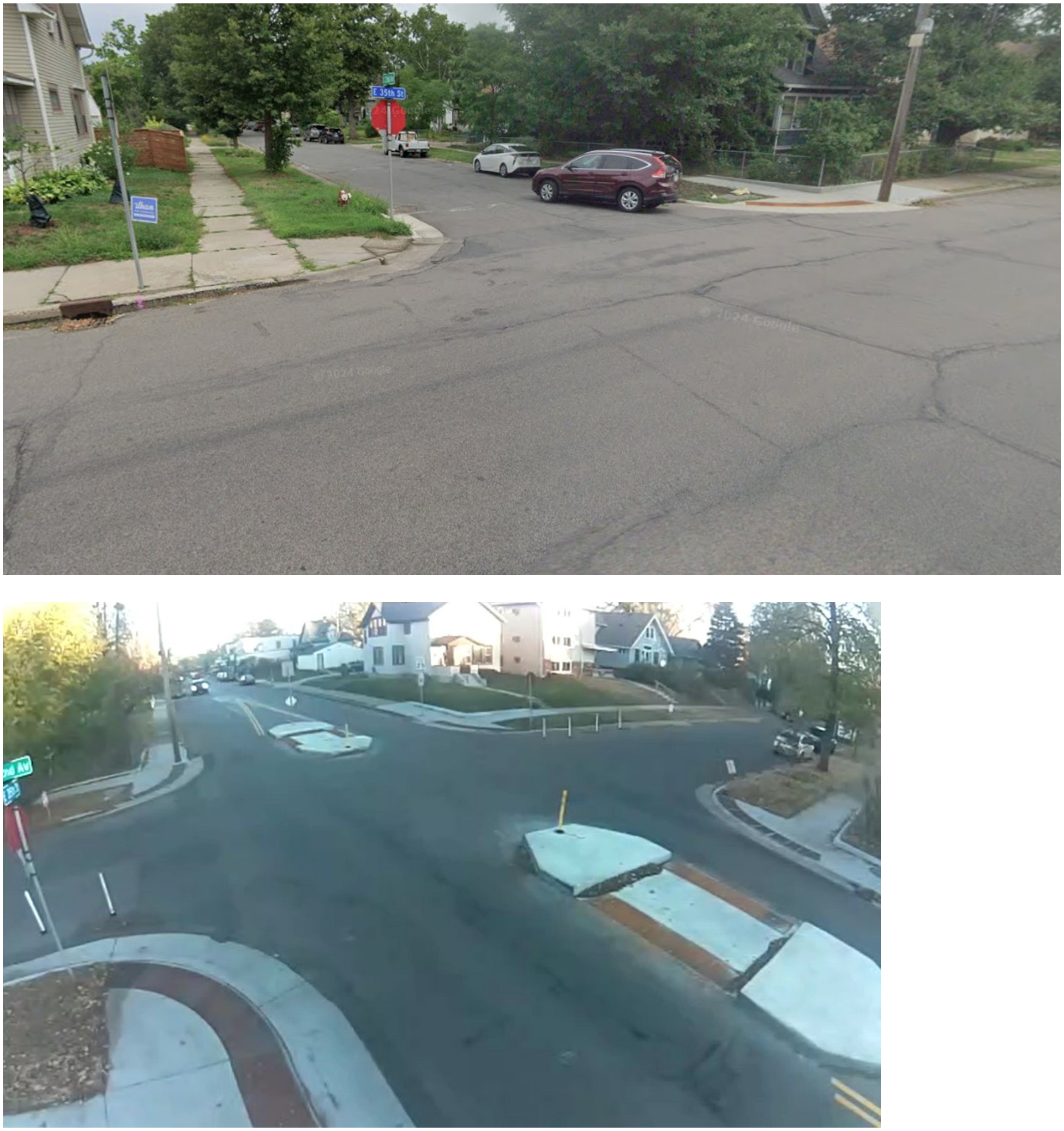
Appendix B

Unsignalized Site Images

Images of **33rd & Lyndale**, pre-installation (top image) and post-installation (bottom image).

Images of **34th & Lyndale**, pre-installation (top image) and post-installation (bottom image).

Images of **36th & Pillsbury**, pre-installation (top image) and post-installation (bottom image). Images are from different orientations.



Images of **35th & 22nd**, pre-installation (top image) and post-installation (bottom image). The pre-installation image (top) was taken from Google Maps © on August 2022.

Images of **Avon & Thomas,** pre-installation (top image) and post-installation (bottom image).

Images of **Longfellow & 38th**, pre-installation (top image) and post-installation (bottom image).

Images of **Milton & Thomas**, pre-installation (top image) and post-installation (bottom image)