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Assessment of a Displaced Pedestrian Crossing for Multilane Arterials

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16. Abstract

This research explores the benefits of a pedestrian crosswalk that is physically displaced from the intersection, using simulation software to estimate the benefits in terms of delay and pedestrian travel time. In many cases, the displaced pedestrian crossing may provide benefits such as reduced vehicle delay, reduced crossing distance, increased opportunity for signal progression, and reduced conflicts with turning vehicles. The concurrent pedestrian service that is traditionally used presents potential conflicts between pedestrians and three vehicular movements: right turns, permissive left turns, and right turns on red. The findings of this research suggest that a displaced pedestrian crossing should be considered as an option by designers when serving pedestrians crossing multi-lane arterials. In addition to reduced delay, pedestrian safety may be improved due to the shorter crossing distance, the elimination of conflicts with turning vehicles, and the potential for high driver compliance rates associated with signals, such as pedestrian hybrid beacons.

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EXECUTIVE SUMMARY

Introduction

This research investigates the operational benefits of a displaced pedestrian crosswalk to traverse multilane arterials. Pedestrian crosswalks at large intersections may be challenging due to the need for pedestrian safety and efficient operation, including vehicle and pedestrian delay and corridor signal progression. Long crossing distances, high traffic volumes, the potential for turning traffic from multiple directions (right turns on green, right turns on red, and permissive left turns) and the increased speed of turning traffic due to a larger turning radius may all reduce pedestrian safety. Pedestrian safety concerns may be exacerbated if pedestrian volumes are low, and motorists are not expecting pedestrian traffic.

At large intersections where pedestrians must cross a multilane roadway, concurrent pedestrian service, in which the pedestrian movement is served simultaneously with the adjacent through movement, may significantly extend the cross street green time, increasing intersection delay for both vehicles and pedestrians and negatively affecting vehicle progression on the arterial.

The objective of this research project is to assess the feasibility of an innovative strategy for the provision of pedestrian service across multilane arterials. This project studies the potential for a "displaced" pedestrian crossing that is physically displaced and relocated upstream and/or downstream of the intersection. A displaced crossing may provide advantages to pedestrians, including a reduced crossing distance and an increased sense of safety due to the reduced impact of turning traffic. A displaced crossing may also provide advantages to motorists, including a shorter pedestrian interval, a shorter cycle length, reduced delay, and fewer potential conflicts with pedestrians. Research has also suggested that driver compliance is very high for a pedestrian hybrid beacon (PHB), which is one signal alternative for a displaced pedestrian crossing.

Findings

The proposed displaced pedestrian crosswalk was investigated using four intersection locations in Indiana. At each intersection, vehicular and pedestrian volumes were entered into the Highway Capacity Software (HCS 7) to obtain appropriate signal phasing and timing plans for the "as-is" scenario with concurrent pedestrian service. Each intersection was then simulated using PTV Vissim 11 to obtain levels of service (LOS) based on the delay to vehicles and travel time for pedestrians for three configurations: (1) the as-is configuration with concurrent pedestrian service, (2) a displaced configuration with a coordinated PHB, and (3) a displaced configuration with two-stage midblock coordinated PHB. The vehicle delay and the pedestrian travel time vary based on intersection characteristics such as pedestrian volume, turning volume, and effective green time distribution to phases.

Implementation

Generally, a displaced pedestrian crossing is expected to provide benefits, including reduced vehicle delay and the elimination of pedestrian conflicts with turning vehicles. This research provides compelling evidence that designers should consider a displaced pedestrian crossing when designing new intersections or modifying existing corridors. Additional research is recommended to confirm the operational benefits in an actual field study and to document the rate of driver compliance with the requirement to yield to pedestrians. As with any change in traffic control, new installations may require an educational campaign to ensure compliance and safety.

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1. INTRODUCTION

1.1 Background

Safety and efficiency are important for all transportation users, including pedestrians and bicyclists. In Indiana in 2016, pedestrians and bicyclists represented less than 1% of all individuals involved in traffic collisions, but they represented 12% of all traffic fatalities (Sapp et al., 2017). This is reasonably consistent with national trends. The National Highway Transportation Safety Administration (NHTSA) reported that pedestrians accounted for 15% of all traffic fatalities in 2015 (5,376 pedestrians and 812 bicyclists) (Coleman & Mizenko, 2018), as well as more than a hundred thousand injuries (70,000 pedestrians and 45,000 bicyclists) (NCSA, 2017a,b). Moreover, the number of pedestrians involved in collisions in Indiana increased at a rate of 6% annually between 2012 and 2016, from 1,754 to 1,913 (Sapp et al., 2017). Indiana is ranked 12th in the number of pedestrian fatalities (Hughes, 2018), which is higher than its state population ranking of 17th (World Population Review, 2018).

Indiana Department of Transportation (INDOT) is committed to serving all transportation modes safely and efficiently. INDOT uses high-visibility crosswalks, countdown crosswalks, audio crosswalks and refuge areas, and conducts pedestrian and cyclist enforcement and education in accordance with its Highway Safety Plan (Retting, 2018).

1.2 Pedestrian Service at Intersections

Pedestrian service at signalized intersections is often provided via concurrent service, i.e., at the same time as adjacent vehicles' through movements. This may be efficient for some intersections in terms of vehicle delay but requires pedestrians to cross in close proximity to moving traffic, and results in potential conflicts with turning traffic. Between the years 1998 and 2007, more than one in five pedestrian fatalities occurred as a result of a collision with a vehicle at an intersection (FHWA, 2009b). Trends in pedestrian fatalities are shown in Figure 1.1.

Pedestrian safety may be compromised at intersections for a variety of reasons, including a lack of traffic control at high-volume intersections. Conflicts with turning vehicles also pose a risk. Data suggests that pedestrians are more often involved in conflicts with turning vehicles than with through movements per the Insurance Institute for Highway Safety (Retting et al., 2003). The length of crossing is another factor affecting the safety of pedestrians at intersections; the crosswalk length increases at intersections due to added roadway width required for turning lanes. Data suggests that pedestrian fatalities at 6-lane intersections are 65% greater than at 4-lane intersections (Petritsch et al., 2007).

1.3 Problem Statement and Research Objective

Crosswalks at large intersections may be especially challenging, both for pedestrian safety and for efficient operation (e.g., minimizing vehicle and pedestrian delay and maintaining corridor signal progression). Long crossing distances, large traffic volumes, the potential for turning traffic from multiple directions (right turns on green, right turns on red and permissive left turns) and the increased speed of turning traffic due to a larger turning radius may all reduce pedestrian safety. Pedestrian safety concerns may be exacerbated if pedestrian volumes are low, and motorists are not expecting pedestrian traffic (Hubbard et al., 2009).

At large intersections where pedestrians must cross a multilane arterial, concurrent pedestrian service, in which pedestrian movement is served simultaneously with the adjacent through movement, may significantly extend the cross street green time, increasing intersection delay for both vehicles and pedestrians and negatively affecting vehicle progression on the arterial. Concurrent pedestrian service is illustrated

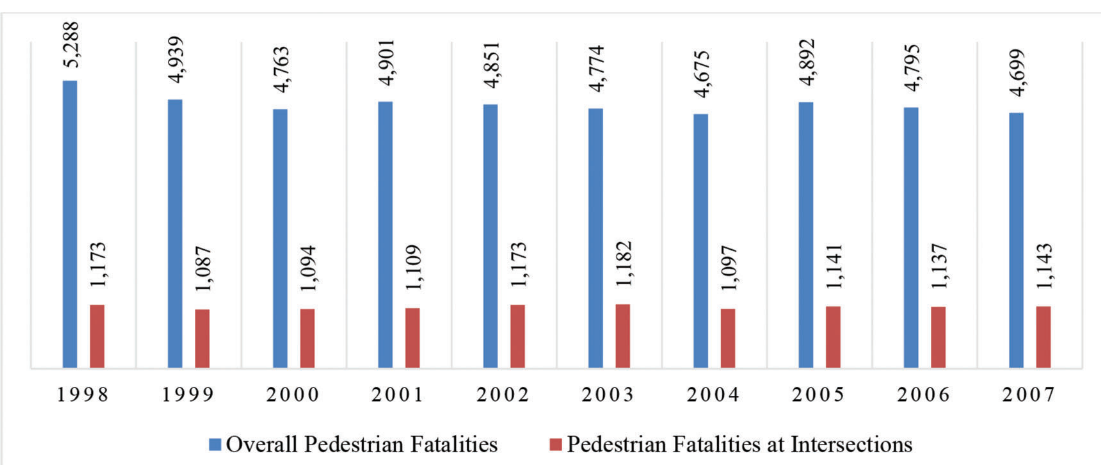


Figure 1.1 Pedestrian fatalities.

in Figure 1.2 using the phase numbering convention defined by the National Electrical Manufacturers Association (NEMA). Pedestrian phases are designated by even numbers with a P prefix (P2, P4, P6, and P8), and with concurrent pedestrian service, P4 and P8 are provided at the same time that vehicle phases 4 and 8 are provided.

This research project will assess the feasibility of innovative strategies for the provision of pedestrian service across multilane arterials, including the potential for an "displaced" pedestrian crossing. A displaced crossing is defined as a crosswalk that is relocated upstream and/or downstream of the intersection, as shown in Figure 1.3. A displaced crossing placed upstream of the turning lanes, as shown in Figure 1.3b, may provide advantages to pedestrians, including a reduced crossing distance and an increased sense of safety due to the reduced impact of turning traffic.

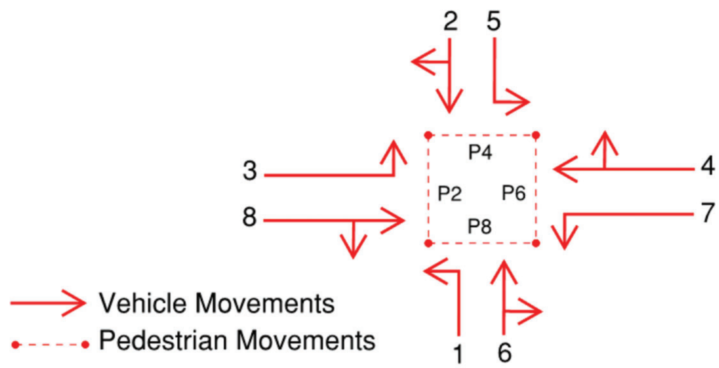
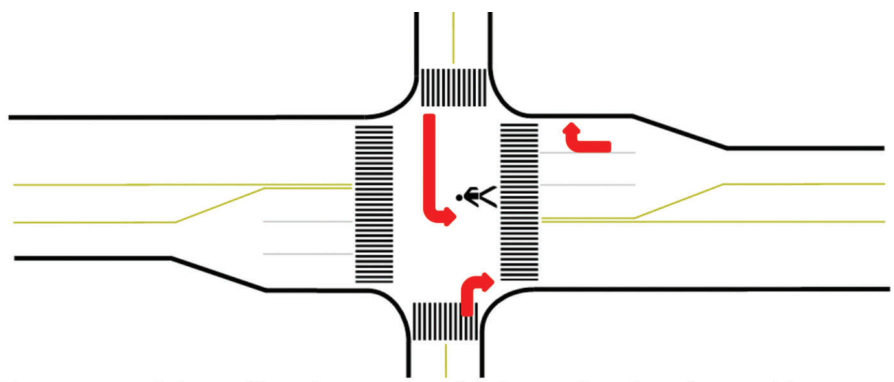
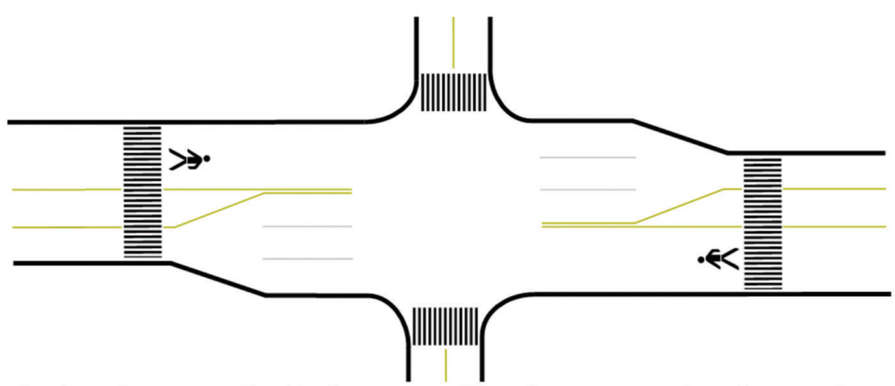


Figure 1.2 NEMA movement groups.



(a) Three potential conflicts between vehicles and pedestrians with concurrent services



(b) Displaced crosswalk eliminates conflicts between pedestrians and turning vehicles

Figure 1.3 Pedestrian-vehicle conflicts.

A displaced crossing may also provide advantages to motorists, including a shorter pedestrian interval, a shorter cycle length, reduced delay, and fewer potential conflicts with pedestrians. The following four intersection locations will be used as case studies to investigate the service provided by a displaced pedestrian crosswalk.

1. Ronald Reagan Pkwy and US 40 in Plainfield, IN (39°43′37.77″N, 86°20′13.24″W).
2. US 52 and Cumberland Ave in West Lafayette, IN (40°27′37.41″N, 86°55′59.27″W).
3. US 31 and Home Ave in Columbus, IN (39°13′49.28"N, 85°54′40.01″W).
4. Ronald Reagan Pkwy and Rockville Rd in Avon, IN (39°45′49.37″N, 86°20′12.41″W).

1.4 Report Organization

The first chapter introduces the background of the research, safety concerns for pedestrian crossings at intersections, the problem statement and research objectives. The second chapter summarizes the results of the literature review conducted for this research. The third chapter provides the research methodology. The fourth chapter presents the simulation results of the displaced crossing treatment. Finally, the fifth chapter contains the conclusions and recommendations of the study.

2. LITERATURE REVIEW

2.1 Traffic Signal Control Strategies

Traditionally, intersections and traffic signal control systems have been designed to provide efficient service for vehicle throughput, and as a result, service for pedestrians and transit have not been a priority and in fact have often been overlooked (He et al., 2014). Concurrent pedestrian service is usually the de facto standard, even though it may result in numerous pedestrian vehicle conflicts.

Concurrent service provides the pedestrian crossing interval while the adjacent traffic has a green ball, which puts pedestrians in conflict with right turning vehicles, with permitted left turning vehicles, and with right-turns on red. To reduce conflicts, traffic signal control strategies such as leading pedestrian intervals (LPI), lagging pedestrian intervals, and exclusive pedestrian phasing are sometimes used.

In an LPI, the pedestrian walk interval begins a few seconds prior to the green for the adjacent through and turning vehicles, which allows the pedestrians to enter the crosswalk with fewer conflicts and makes the pedestrians more visible to the turning motorists. However, when pedestrian volumes are high, some research suggests that pedestrian conflicts with turning vehicles are inevitable (Lalani, 2001). With a lagging pedestrian interval, the pedestrian walk interval begins a few seconds after the green for the adjacent through and turning vehicles. This allows the queue of turning vehicles to clear before the pedestrian phase starts, but when turning volumes are high, some research suggests pedestrian conflicts with turning vehicles are still inevitable (Lalani, 2001). In an exclusive pedestrian phase, an additional phase is solely dedicated to pedestrians in which all vehicle movements are stopped; this eliminates pedestrian-vehicle conflicts but increases the cycle time and delay.

2.2 Signalized Intersection Level of Service (LOS)

Level of Service (LOS) is used to describe the service provided to users, which includes both vehicles and pedestrians. For vehicles at signalized intersections, LOS is assessed based on the delay experienced by drivers. For pedestrians crossing at signalized intersections, LOS is assessed based on the average delay per pedestrian or the average space per pedestrian. The *Highway Capacity Manual* defines delay as "the additional travel time experienced by a driver, passenger, bicyclist, or pedestrian beyond that is required to travel at the desired speed" (TRB, 2010).

2.2.1 Vehicle LOS

At signalized intersections, control delay is used to measure LOS, as shown in Equation 2.1, where control delay accounts for the delay experienced due to the traffic signal and to traffic conflicts. Control delay consists of three types of delay: (1) uniform delay, (2) incremental delay, and (3) initial queue delay (TRB, 2010).

$$\text{Control Delay} = d_1 * (PF) + d_2 + d_3 \qquad \text{(Eq. 2.1)}$$

$$d_1 = \text{uniform delay}\left(\frac{\text{sec}}{\text{veh}}\right) = \frac{\left(C * \left[1-\left(\frac{g}{C}\right)\right]^2\right)}{2 * \left[1-\left(\frac{g}{C}\right) * \min(1,X)\right]} \qquad \text{(Eq. 2.2)}$$

$$d_2 = \text{incremental delay}\left(\frac{\text{sec}}{\text{veh}}\right) = 900 * T * \left\{(X-1) + \sqrt{(X-1)^2 + \frac{8*k*I*X}{cap*T}}\right\} \qquad \text{(Eq. 2.3)}$$

$$d_3 = \text{initial queue delay}\left(\frac{\text{sec}}{\text{veh}}\right) \qquad \text{(Eq. 2.4)}$$

where:

PF = Progression adjustment factor
C = Cycle length (typically 30 seconds times the number of phases)
g = Effective green time for the lane group (sec)
k = Actuated control factor
I = Upstream filtering factor
v = Volume per hour (veh/hr)
cap = Capacity (sat * g/C) for the through lane group (veh/hr)
T = Duration of analysis period (hr)

Uniform delay, shown in Equation 2.2, is affected by lane group volume, lane group capacity, cycle length, and effective green time. Incremental delay, shown in Equation 2.3, accounts for the effect of random and cycle-by-cycle fluctuations in demand that sometimes exceed capacity and the sustained oversaturation, when aggregate demand exceeds aggregate capacity. Finally, initial queue delay, shown in Equation 2.4, accounts for the residual demand delay that may have existed prior to the analysis period. Delay thresholds for the various LOS are given in Table 2.1, where LOS F is the worst.

2.2.2 Pedestrian LOS

Pedestrian LOS is assessed based on the average pedestrian delay (wait time) due to the signal. Pedestrian delay is calculated using cycle length and the effective green time for pedestrians. When field data is not available, it is recommended to use an effective green time based on the walk interval, 4 seconds, plus the clearance interval (calculated as the crosswalk length divided by the pedestrian speed). Equation 2.5 below calculates the average pedestrian delay (TRB, 2010).

$$\text{Average Pedestrian Delay} = d_p = \frac{0.5 * (C-g)^2}{C} \quad \text{(Eq. 2.5)}$$

$$\textit{Example Delay Calculation} =$$

$$d_p = \frac{0.5 * (120-36)^2}{120} = 29.4 \textit{ seconds}$$

where:

C = Cycle length (secs)

g = Effective green time for pedestrians (secs) = Walk + Flashing Don't Walk

TABLE 2.1
LOS Thresholds at Signalized Intersections (TRB, 2010)

	Operating at or Below Capacity
Control Delay per Vehicle (S/Veh)	**LOS at V/C Ratio ≤ 1**
≤10	A
>10–20	B
>20–35	C
>35–55	D
>55–80	E
>80	F

TABLE 2.2
Pedestrian LOS Thresholds at Signalized Intersections (TRB, 2010)

LOS	Pedestrian Delay (sec/ped)
A	<10
B	≥10–20
C	>20–30
D	>30–40
E	>40–50
F	>60

The pedestrian LOS thresholds are summarized in Table 2.2.

In typical signal operation, where the pedestrian phase is served concurrently with the adjacent thru movement, higher right and left turn volumes may cause vehicle-pedestrian conflicts as well as increased delay to both vehicles and pedestrians (Hubbard, et al., 2008).

Another measure of pedestrian service is obtained thru the average available space given per pedestrian (ft^2/pedestrian). The *Highway Capacity Manual* survey asks pedestrians to rate the quality of service associated with a specific trip along an urban street. The score "1" used for the "best" quality and "5" for the "worst" quality. Table 2.3 lists the range of scores associated with each LOS for pedestrians. This LOS measure may be appropriate in urban areas where there are very high pedestrian volumes but is less likely to be relevant for typical pedestrian volumes in other areas.

Neither of the methods presented in the HCM, pedestrian delay or pedestrian space, considers pedestrian safety or the discomfort pedestrians may face when they are in close proximity to vehicles turning into the crosswalk during the pedestrian phase during concurrent pedestrian service. Some researchers have addressed this by measuring and reporting vehicle-pedestrian conflicts and by measuring driver compliance based on drivers yielding to pedestrians.

2.3 Pedestrian Crossing Treatments at Midblock

Midblock crossings are locations between intersections where crosswalks are provided. Midblock crosswalks can be either signalized or unsignalized. Unsignalized crosswalks with "State Law Yield to Pedestrian within Crosswalk" signs are called semi-controlled crosswalks (Fricker & Zhang, 2019). Due to the lack of signals, pedestrians are often hesitant about whether to proceed in the presence of drivers. Such confusion is obvious when watching pedestrians and motorists interact at unsignalized crosswalks, and this confusion can lead to unsafe situations. At signalized midblock crossings, several signal strategies have been used. Each was found to have a different impact on pedestrians' perceived safety and driver compliance. A summary of midblock crosswalk signal strategies is presented below.

2.3.1 Overhead Flashing Beacons and Rectangular Rapid Flashing Beacons

The Overhead Flashing Beacon (OFB) is a diamond pedestrian warning sign mounted overhead in conjunction with two round flashing lights as shown in Figure 2.1a. The beacon yellow lights flash to indicate the presence of a pedestrian to motorists. This enhancement also has a round, yellow flashing light that announces its activation and deactivation to pedestrians on either side of the road. The Rectangular Rapid Flashing Beacon (RRFB) is a rectangular device, used in conjunction with a pedestrian sign. It is used at unsignalized intersections and at midblock crossings. Average driver compliance rates were found to be 77% for the OFB and 57% for the RRFB (Fayyaz et al., 2019). Figure 2.1 shows pictures of both OFB and RRFB (Murphy & Hummer, 2007); OFB and RRFB are typically actuated by a pedestrian pushbutton.

2.3.2 Pedestrian Hybrid Beacon

A pedestrian hybrid beacon (PHB) is also known as a High-intensity Activated crosswalk (HAWK). The PHB is pedestrian-activated and was developed by the City of Tucson, Arizona. PHB are recommended for multilane, high-volume, high speed locations, that are away from intersections (FHWA, n.d.b). PHB have the highest driver compliance rate among midblock crossing treatments, with approximately 90% compliance (Fayyaz et al., 2019; Redmon, 2014). The high compliance rate, resulting in safer crossing for pedestrian, can be related to how pedestrians often are willing to increase the length of their trip to take a route that is facilitated with a PHB (Fitzpatrick et al., 2006). The operational sequence of a PHB is shown in Figure 2.2.

TABLE 2.3
Pedestrian LOS Based on Spacing

	LOS by Average Pedestrian Space (ft²/pedestrian)					
Pedestrian LOS Score	**>60**	**>40–60**	**>24–40**	**>15–24**	**>8–15**	**≤8**
≤2	A	B	C	D	E	F
>2–2.75	B	B	C	D	E	F
>2.75–3.5	C	C	C	D	E	F
>3.5–4.25	D	D	D	D	E	F
>4.25–5.0	E	E	E	E	E	F
>5.0	F	F	F	F	F	F

(a) Overhead Flashing Beacon (OFB) (b) Rectangular Rapid Flashing Beacon (RRFB)

Figure 2.1 OFB and RRFB enhance the conspicuity of pedestrian crosswalks (City of Laguna Beach, n.d.).

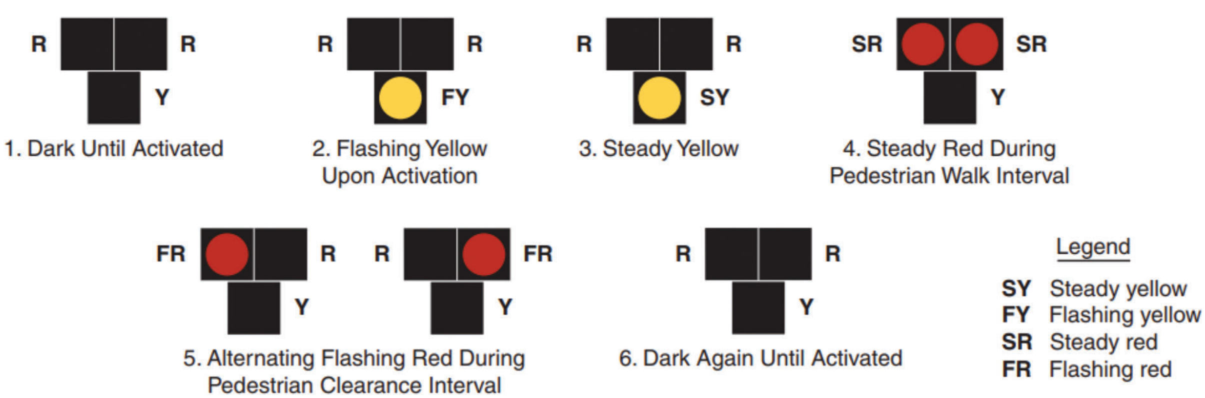


Figure 2.2 PHB operational sequence (FHWA, 2009a).

2.3.3 Median Refuge Island

Used at both signalized and unsignalized crossings, a median refuge island is a raised longitudinal space separating opposing traffic lanes. This island serves as a refuge for a pedestrian crossing the roadway and also is used to shorten the crosswalk length. Medians may improve safety and efficiency for both pedestrians and motorists. On multilane minor and major arterials, refuge islands may reduce pedestrian exposure to high-speed vehicles and simplify the crossing, allowing pedestrians to cross to the median when there is a gap in vehicle traffic in one direction, and then safely wait on the median until there is a gap in vehicular traffic in the other direction. The refuge island may be especially helpful for older pedestrians, for pedestrians who walk slowly, or for pedestrians crossing at night. Medians may also allow for a shortened walk interval if a two-stage crossing is used. Two-stage crossings may allow for enhanced signal progression along the corridor (Tian et al., 2001), however, pedestrians may not feel comfortable waiting on the median while vehicles travel at high speeds in nearby travel lanes.

2.4 Pedestrian Willingness-to-Walk

From the pedestrian point of view, the willingness to walk takes into account the distance of the trip, the perceived safety of the route, and the comfort and convenience of walking versus an alternative mode (AASHTO, 2004). Distance is often the primary factor in the initial decision, with most pedestrian trips (73%) less than 0.5 miles in length (US DOT, 1995). Previous research suggests pedestrians are unwilling to increase their trip length by more than 10% to access a crossing facility (Fitzpatrick et al., 2006).

Although most crosswalks are located at intersections, intersections are not always the best location. The location of a crosswalk should consider both the location where pedestrians are expected to cross and where pedestrians will be most visible to motorists (FHWA, n.d.a).

The type of crossing treatment and corresponding pedestrian volumes are directly related to safety. Different treatments also yield different driver compliance rates. Greater driver compliance (e.g., yielding to pedestrians) may increase the number of pedestrians because pedestrians are more willing to cross if they expect that drivers will yield. The number of pedestrians that wish to cross and will cross if adequate service is provided is considered the latent demand; latent demand reflects the number of pedestrians that are not willing to cross at a crosswalk where they do not feel safe (Jacobsen, 2015).

Although safer treatments often lead to higher volumes of pedestrians, existing treatments might have been chosen for budgetary reasons. In one on-street survey, pedestrian opinions of crossing treatments were collected. Respondents were asked, "if this crossing was not here, would you walk to the next intersection?" and were also asked to rank the safety of different crossing treatments. Responses suggest that the willingness-to-walk to the next available crosswalk is influenced by the type of crossing treatment, the number of lanes to be crossed, and the distance to the next intersection. Pedestrians were willing to walk an additional distance to access a crossing facility if it allowed them to cross fewer lanes and provided a safer option. Pedestrians were least interested in walking an additional distance when they would be required to cross a road with six or more lanes; PHB and two-stage midblock signal were ranked as the safest treatment by pedestrians (Fitzpatrick et al., 2006).

3. RESEARCH METHODOLOGY

The research methodology was designed to compare existing concurrent pedestrian service at multilane arterials with a proposed displaced pedestrian crossing. The proposed displaced pedestrian crossing may increase pedestrian safety by reducing conflicts with turning vehicles and may provide additional options to enhance signal coordination for vehicles traveling in the corridor. The geometric and phasing considerations, simulation, and implications for pedestrian service are described below.

3.1 Geometric Configurations and Phasing

For the intersections selected for our study, vehicular and pedestrian volumes were entered into the Highway Capacity Software (HCS 7) with concurrent pedestrian service at existing crosswalks to obtain appropriate phasing and timing plans for the "as-is" scenario (see Appendix A). Operation at each intersection was then simulated using PTV Vissim 11 to obtain levels of service (LOS) based on delay to pedestrians and vehicles for three configurations.

1. As-is configuration.
2. Displaced configuration with coordinated PHB.
3. Displaced configuration with two-stage midblock coordinated PHB.

Each configuration is evaluated using peak-hour LOS for the vehicle movement group and the overall intersection average delay per vehicle. The movement groups are shown in Figure 3.1, and the numbering is consistent with the National Electrical Manufacturing Association (NEMA) phase numbers.

As-is (baseline). The as-is scenario is the baseline and reflects the existing intersection geometrics, timing, and phasing, including concurrent phasing for the pedestrian crosswalks.

Displaced configuration with coordinated PHB. In this configuration, the displaced PHB is coordinated with the adjacent intersection; the pedestrian phase is served concurrently with the adjacent through movement in phase D. Phasing of this layout can be seen in Figure 3.2.

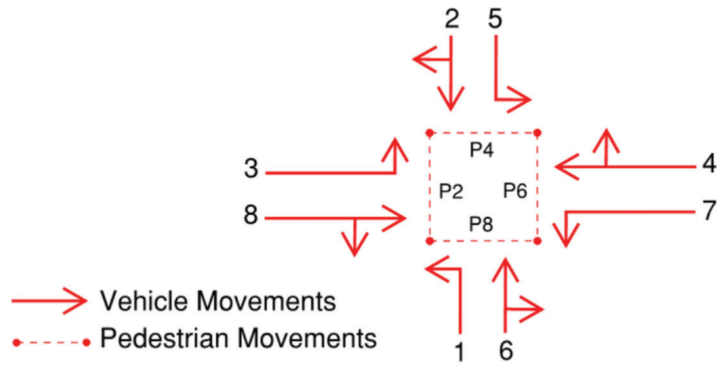


Figure 3.1 NEMA movement groups.

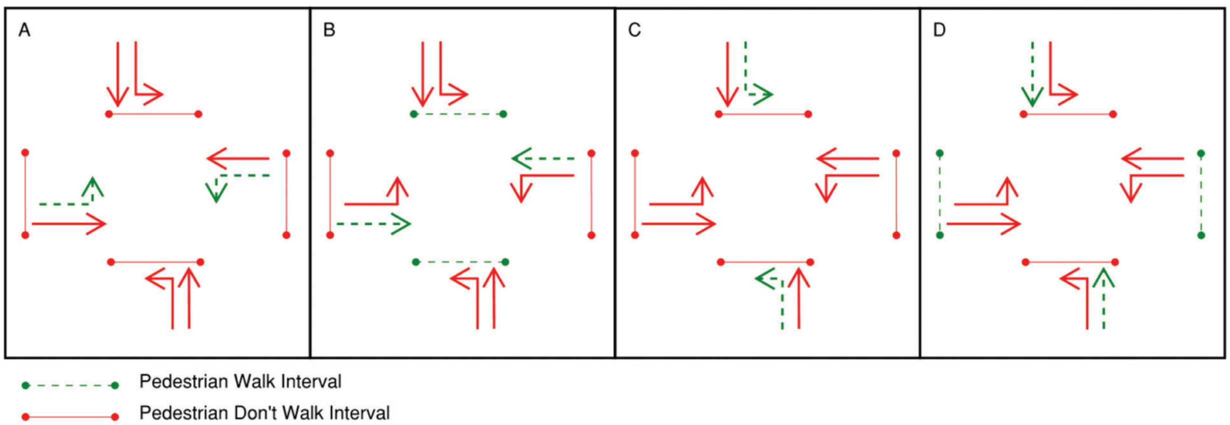


Figure 3.2 Displaced crossing phasing.

Displaced configuration with two-stage midblock coordinated PHB. In this configuration, the Displaced Two-Stage Midblock (two-stage pedestrian movement) PHB is coordinated with the adjacent intersection. The pedestrian phase is served concurrently with phases A, C, and D. Phasing of this layout can be seen in Figure 3.3.

Pedestrian interval signal timing was calculated for each layout using the following equations.

$$\text{Pedestrian Clearance Time} = \frac{\text{Length of Crosswalk}}{\text{Pedestrian Walking Speed}} \quad \text{(Eq. 3.1)}$$

$$\text{Pedestrian Interval} = \text{Walk Interval} + \text{Pedestrian Clearance Time} \quad \text{(Eq. 3.2)}$$

The walk interval is assumed to be 4 seconds in accordance with the guidance of the MUTCD (FHWA, 2009a). Pedestrian walking speed is assumed to be 3 ft/s; this is slightly faster than the current guidance of 3.5 ft/s (FHWA, 2009a), which may understate the benefits of a displaced crossing since a slower walk speed requires a longer extension to the minimum green to accommodate the concurrent pedestrian phase.

3.2 Simulation Parameters

The simulation executed using PTV Vissim 11 has the parameters shown in Table 3.1.

3.3 Techniques to Leverage Simulation Capabilities for Pedestrian Crossing Alternatives

In the Vissim simulation environment, some lessons were learned as we examined several geometric configurations. Below are the main findings.

- Pedestrian decision-making perception is considered similar to that of a driver's decision-making perception. Pedestrians often take into account the time left in a pedestrian clearance time interval when making the decision to begin crossing the road. When the time left is not enough to fully cross the road, a pedestrian will wait till the next pedestrian interval. However, in the simulation there is no distinction between the walk interval and the pedestrian clearance interval, and pedestrians will enter the crosswalk anytime during the walk or pedestrian clearance interval. This led to pedestrians in the middle of the crosswalk at the end of the pedestrian phase when it is the vehicle's turn to proceed.
- The simulation results depend on the area modeled. When drafting the roadway geometrics (lane width, lane length, etc.), intersection approaches should be long enough to accommodate all vehicles that could queue within the

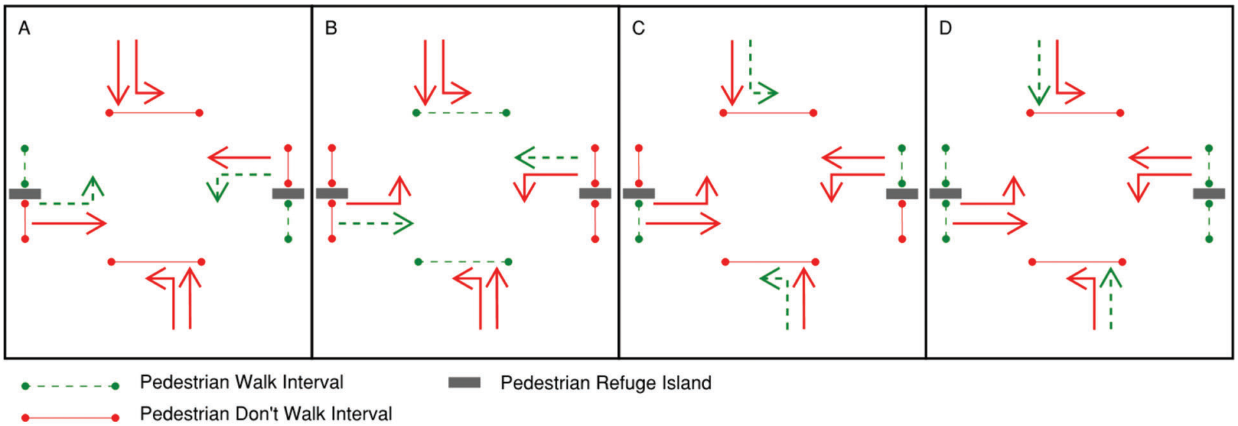


Figure 3.3 Two-stage midblock phasing.

TABLE 3.1
Simulation Parameters

Parameter	Description	
Time Interval	60-Minute Intervals	Data input at that interval scale (pedestrian and vehicle volumes).
Vehicle Volume Distribution per Time Interval	Stochastically Distributed	
Vehicle Speed	Posted Speed Limit +/- 5 mph	
Vehicle Speed Distribution	Stochastically Distributed	
Pedestrian Volume Distribution per Time Interval	Stochastically Distributed	
Pedestrian Speed	2–4 ft/s	MUTCD recommended range.
Pedestrian Speed Distribution	Stochastically Distributed	
Front Gap	4 Seconds	Time that a yielding vehicle waits before entering the conflict area, after the pedestrian with the right of way has left it.
Rear Gap	4 Seconds	Minimum gap time in seconds between the rear end of a vehicle in the minor traffic stream and the front end of a vehicle/pedestrian in the main traffic stream. This is the time that must be provided, after a yielding vehicle has left the conflict area and before a vehicle/pedestrian with the right of way enters it.
Additional Stopping Distance	5 ft	Only relevant for vehicles that are required to yield: Distance that moves the (imaginary) stop line upstream of the conflict area. As a result, vehicles required to yield stop further away from the conflict and thus also have to travel a longer distance to pass the conflict area.

evaluation interval. If the approaches are too short and do not allow space for all vehicles in a queue, the simulation LOS results will not reflect the actual LOS.

- A node (a shape) is drafted so that vehicle LOS is measured within the boundary of that shape. This step should be executed cautiously to avoid bias in results when comparing alternative configurations. The node drafted should be large enough to contain all queueing vehicles. (Some configurations may have lengthier queues, and hence, require larger nodes to contain all vehicles in the queue.)

3.4 Pedestrian Projections

Many intersections do not have accurate pedestrian counts for existing conditions or forecasts for future years. To overcome analysis limitations associated with this lack of data, a range of pedestrian volumes was considered for each intersection in this study. The pedestrian volume impacts the number of times the pedestrian phase is called, which has a significant impact on the vehicle and intersection LOS. To ensure that the analysis can accommodate future pedestrian volumes, the simulation for each layout used three scenarios: (1) the existing pedestrian counts, (2) doubled counts, and (3) quadrupled counts, as shown in Figure 3.4. When there were no existing pedestrian counts for an intersection, 100 pedestrians per day was assumed. Additional information about specific count data for each intersection is shown in Appendix B.

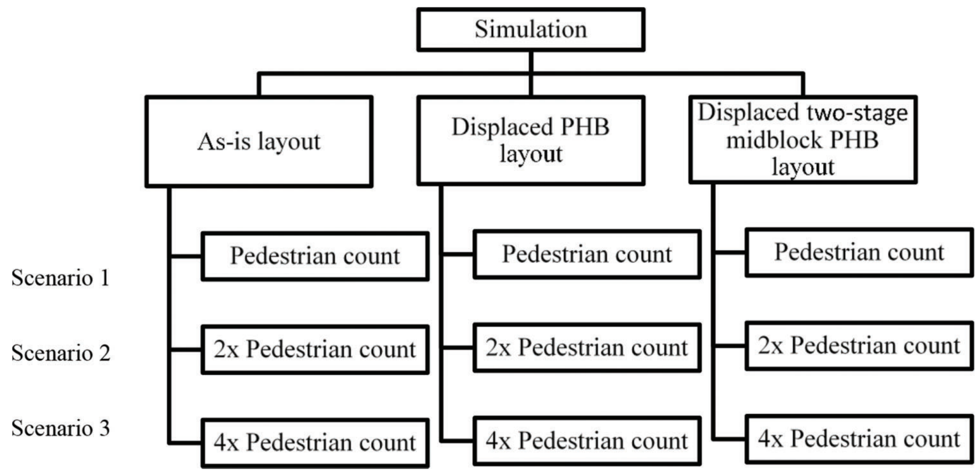


Figure 3.4 Simulation scenarios.

3.5 Pedestrian Travel Time Evaluation

The displaced crosswalk is located far enough from the intersection to avoid crossing turning lanes on the approach to the intersection. This shortens the crosswalk distance, reduces pedestrian exposure to moving traffic, reduces the time required for the pedestrian interval in the signal cycle, and reduces delay for both pedestrians and vehicles. The location of the displaced crossing will vary from one intersection to another, based on the length of the turning lanes (which is related to the turning vehicle volume), intersection geometry, and constraints such as driveway access for adjacent property.

As the crosswalk location is shifted away from the intersection, some pedestrian trips may be lengthened and others shortened, depending on the pedestrian's trip origin, destination, and preferred path. The pedestrian travel times were calculated in an attempt to capture the impact of crosswalk locations on pedestrian service. There is no widely accepted methodology for the determination of pedestrian travel time, and this research presents one way to distribute pedestrian trips and estimate average travel times.

In this research, it is assumed that pedestrian trips do not originate at the corners of intersections, nor do corners serve as attractions/destinations (although this would be the case if a bus stop is located at a corner). Pedestrian trips served by crosswalks are considered to originate at locations some distance away from the intersection and pedestrians proceed on a path toward their destinations in another quadrant of the intersection. A pedestrian trip consists of the following components.

1. Walk from origin to crosswalk, if applicable.
2. Wait at crosswalk, if necessary.
3. Walk in crosswalk to median (if applicable) or to the far side of street.
4. Wait on median, if applicable.
5. Finish crossing in crosswalk if median was used.
6. Walk from crosswalk to destination, if applicable.

In each of the four quadrants of the intersection (A, B, C, D) seen in Figure 3.5, three potential points are used to represent pedestrian origins and destinations. The points along the east-west arterial in Figure 3.5 are located [3] 100 feet from the intersection's corner, [2] at the displaced crosswalk (right before turning lanes), and [1] 100 feet beyond the displaced crosswalk.

The analysis of pedestrian LOS in this research assumes the following.

- The total number of pedestrians is evenly distributed among each of the origin and destination points: each point will produce and attract the same number of pedestrians as the other points.
- The nearest point to the intersection, from which pedestrians originated or are attracted to, is 100 feet from the intersection's corner.
- A displaced crosswalk attraction/origin location accounts for the presence of a transit stop or significant trip generator there.

Pedestrian LOS in this research is evaluated based on both distance and time travelled. The distance travelled may be less critical for some users, such as bicyclists who are using a trail for recreation. The distance travelled may be more critical for other users, such as pedestrians who have a mobility impairment and/or groceries to carry. Distance is measured without regard to the method of traffic control or the vehicle volume from the quadrant origin point to the quadrant destination point. Time is measured using the three different traffic control layouts: (1) as-is (current pedestrian service at the intersection), (2) displaced PHB, and (3) two-stage midblock displaced PHB from the quadrant origin point to the quadrant destination point. The simulation scenarios analyzed in this research are shown in Figure 3.6. An example of the different pedestrian routes for the as-is and displaced configurations can be seen in Appendix C.

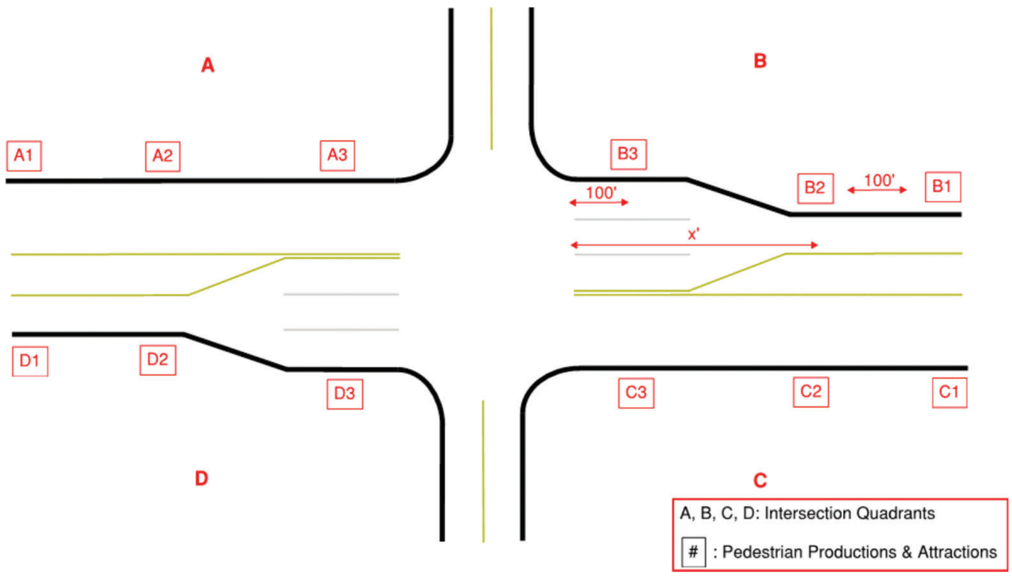


Figure 3.5 Pedestrian origins and destinations.

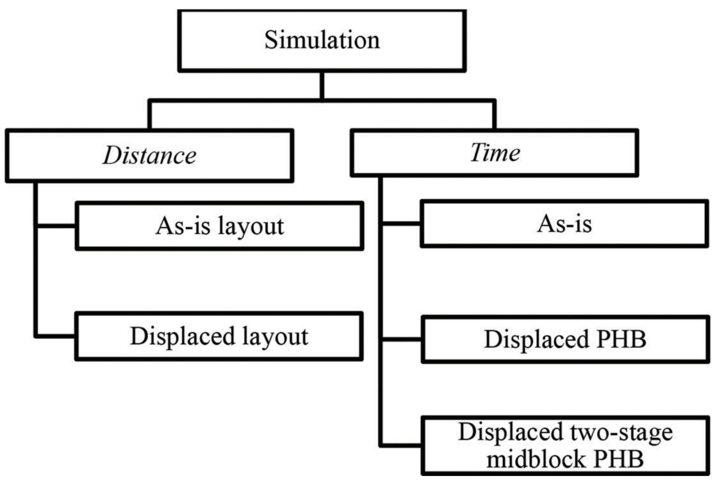


Figure 3.6 Pedestrian service simulation scenarios.

4. SIMULATION RESULTS

4.1 Ronald Reagan Pkwy and US 40 in Plainfield, IN

The intersection of Ronald Reagan and US 40, shown in Figure 4.1, has a speed limit of 45 mph on both approaches and the following lane configuration.

- Five southbound approach lanes (two thru, one right turn, and two left turn lanes).
- Four westbound approach lanes (two thru, one right turn, and one left turn lanes).
- Five northbound approach lanes (two thru, one right turn, and two left turn lanes).
- Five eastbound approach lanes (two thru, one right turn, and two left turn lanes).

The surrounding development consists of residential, commercial, and industrial properties. Pedestrian sidewalks exist on the east side of the southbound and northbound approaches, and on the south side of the eastbound approach. In the simulation of this intersection, pedestrian sidewalks were assumed to be present on both sides of each approach. Peak hour traffic and pedestrian volumes are listed in Table 4.1.

In the as-is configuration, pedestrians cross a distance of 120 ft when crossing north-south, and a distance of 132 ft when crossing east-west, as shown in Figure 4.2. The evaluation of this intersection considered all possible crossing configurations along both north-south and east-west approaches. Figure 4.3 illustrates the configurations and phasing that was chosen for analysis.

4.1.1 Vehicles LOS

A summary of the peak hour LOS per movement group and the average daily delay is presented in Table 4.2.

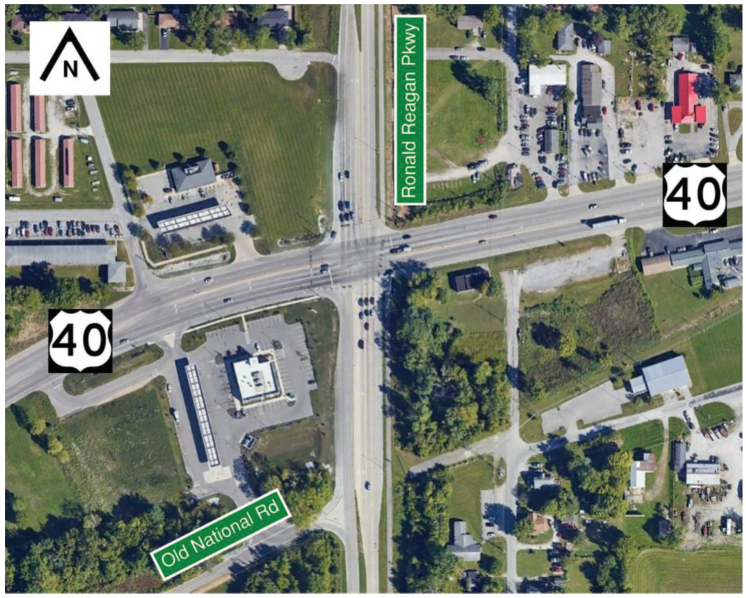


Figure 4.1 Ronald Reagan Pkwy and US 40 (Google, n.d.b).

TABLE 4.1
Peak Hour Volumes (5:00 PM–6:00 PM)

Movement	1	2	3	4	5	6	7	8
Vehicle Volume	167	829	336	1,402	314	911	247	986
Pedestrian Volume	–	10	–	10	–	10	–	10

During the peak hour, the vehicle LOS for movement groups is consistent for all analyzed configurations, with the exception of movement groups 4, 6, and 8. Some of the notable findings are described below.

- The Displaced Two-Stage Midblock North–South configuration is superior because it reduces pedestrian conflicts with right turning vehicles from the westbound approach and as a result the LOS for movement group 4 improves from LOS E to D.
- The Displaced Two-Stage Midblock East-West configuration is superior based on the average delay (s/veh), because it serves pedestrians with vehicle phases that have no conflicts (movement groups 1 and 5, and 3 and 7).
- Both the Displaced Two-Stage Midblock North-South and the Displaced Two-Stage Midblock East-West configurations require the least green time extension for the concurrently served vehicle movements when compared to the as-is configuration. The as-is configuration requires an extension of 11 seconds for the vehicle phase when serving pedestrians crossing north-south with movement groups 2 and 6, increasing the minimum green time to 44 seconds from 33 seconds.

Table 4.3 lists the green time extension required for each movement group to serve a pedestrian phase, when a pedestrian call is placed.

4.1.2 Pedestrian Service

The pedestrian travel time, from any origin to any destination, consists of the time spent walking to the pedestrian crosswalk and the time spent waiting for the pedestrian interval. Therefore, travel time will be a function of the length of the trip (including additional walk time to the displaced crossing) and the traffic control used to facilitate pedestrian crossings. Average travel times from each quadrant to the opposing quadrants are shown in Figures 4.5 and 4.6. A summary of the pedestrian average travel time of each configuration is shown in Table 4.4 below and disaggregated results of pedestrian travel times are provided in Appendix C. The distance to displaced crossings can be seen in Figure 4.4.

4.1.3 Ronald Reagan Pkwy and US 40 Overall Findings

Staging crossing into two stages in the Displaced Two-Stage Midblock East-West configuration eliminates conflicts with concurrently served movement groups (1 and 5, and 3 and 7). As a result, the LOS for movement group 4 improves from LOS E to D.

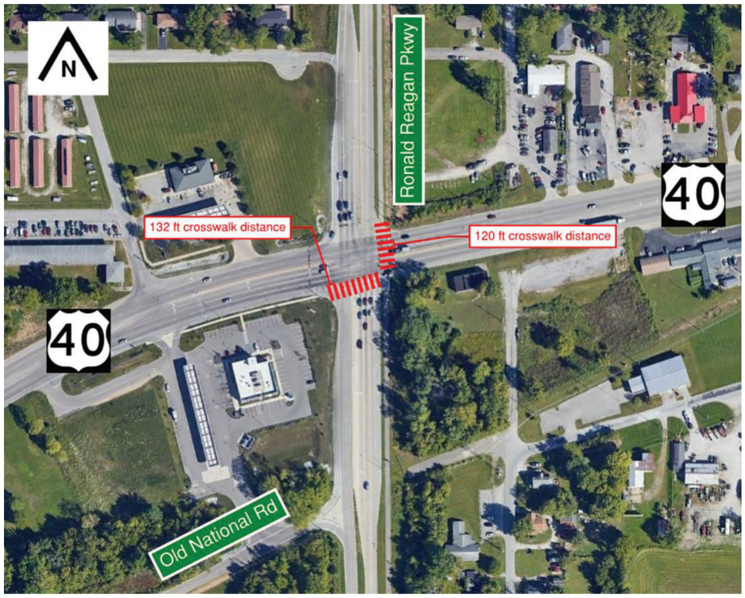
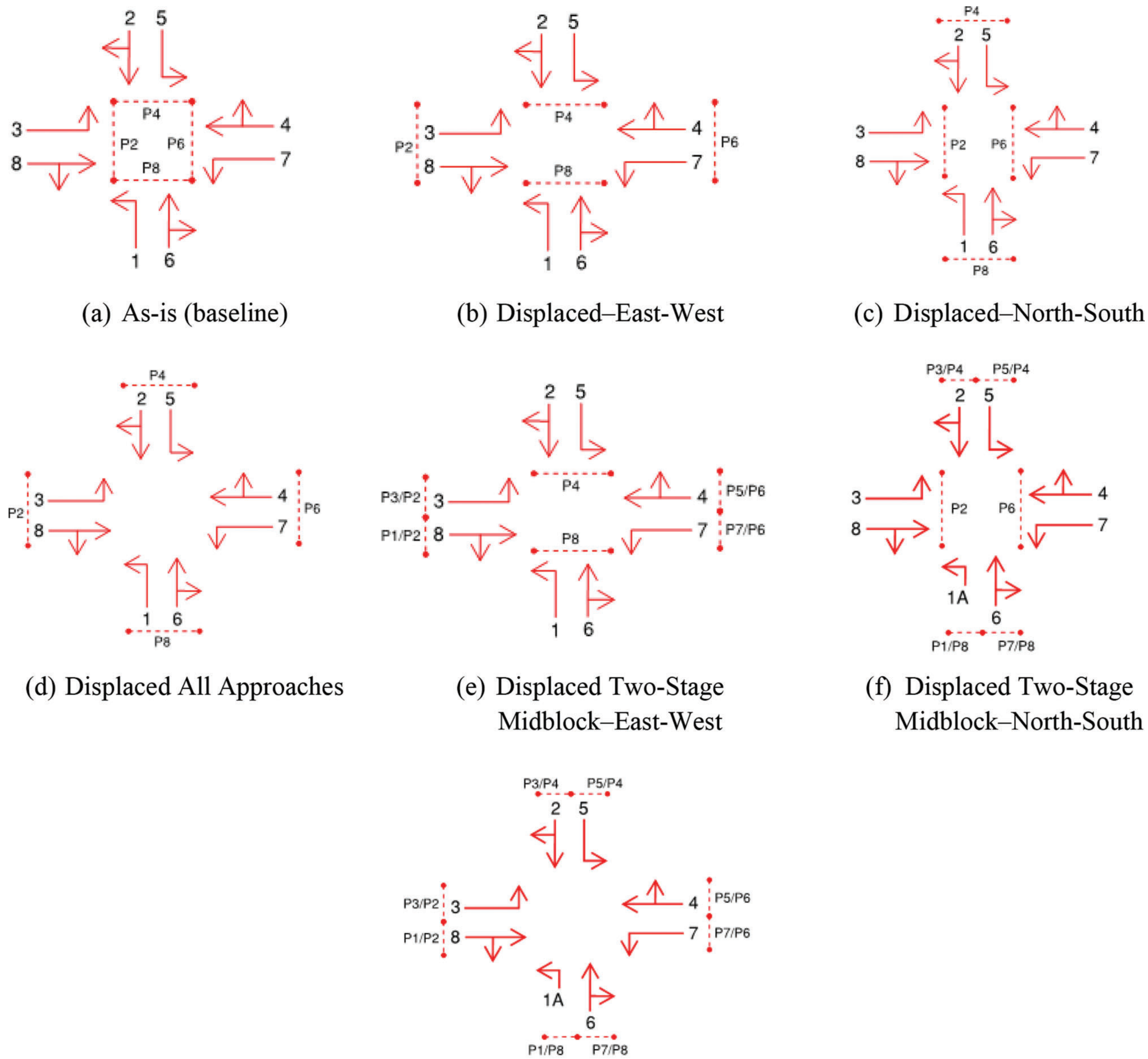


Figure 4.2 Pedestrian crossing distances (Google, n.d.b).

The existing crossing distances (in the as-is configuration) require a pedestrian interval of 44 seconds and 48 seconds, for the north-south and east-west crossings respectively. This requires an extension of the minimum green for the adjacent concurrent phases and increases the cycle length and delay. Configurations in which the pedestrian crossing interval does not require an extension to the minimum green time of the concurrently served vehicle movements provide advantages in terms of vehicle delay.

In addition, the Displaced Two-Stage Midblock East-West configuration can accommodate a higher pedestrian volume (scenarios 2x and 4x), without significant impacts on the average vehicle delay (s/veh).

In terms of pedestrian travel time, all of the displaced configurations have a superior average travel time when compared to the as-is configuration. However, the Displaced Two-Stage Midblock North-South configuration is superior since it has a shorter displacement distance than the displacements on the Two-Stage Midblock East-West configuration.



(a) As-is (baseline)

(b) Displaced–East-West

(c) Displaced–North-South

(d) Displaced All Approaches

(e) Displaced Two-Stage Midblock–East-West

(f) Displaced Two-Stage Midblock–North-South

(g) Displaced Two-Stage Midblock–All Legs

Figure 4.3 Alternate configurations analyzed for pedestrian crosswalk.

TABLE 4.2
Ronald Reagan Pkwy and US 40 LOS

Crossing Configuration	Pedestrian Volume	1	2	3	4	5	6	7	8	Average Delay (S/Veh) / LOS
		Movement Group LOS (peak hour) 120-Second Cycle Length								
As-is (baseline)	Current[1]	E	C	E	E	E	C	F	C	49.7 / D
	2 ×	E	C	E	D	E	C	F	C	44.7 / D
	4 ×	E	C	E	E	E	C	F	D	50.8 / D
Displaced: East-West	Current[1]	E	C	E	F	E	C	F	C	53.3 / E
	2 ×	E	C	E	F	E	C	F	C	53.6 / E
	4 ×	E	C	E	F	E	C	F	C	54.6 / E
Displaced: North-South	Current[1]	E	C	E	D	E	C	F	C	48.7 / D
	2 ×	E	C	E	E	E	C	F	C	50.4 / D
	4 ×	E	C	E	E	E	C	F	C	50.7 / D
Displaced: All Legs	Current[1]	E	C	E	F	E	C	F	C	53.5 / E
	2 ×	E	C	E	F	E	C	F	C	55.9 / E
	4 ×	E	C	E	F	E	C	F	C	56.3 / E
Displaced Two-Stage Midblock: East-West	Current[1]	E	C	E	E	E	C	F	C	41.1/ D
	2 ×	E	C	E	E	E	D	F	C	41.6 / D
	4 ×	E	C	E	E	E	D	F	C	42.8 / D
Displaced Two-Stage Midblock: North-South	Current[1]	E	C	E	D	E	C	F	C	54.3 / D
	2 ×	E	C	E	D	E	C	F	C	55.1 / D
	4 ×	E	C	E	E	E	C	F	C	55.4 / D
Displaced Two-Stage Midblock: All Legs	Current[1]	E	C	E	F	E	D	F	C	59.9 / E
	2 ×	E	C	E	E	E	E	F	C	66.7 / E
	4 ×	E	C	E	E	E	E	F	C	67.1 / E

[1]Assumed volume (see Appendix B).

TABLE 4.3
Ronald Reagan Pkwy and US 40 Green Time Extension per Configuration

		Configuration				
		As-is	**Displaced-EW**	**Two-Stage Displaced-EW**		
North–South Crossing	Crosswalk Length	120 ft	60 ft		24 ft	
	Crossing Time	44 sec	24 sec		12 sec	
	Served with NEMA Groups	2,6	2,6	3,7	1,5	2,6
	Min Green	33 sec	33 sec	15 sec	9 sec	33 sec
	Green Time Extension	+11 sec	0 sec	0 sec	+ 3 sec	0 sec
		As-is	**Displaced-NS**	**Two-Stage Displaced-NS**		
East–West Crossing	Crosswalk Length	132 ft	60 ft		24 ft	
	Crossing Time	48 sec	24 sec		12 sec	
	Served with NEMA Groups	4,8	4,8	3,7	4,8	1,5
	Min Green	49 sec	49 sec	15 sec	49 sec	9 sec
	Green Time Extension	0 sec	0 sec	0 sec	0 sec	+ 3 sec

Note: Red text indicates a time extension to the cycle length to accommodate pedestrians crossing.

TABLE 4.4
Pedestrian Travel Time per Configuration

Configuration	Average Travel Time (seconds)
As-is (baseline)	368.8
Displaced–East-West	303.7
Displaced–North-South	297.9
Displaced Two-Stage Midblock–East-West	321.4
Displaced Two-Stage Midblock–North-South	280.7

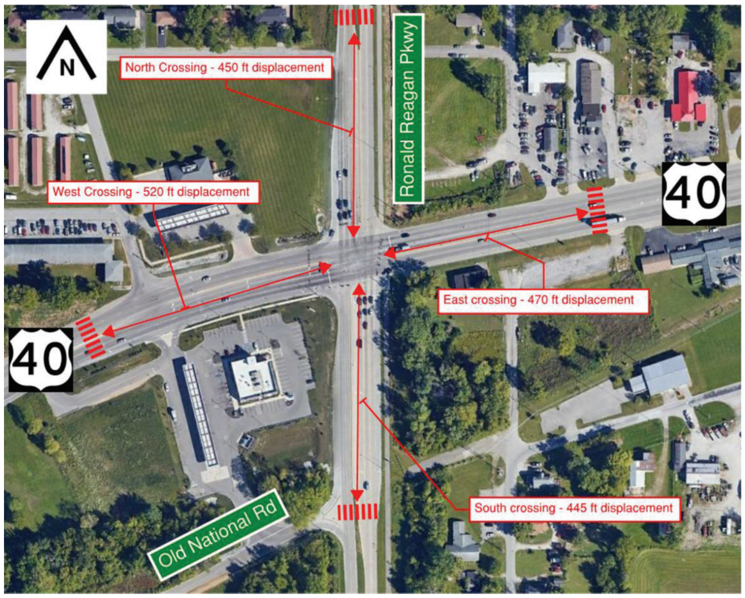


Figure 4.4 Displacement distance.

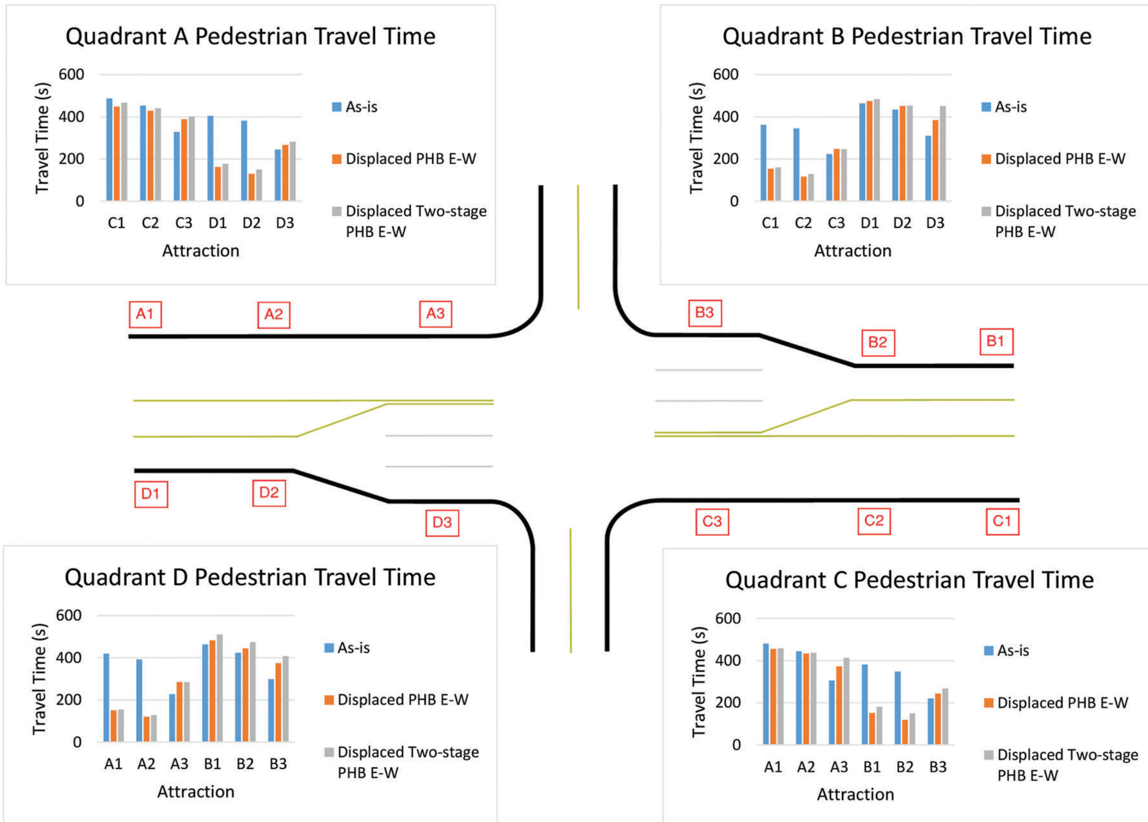


Figure 4.5 Pedestrian travel times per traffic control—east-west displaced.

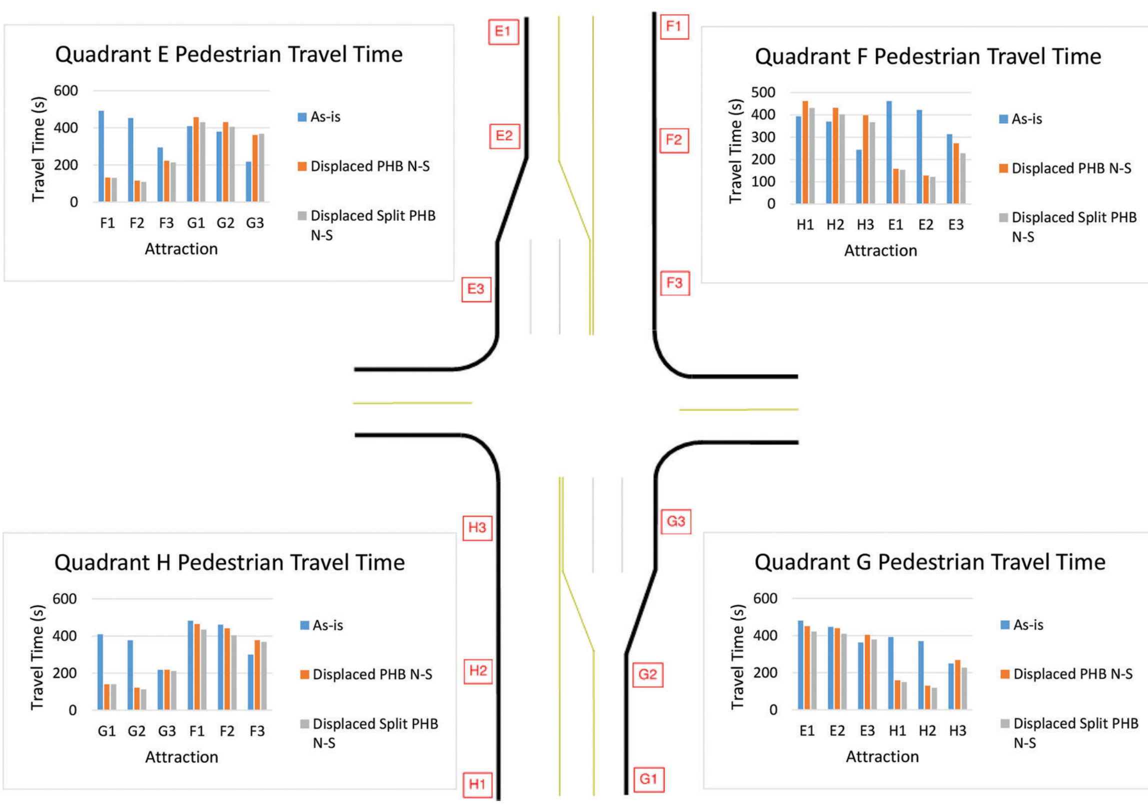


Figure 4.6 Pedestrian travel times per traffic control—north south displaced.

4.2 US 52 and Cumberland Ave in West Lafayette, IN

The intersection of US 52 and Cumberland Ave, shown in Figure 4.7, has a speed limit of 45 mph along US 52 and 30 mph along Cumberland Ave, and has the following lane configuration.

- Four southbound approach lanes (two thru, one right turn, and one left turn lane).
- Three westbound approach lanes (one thru, one right turn, and one left turn lanes).
- Three northbound approach lanes (one thru, one right turn, and one left turn lane).
- Four eastbound approach lanes (two thru, one right turn, and one left turn lane).

The surrounding development consists of commercial properties. Pedestrian sidewalks (or paved pedestrian and bike trails) exist on the east side of the southbound, and on the south side of the eastbound and westbound approaches. In the simulation of this intersection, pedestrian sidewalks were assumed to be present on both sides of each approach. Peak hour traffic and pedestrian volumes are listed in Table 4.5.

In the as-is configuration, pedestrians cross a distance of 99 ft when crossing north-south, and a distance of 126 ft when crossing east-west, as shown in Figure 4.8. The evaluation of this intersection considered a displaced crossing along the north and south approaches. Figure 4.9 illustrates the configurations and phasing that was chosen for analysis.

4.2.1 Vehicles LOS

A summary of the peak hour LOS per movement group and the average daily delay is presented in Table 4.6.

The Displaced Two-Stage Midblock North-South configuration is superior based on both the movement group LOS and the average delay (s/veh), because it serves pedestrians with vehicle phases that have no conflicts (movement groups 1 and 5, and 3 and 7).

Both the Displaced North-South and Displaced Two-Stage Midblock North-South configurations require the least green time extension for the concurrently served vehicle movements when compared to the as-is configuration. An extension of 24 seconds is required to serve pedestrians crossing east-west concurrently with vehicle movement groups 4 and 8, making the minimum green time for the concurrent vehicle phase 46 seconds instead of 22 seconds. Table 4.7 lists the green time extension required per movement group to serve a pedestrian, if a pedestrian call is placed.

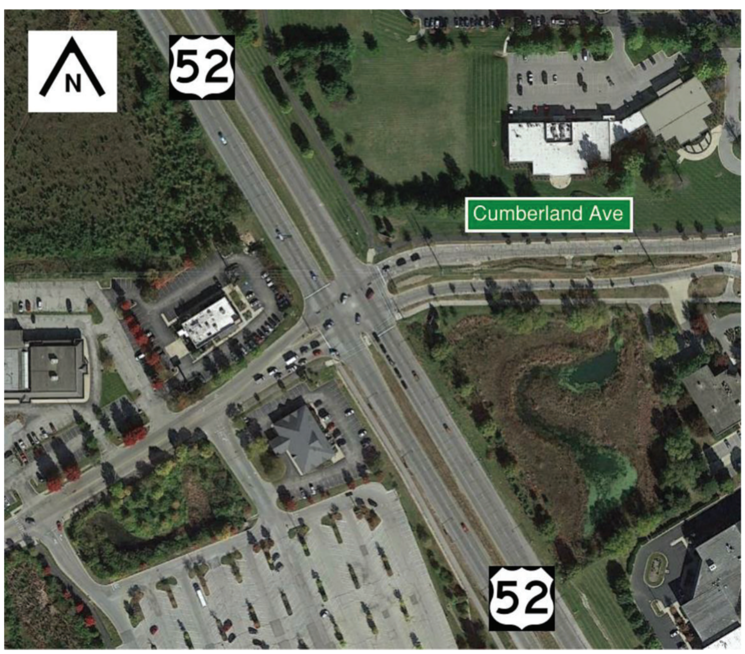


Figure 4.7 US 52 and Cumberland Ave (Google, n.d.d).

TABLE 4.5
Peak Hour Volumes (4:00 PM–5:00 PM)

Movement	1	2	3	4	5	6	7	8
Vehicle Volume	241	1,843	106	436	245	1,636	108	428
Pedestrian Volume	–	10	–	10	–	10	–	10

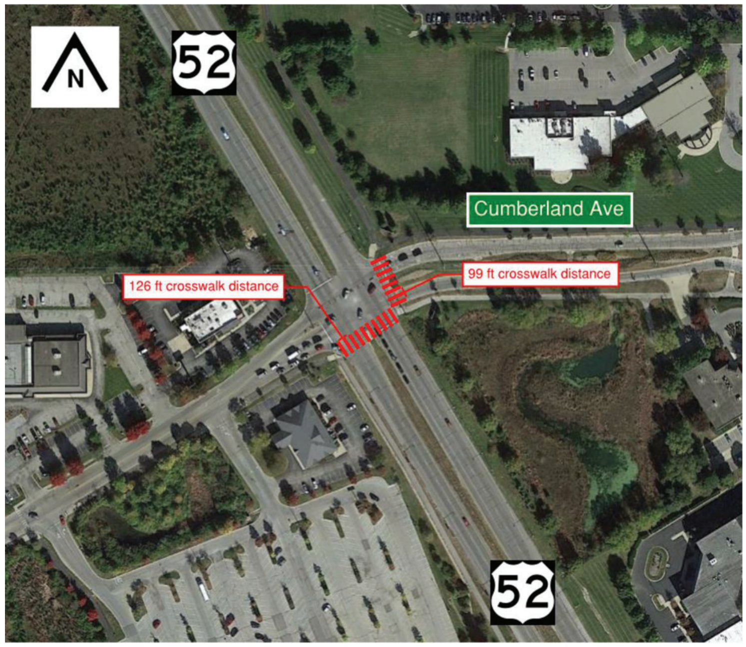


Figure 4.8 Pedestrian crossing distances (Google, n.d.c).

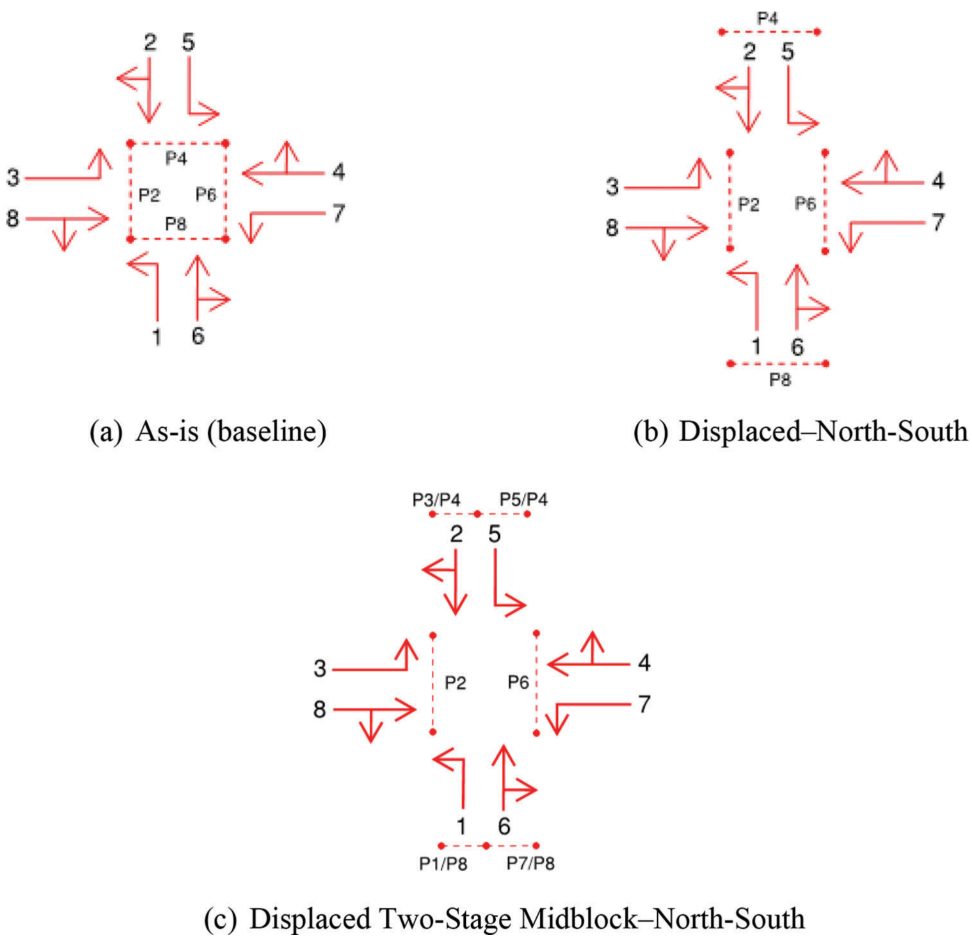


Figure 4.9 Alternate configurations analyzed for pedestrian crosswalk.

TABLE 4.6
US 52 and Cumberland Ave Movement Group LOS

Crossing Configuration	Pedestrian Volume	Movement Group LOS (Peak Hour) 120 Second Cycle Length 1	2	3	4	5	6	7	8	Average Delay (S/Veh) / LOS
As-is (baseline)	Current[1]	F	F	F	C	F	E	E	D	36.7 / C
	2×	F	F	F	C	F	E	E	D	37.3 / C
	4×	F	F	F	C	F	E	E	D	38.6 / C
Displaced: North-South	Current[1]	E	F	F	D	F	D	F	F	29.4 / B
	2×	F	F	F	D	F	D	F	F	30.6 / C
	4×	F	F	F	D	F	D	F	F	32.4 / C
Displaced Two-Stage Midblock: North-South	Current[1]	D	F	F	E	F	C	E	E	26.0 / B
	2×	D	F	F	E	F	C	F	F	27.2 / B
	4×	D	F	F	E	F	C	F	F	27.3 / B

[1]Assumed volume (see Appendix B).

TABLE 4.7
US 52 and Cumberland Ave Green Time Extension per Configuration

		Configuration As-is	Displaced-NS	Two-Stage Displaced-NS		
East-West Crossing	Crosswalk Length	126 ft	60 ft		24	
	Crossing Time	46 sec	24 sec		12 sec	
	Served with NEMA Groups	4,8	4,8	3,7	4,8	1,5
	Min Green	22 sec	22 sec	10 sec	20 sec	9 sec
	Green Time Extension	+ 24 sec	+ 2 sec	+ 2 sec	0 sec	+ 3 sec

Note: Red text indicates a time extension to the cycle length to accommodate pedestrians crossing.

TABLE 4.8
Pedestrian Travel Time per Configuration

Configuration	Average Travel Time (seconds)
As-is (baseline)	447.1
Displaced: North-South	373.5
Displaced Two-Stage Midblock: North-South	406.7

4.2.2 Pedestrian Service

The pedestrian travel time, from any origin to any destination, consists of the time spent walking to the pedestrian crosswalk and the time spent waiting for the pedestrian interval. Therefore, travel time will be a function of the length of the trip (including additional walk time to the displaced crossing) and the traffic control used to facilitate pedestrian crossings. Average travel times from each quadrant to the opposing quadrants are shown in Figure 4.11. A summary of the pedestrian average travel time of each configuration is shown in Table 4.8; disaggregated results of pedestrian travel times are provided in Appendix C. The distance to displaced crossings can be seen in Figure 4.10.

4.2.3 US 52 and Cumberland Ave Overall Findings

The existing crossing distances (in the as-is configuration) require a pedestrian interval of 46 for the east-west crossing. This requires an extension of the minimum green for the adjacent concurrent phases of 24 seconds, and hence, increases the cycle length and delay. Configurations in which the pedestrian crossing

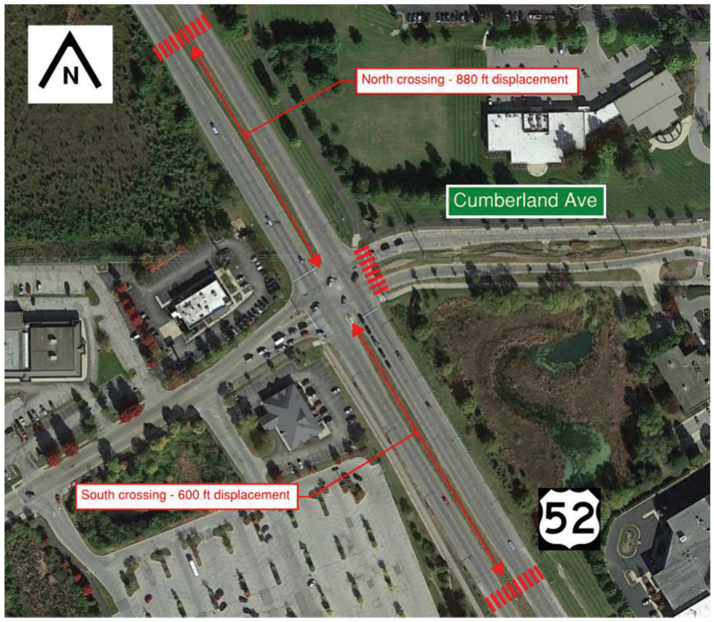


Figure 4.10 Displacement length.

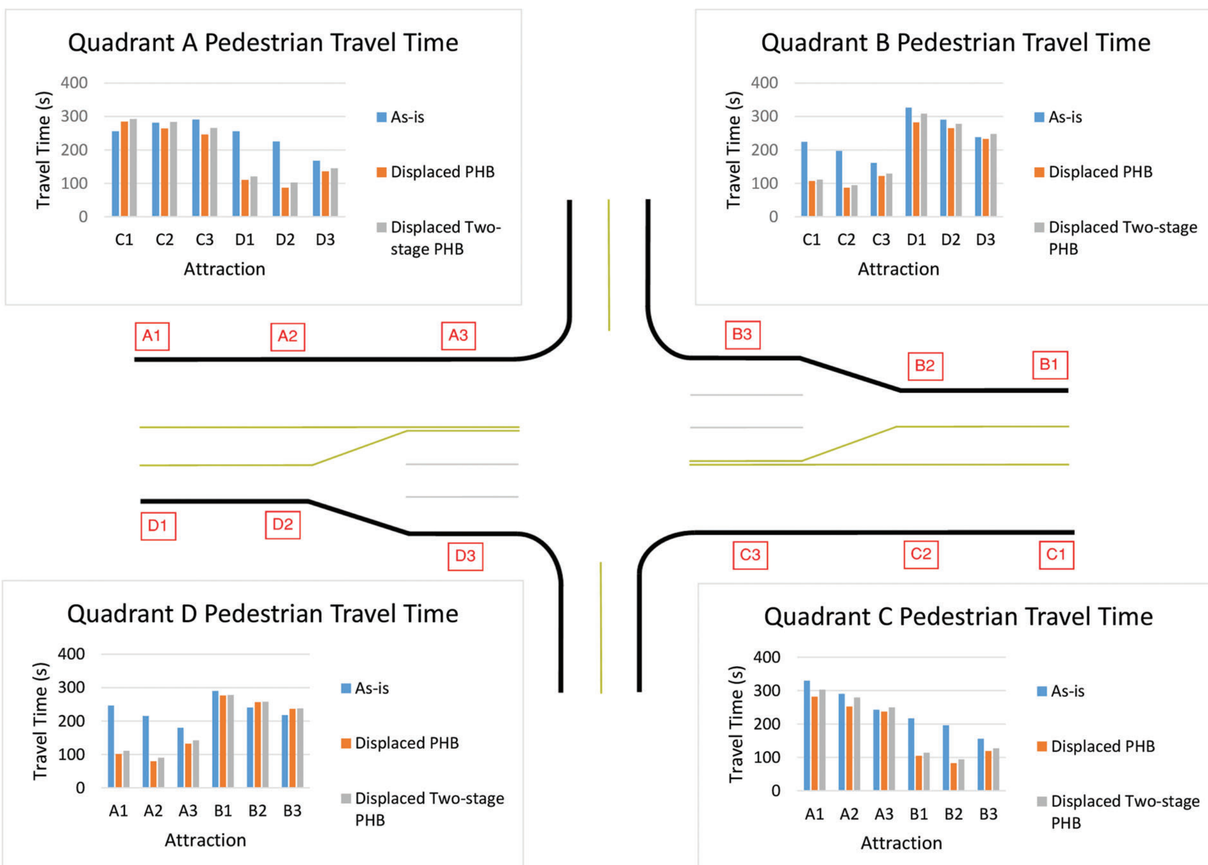


Figure 4.11 Pedestrian travel times per traffic control.

interval does not require a green time extension for the concurrently served vehicle movements provide advantages for in terms of vehicle delay. The Displaced North-South and Displaced Two-Stage Midblock North-South require an extension of 2 and 5 seconds, respectively, to serve pedestrians. The Displaced Two-Stage

Midblock North-South configuration can also accommodate an increasing volume of pedestrians (scenarios 2x and 4x), making it superior for future pedestrian growth.

In terms of pedestrian travel time, all examined displaced configurations are superior based on average travel time when compared to the as-is configuration. However, the Displaced Two-Stage North-South configuration is an overall superior configuration.

Typically, the nearest point in the opposing quadrant (point C3 from quadrant A, in this case) would yield the shortest travel time for the as-is configuration. However, in some cases, the simulation provides different results; this is presumably caused by the probabilistic rather than deterministic methodology used for simulation. Probabilistic simulation uses randomly distributed pedestrians both in terms of time and special distribution. As a result of this probabilistic methodology, there may be anomalies for specific locations, but overall trends will provide an assessment of operations that is consistent with what could be expected in the field. The simulation anomalies may include the following.

1. With pedestrians generated randomly each hour, the results might have slight variation as to when the pedestrian was generated during the traffic cycle (each configuration will have different generation times, but the same total number of pedestrians).
2. The simulation environment used in this study limits the total number of pedestrians per time frame to 20 (for all generation/attraction points); sometimes a certain location will stop producing pedestrians to stay within the 20 pedestrian threshold limit and will result in results (often for only one quadrant, in this case, quadrant A).

4.3 US 31 and Home Ave in Columbus, IN

The intersection of US 31 and Home Ave, shown in Figure 4.12, has a speed limit of 35 mph along US 31 and 30 mph along Home Ave, and has the following lane configuration.

- Two southbound approach lanes (one thru and right, and one left turn lane).
- Four westbound approach lanes (two thru, one right turn, and one left turn lanes).
- Three northbound approach lanes (one thru, one right turn, and one left turn lane).
- Four eastbound approach lanes (two thru, one right turn, and one left turn lane).

The surrounding development is mainly residential, with a high school on the southeast quadrant of the intersection. Pedestrian sidewalks exist on both sides of the westbound and northbound approaches, on the north side of the eastbound approach, and on the east side of the southbound approach. In the simulation of this intersection, pedestrian sidewalks were assumed to be present on both sides of each approach. Peak hour traffic and pedestrian volumes are listed in Table 4.9.

In the as-is configuration, pedestrians cross a distance of 114 ft when crossing north-south, and a distance of 99 ft when crossing east-west, as shown in Figure 4.13. The evaluation of this intersection considered a displaced crossing along the north and south approaches. Figure 4.14 illustrates the configurations and phasing that was chosen for analysis.

4.3.1 Vehicles LOS

A summary of the peak hour LOS per movement group and the average daily delay is presented in Table 4.10.

The Displaced North-South configuration requires no green time extension for the concurrently served vehicle movements. The as-is and Two-Stage Displaced East-West configurations require extensions of 5 and 13 seconds, respectively, to serve pedestrians crossing

Figure 4.12 US 31 and Home Ave (Google, n.d.c).

TABLE 4.9
Intersection Peak Hour Volumes (5:00 PM–6:00 PM)

Movement	1	2	3	4	5	6	7	8
Vehicle Volume	61	63	44	958	31	90	31	1,193
Pedestrian Volume	–	10	–	10	–	10	–	10

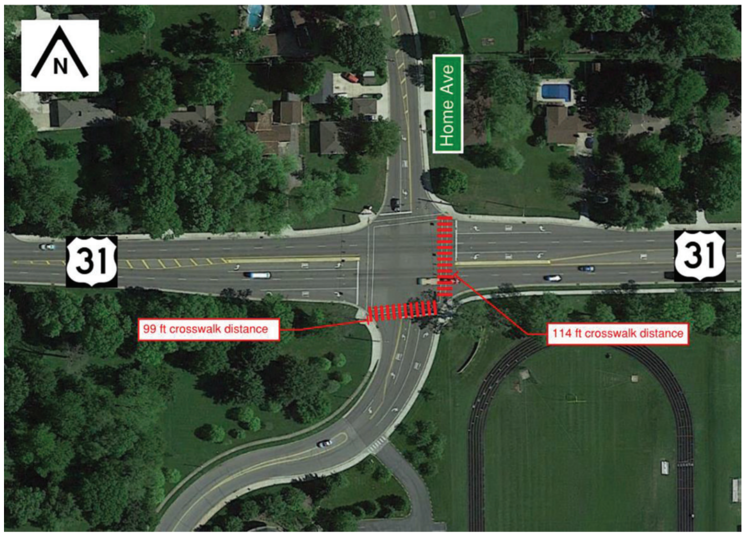


Figure 4.13 Pedestrian crossing distances (Google, n.d.c).

north-south. Table 4.11 lists the green time extension required per movement group to serve a pedestrian, if a pedestrian call is placed.

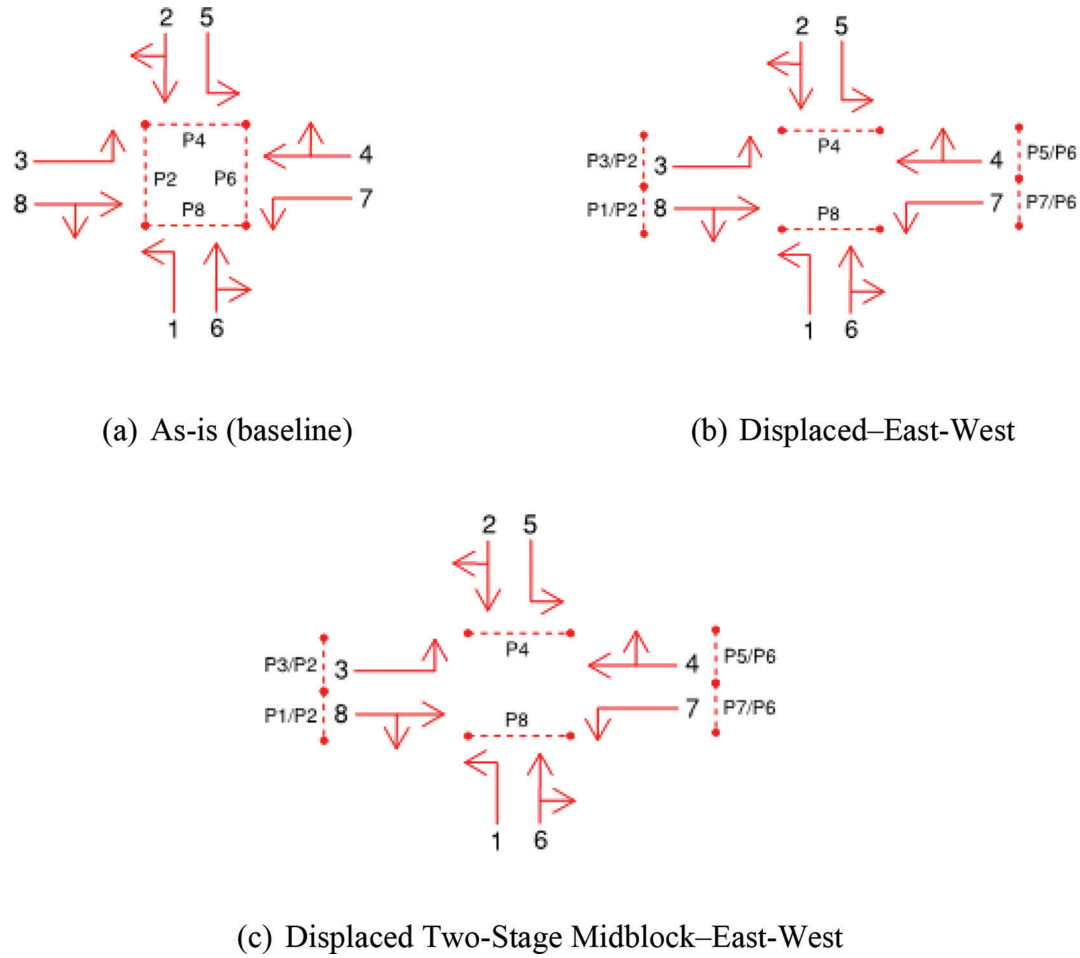
4.3.2 Pedestrian Service

The pedestrian travel time, from any origin to any destination, consists of the time spent walking to the pedestrian crosswalk and the time spent waiting for the pedestrian interval. Therefore, travel time will be a function of the length of the trip (including additional walk time to the displaced crossing) and the traffic control used to facilitate pedestrian crossings. Average travel times from each quadrant to the opposing quadrants are shown in Figure 4.16. A summary of the pedestrian average travel time of each configuration is shown in Table 4.12 and disaggregated results of pedestrian travel times are provided in Appendix C. The distance to displaced crossings can be seen in Figure 4.15.

4.3.3 US 31 and Home Ave Overall Findings

The existing crossing distances (in the as-is configuration) require a pedestrian interval of 46 seconds for the north-south crossing. This requires a 5-second extension of the minimum green required for the adjacent concurrent phases and increases the cycle length and delay. Similarly, the two-stage displaced configuration requires an extension of 13 seconds. Configurations in which the pedestrian crossing interval does not require green time extension for the concurrently served vehicle movements provide advantages for vehicles and pedestrians in terms of delay. In the Displaced East-West, no extension is required to serve pedestrians, and hence it is the superior alternative. In addition, the Displaced East-West configuration can accommodate an increased volume of pedestrians (scenarios 2x and 4x), making it superior in terms of accommodating future pedestrian growth.

In terms of pedestrian travel time, all examined displaced configurations are superior in terms of average travel time when compared to the as-is configuration. However, the Displaced East-West configuration is an overall superior configuration. Typically, the opposing nearest point from quadrant A (C3, in this case) would yield the shortest travel time for the as-is configuration. However, it appears that the results shown are contradicting, likely, due to the same simulation anomalies mentioned for US 52 and Cumberland Ave as discussed in Section 4.2.3.



(a) As-is (baseline)

(b) Displaced–East-West

(c) Displaced Two-Stage Midblock–East-West

Figure 4.14 Alternate configurations analyzed for pedestrian crosswalk.

TABLE 4.10
US 31 and Home Ave Movement Group LOS

Crossing Configuration	**Pedestrian Volume**	**Movement Group LOS (Peak Hour) – 120 Seconds Cycle Length: 1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average Delay (S/Veh) / LOS**
As-is (baseline)	Current[1]	E	D	F	C	D	D	E	C	34.28 / C
	2 ×	E	D	E	C	E	D	E	C	44.47 / D
	4 ×	F	D	E	C	E	D	E	C	51.67 / D
Displaced: East-West	Current[1]	E	D	E	C	D	E	E	C	28.27 / C
	2 ×	E	D	E	C	E	D	E	C	28.91 / C
	4 ×	E	D	E	C	E	D	E	C	29.25 / C
Displaced Two-Stage Midblock: East-West	Current[1]	E	C	F	C	E	D	E	C	39.27 / D
	2 ×	E	C	E	C	E	D	E	C	39.29 / D
	4 ×	D	C	E	C	E	D	E	C	44.52 / D

[1]Assumed volume (see Appendix B).

TABLE 4.11
US 31 and Home Ave Green Time Extension per Configuration

		Configuration				
		As-is	**Displaced-EW**	**Two-Stage Displaced-EW**		
North-South Crossing	Crosswalk Length	114 ft	60 ft	24 ft		
	Crossing Time	42 sec	24 sec	12 sec		
	Served with NEMA Groups	2,6	2,6	3,7	2,6	1,5
	Min Green	37 sec	37 sec	6 sec	37 sec	5 sec
	Green Time Extension	+ 5 sec	0 sec	+ 6 sec	0 sec	+ 7 sec

Note: Red text indicates a time extension to the cycle length to accommodate pedestrians crossing.

TABLE 4.12
Pedestrian Travel Times per Configuration

Configuration	Average Travel Time (seconds)
As-is (baseline)	239.1
Displaced: East-West	182.8
Displaced Two-Stage Midblock: East-West	197.1

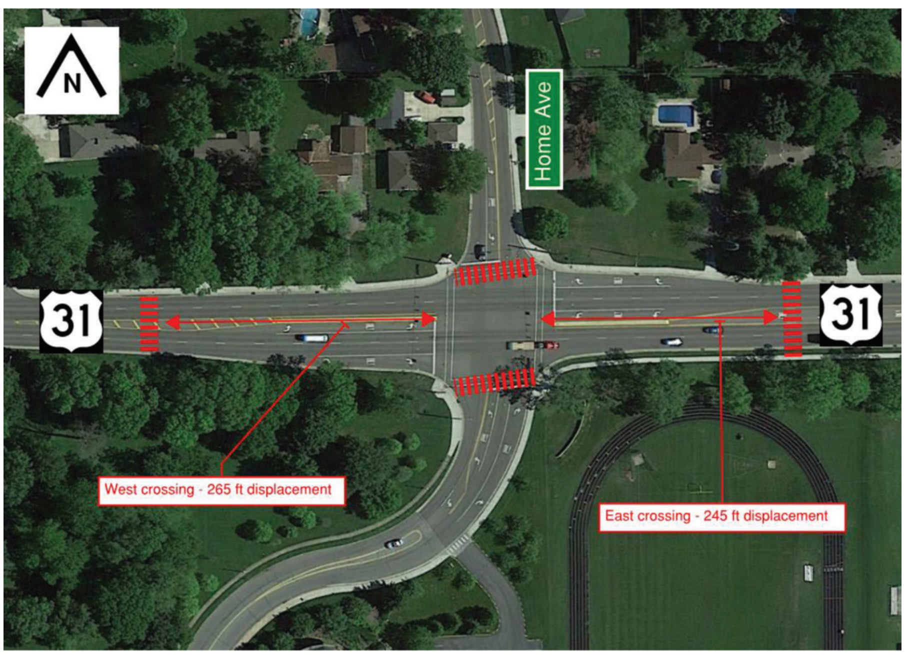


Figure 4.15 Displacement length.

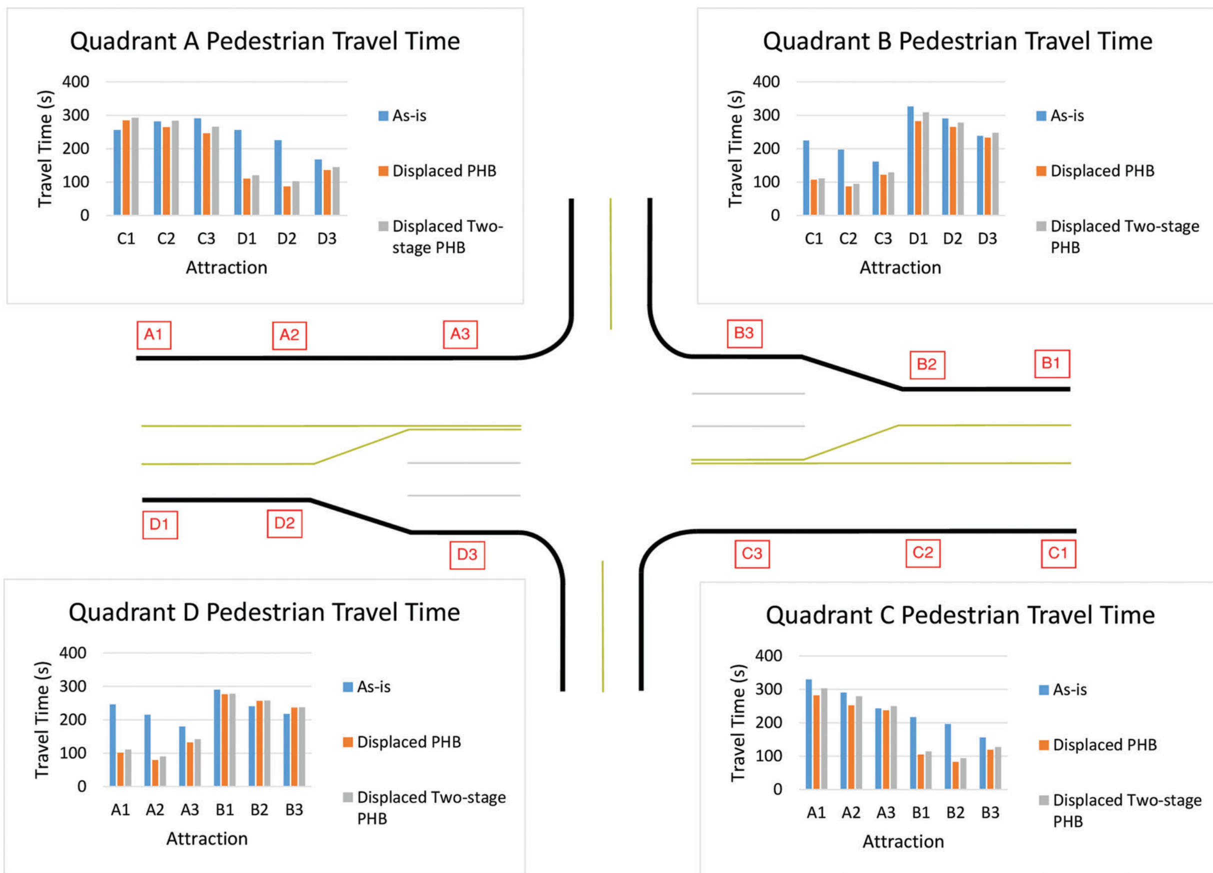


Figure 4.16 Pedestrian travel times per traffic control.

4.4 Ronald Reagan Pkwy and Rockville Rd in Avon, IN

The intersection of Ronald Reagan Pkwy and Rockville Rd, shown in Figure 4.17, has a speed limit of 45 mph on both approached and has the following lane configuration.

- Five southbound approach lanes (two thru, one right turn, and two left turn lanes).
- Four westbound approach lanes (two thru, one right turn, and one left turn lane).
- Five northbound approach lanes (two thru, one right turn, and two left turn lanes).
- Four eastbound approach lanes (two thru, one right turn, and one left turn lane).

The surrounding development is mainly commercial, with some residential buildings on the northeast quadrant of the intersection. Pedestrian sidewalks exist only on both sides of the southbound approach. In the simulation of this intersection, pedestrian sidewalks were assumed to be present on both sides of each approach.

The Indiana Department of Transportation (INDOT) has scheduled reconstruction and both westbound and eastbound approaches. This research modeled six lanes from Shiloh Dr. to Raceway Rd. based on information that was provided in a consultant report (three thru, one right turn, and two left turn lanes); subsequently, plans call for only one left turn lane, however the future scenario is still considered valid for comparison between a traditional and displaced crossing. The current and future configurations are shown in Figure 4.18. Peak hour traffic and pedestrian volumes are listed in Table 4.13. In the as-is configuration, pedestrians cross a distance of 130 ft when crossing north-south, and a distance of 105 ft when crossing east-west, the east-west crossing, however, will be increased to 166 ft in the future 6-lane configuration as shown in Figure 4.19.

The evaluation of this intersection considered a displaced crossing along the east and west approaches. An added left turn route was also considered, as indicated by the red arrow in Figure 4.20c,e. The added left turns will be routed through Shiloh Crossing Dr. on the west approach and through Menards entrance on the east approach. Added left turns are assumed to re-route 20% of the total eastbound and westbound left turns (movement groups 3 and 7) from the main intersection. Figure 4.20 illustrates the configurations and phasing that were chosen for analysis.

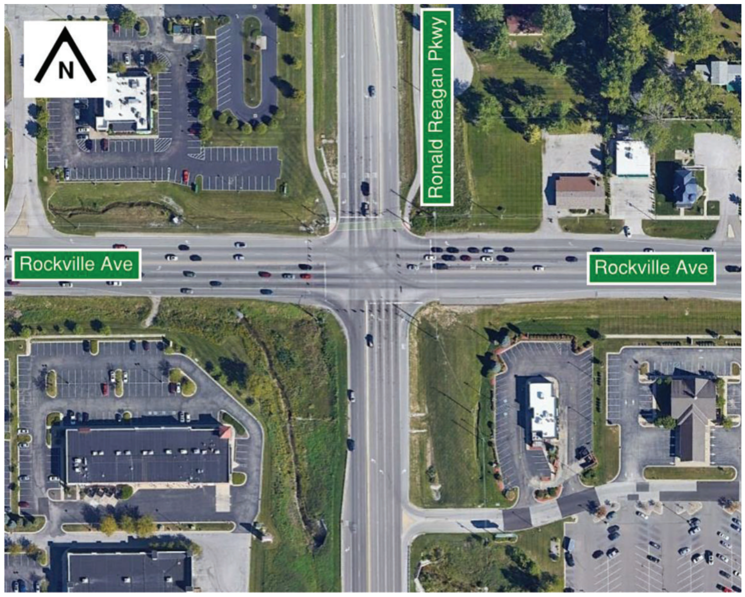


Figure 4.17 Ronald Reagan Pkwy and Rockville Ave (Google, n.d.a).

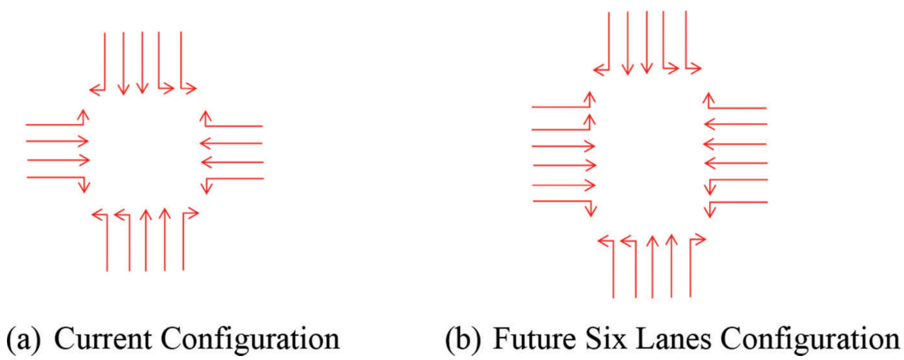


Figure 4.18 Ronald Reagan Pkwy and Rockville Rd current and future configurations.

TABLE 4.13
Intersection Peak Hour Volumes (6:00 AM–7:00 AM)

Movement	1	2	3	4	5	6	7	8
Vehicle Volume	427	604	227	1,489	211	660	285	1,345
Pedestrian Volume	–	8	–	8	–	8	–	8

4.4.1 Vehicles LOS

A summary of the peak hour LOS per movement group and the average daily delay are presented in Tables 4.14 and 4.15.

Both the Displaced Two-Stage East-West and the Displaced Two-Stage East-West with Early Left Turn configurations require a 2-second green time extension for the concurrent vehicle movements to serve pedestrians. The as-is and Displaced East West configurations require an extension of 27 and 5 seconds, respectively, to serve pedestrians crossing north-south. Table 4.15 lists the green time extension required per movement group to serve a pedestrian, if a pedestrian call is placed.

As seen in Tables 4.14 and 4.16, both the Displaced East-West and the Displaced Two-Stage East-West with Early Left Turn configurations require a 13-second extension to green time of the concurrently served vehicle movements. In comparison, the as-is configuration requires a 31-seconds extension to the minimum great time to serve pedestrians crossing north-south. Table 4.17 lists the green time extension required per movement group to serve a pedestrian, if a pedestrian call is placed.

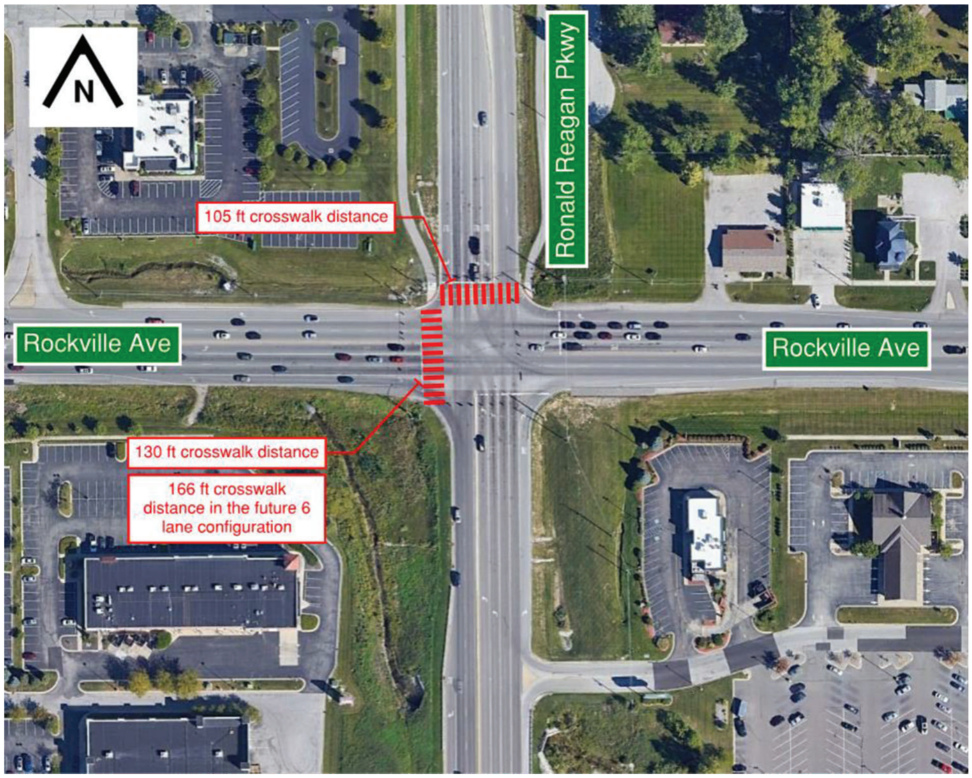


Figure 4.19 Pedestrian crossing distances (Google, n.d.a).

4.4.2 Pedestrian Service

The pedestrian travel time, from any origin to any destination, consists of the time spent walking to the pedestrian crosswalk and the time spent waiting for the pedestrian interval. Therefore, travel time will be a function of the length of the trip (including additional walk time to the displaced crossing) and the traffic control. Average travel times from each quadrant to the opposing quadrants are shown in Figures 4.22 and 4.23. A summary of the pedestrian average travel time of each configuration is shown in Table 4.18 below; disaggregated results of pedestrian travel times are provided in Appendix C. The distance to displaced crossings can be seen in Figure 4.21.

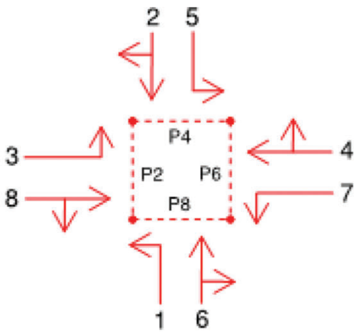
4.4.3 Ronald Reagan Pkwy and Rockville Avenue Overall Findings

The crossing distances at the intersection (as-is crosswalk location) for the future 6-lane configuration requires a pedestrian interval of 60 seconds for the north-south crossing. This requires an extension of the minimum green time of 31 seconds and, increases the cycle length and delay. However, the Displaced and Displaced Two-Stage configurations require an extension of 13 seconds, and 6 seconds, respectively. Configurations in which the pedestrian crossing interval requires the least green time extension to the concurrent vehicle phases provide advantages for vehicles and pedestrians in terms of delay. The Displaced Two-Stage East-West requires the least extension to the minimum green to serve pedestrians and is the superior alternative.

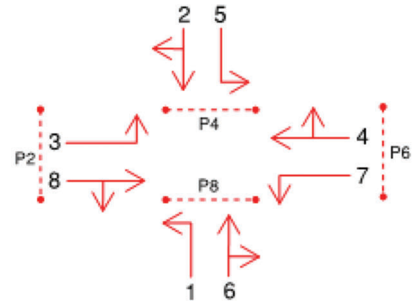
When the model includes early left turns, as shown in Figures 4.20c,e, the volume of left turns was divided and the timing of the intersection changes accordingly to accommodate new volumes. The Displaced Two-Stage Early Left configuration requires the least green time extension and therefore is the overall superior alternative configuration. The Displaced Two-Stage Early Left configuration is also superior in accommodating future pedestrian growth since the increase in average delay (s/veh) stabilizes with increased pedestrian volumes (scenarios 2x and 4x).

In terms of pedestrian travel time, all examined displaced configurations are superior to the as-is configuration. However, the Displaced Two-Stage East-West configuration is an overall superior configuration.

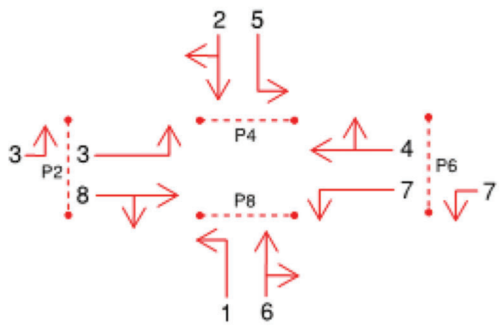
Typically, the opposing nearest point from quadrant D would yield the shortest travel time for the as-is configuration, followed by the second nearest point and then the furthest point is expected to have the lengthiest travel time. However, it appears that the results shown are contradicting (from quadrant D to B2, in this case), likely, due to the same simulation anomalies mentioned for US 52 and Cumberland Ave in Section 4.2.3.



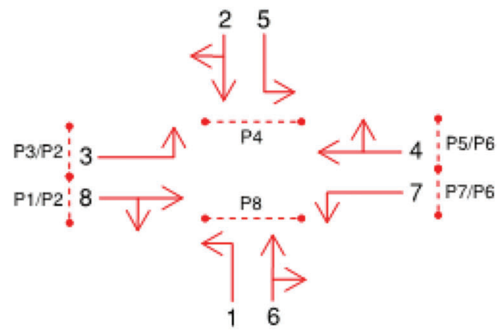
(a) As-is (baseline)



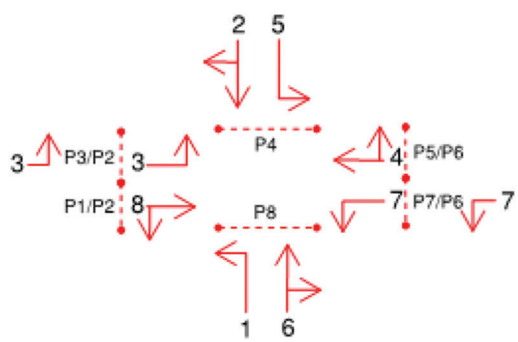
(b) Displaced–East-West



(c) Displaced–East-West, Early Left Turn



(d) Displaced Two-Stage Midblock–East-West



(e) Displaced Two-Stage Midblock–East-West, Early Left Turn

Figure 4.20 Alternate configurations analyzed for pedestrian crosswalk.

TABLE 4.14
Ronald Reagan Pkwy and Rockville Ave LOS—Current Configuration

Crossing Configuration	Pedestrian Volume	Movement Group LOS (Peak Hour), 120 Seconds Cycle Length: 1	2	3	4	5	6	7	8	Average Delay (S/Veh) / LOS
As-is (baseline)	Current[1]	E	C	F	C	E	D	E	D	49.3 / D
	2 ×	F	D	F	D	E	D	E	D	51.6 / D
	4 ×	F	D	F	D	E	E	E	E	53.6 / D
Displaced: East-West	Current[1]	E	C	F	C	E	D	E	D	46.1 / D
	2 ×	E	C	F	C	E	D	E	D	48.3 / D
	4 ×	F	D	F	D	E	E	E	E	50.7 / D
Displaced: East-West Early Left Turn	Current[1]	E	C	F	C	E	D	E	D	44.2 / D
	2 ×	E	C	F	C	E	D	E	D	45.5 / D
	4 ×	F	D	F	D	E	D	E	E	47.1 / D
Displaced Two-Stage Midblock: East-West	Current[1]	E	C	F	C	E	D	E	D	43.6 / D
	2 ×	E	C	F	C	E	D	E	D	44.3 / D
	4 ×	E	C	F	C	E	D	E	D	44.9 / D
Displaced Two-Stage Midblock: East-West Early Left Turn	Current[1]	E	C	F	C	E	D	E	D	42.9 / D
	2 ×	E	C	F	C	E	D	E	D	43.7 / D
	4 ×	E	C	F	C	E	D	E	D	44.1 / D

[1]Assumed volume (see Appendix B).

TABLE 4.15
Ronald Reagan and Rockville Ave Green Time Extension per Configuration

		Configuration: As-is	Displaced-EW	Displaced-EW, Early Left	Two-Stage Displaced-EW			Two-Stage Displaced-EW, Early Left		
North-South Crossing	Crosswalk Length	130	64	64		24			24	
	Crossing Time	48 sec	26 sec	26 sec		12 sec			12 sec	
	Served with NEMA Groups	2,6	2,6	2,6	3,7	2,6	1,5	3,7	2,6	1,5
	Min Green	21 sec	21 sec	21 sec	18 sec	21 sec	10 sec	15 sec	21 sec	10 sec
	Green Time Extension	+ 27 sec	+ 5 sec	+ 5 sec	+ 0 sec	+ 0 sec	+ 2 sec	+ 0 sec	+ 0 sec	+ 2 sec

Note: Red text indicates a time extension to the cycle length to accommodate pedestrians crossing.

TABLE 4.16
Ronald Reagan Pkwy and Rockville Ave LOS—Future 6-Lane Configuration

Crossing Configuration	Pedestrian Volume	Movement Group LOS (Peak Hour), 120 Seconds Cycle Length: 1	2	3	4	5	6	7	8	Average Delay (S/Veh) / LOS
As-is (baseline)	Current[1]	E	C	E	C	E	E	E	C	38.95 / D
	2×	E	C	E	C	E	E	E	C	39.90 / D
	4×	E	C	E	C	E	E	E	C	41.23 / D
Displaced: East-West	Current[1]	E	C	E	C	E	E	E	C	36.89 / D
	2×	E	C	E	C	E	E	E	C	37.25 / D
	4×	E	C	E	C	E	E	E	C	38.01 / D
Displaced: East-West Early Left Turn	Current[1]	E	C	E	C	E	E	E	C	36.41 / D
	2×	E	C	E	C	E	E	E	C	36.77 / D
	4×	E	C	E	C	E	E	E	C	37.65 / D
Displaced Two-Stage Midblock: East-West	Current[1]	E	C	E	C	E	E	E	C	36.18 / D
	2×	E	C	E	C	E	E	E	C	36.37 / D
	4×	E	C	E	C	E	E	E	C	36.81 / D
Displaced Two-Stage Midblock: East-West Early Left Turn	Current[1]	E	C	E	C	E	E	E	C	35.20 / D
	2×	E	C	E	C	E	E	E	C	35.55 / D
	4×	E	C	E	C	E	E	E	C	36.02 / D

[1]Assumed volume (see Appendix B).

TABLE 4.17
Ronald Reagan and Rockville Ave Future 6-Lane Layout Green Time Extension per Configuration

		Configuration: As-is	Displaced-EW	Displaced-EW, Early Left	Two-Stage Displaced-EW			Two-Stage Displaced-EW, Early Left		
North-South Crossing	Crosswalk Length	166	88	88		36			36	
	Crossing Time	60 sec	34 sec	34 sec		16 sec			16 sec	
	Served with NEMA Groups	2,6	2,6	2,6	3,7	2,6	1,5	3,7	2,6	1,5
	Min Green	21 sec	21 sec	21 sec	11 sec	21 sec	10 sec	9 sec	21 sec	10 sec
	Green Time Extension	+ 31 sec	+ 13 sec	+ 13 sec	+ 5 sec	0 sec	+ 6 sec	+ 7 sec	0 sec	+ 6 sec

Note: Red text indicates a time extension to the cycle length to accommodate pedestrians crossing.

TABLE 4.18
Pedestrian Travel Times per Configuration

Current Configuration	Average Travel Time (Seconds)
As-is (baseline)	441.5
Displaced: East-West	308.6
Displaced: East-West, Early Left	310.7
Displaced Two-Stage Midblock: East-West	290.2
Displaced Two-Stage Midblock: East-West, Early Left	293.4
Future 6-Lane Configuration	**Average Travel Time (Seconds)**
As-is (baseline)	468.9
Displaced: East-West	315.7
Displaced: East-West, Early Left	318.2
Displaced Two-Stage Midblock: East-West	265.9
Displaced Two-Stage Midblock: East-West, Early Left	266.7

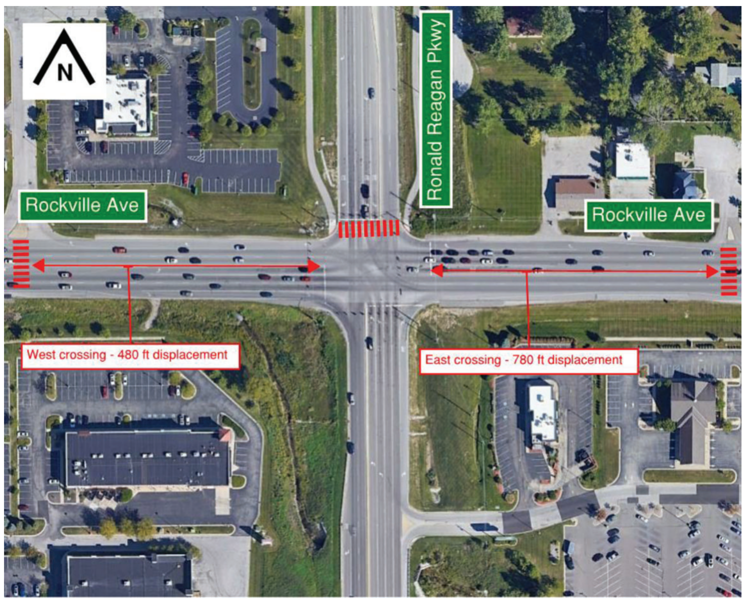


Figure 4.21 Displacement length.

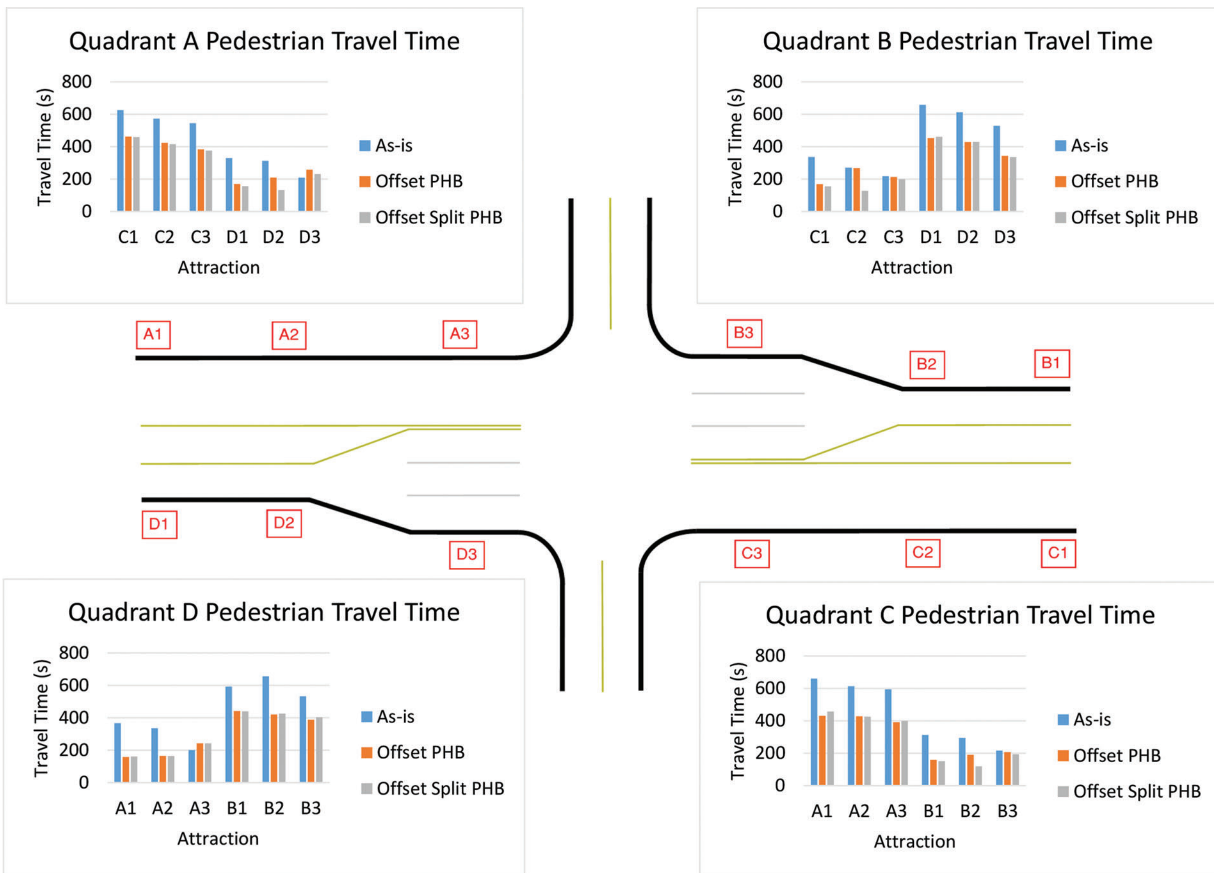


Figure 4.22 Pedestrian travel times per traffic control (current configuration).

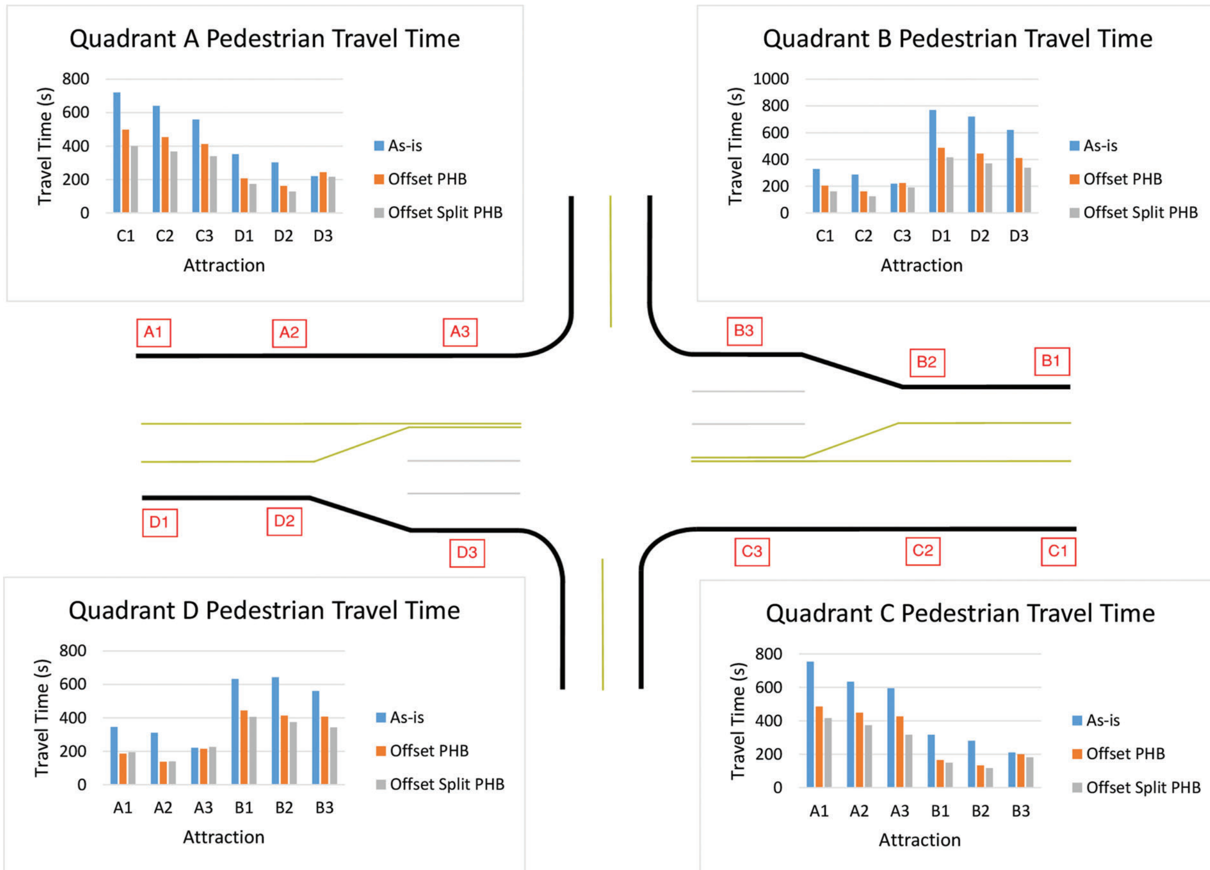


Figure 4.23 Pedestrian travel time per traffic control (future 6-lane configuration).

5. CONCLUSIONS AND RECOMMENDATIONS

Pedestrians at signalized intersections are typically served concurrently with the adjacent through traffic movements. This poses safety concerns since pedestrians must cross in close proximity to turning traffic (right turns on green, right turns on red and permissive left turns). Concurrent pedestrian service may also increase delay for vehicles and pedestrians (due to a longer cycle length required for the pedestrian clearance phase), and compromise corridor signal progression. Existing traffic control strategies such as LPI and exclusive pedestrian phases may increase safety but may also increase delay for both vehicles and pedestrians.

As an alternative crossing treatment, a "Displaced" pedestrian crossing located upstream and/or downstream of the intersection may provide an alternative to improve service for vehicles and safety for pedestrians. A displaced crossing may provide advantages to pedestrians, including a reduced crossing distance and an increased sense of safety due to the reduced impact of turning traffic into the crosswalk. A displaced crossing may also provide advantages to vehicles, including a shorter pedestrian interval (due to a reduced crossing distance), a shorter cycle length, reduced delay, fewer conflicts with pedestrians. Although not investigated as part of this research, there may also be benefits of the displaced crossing in conjunction with an early left turn; it is expected that this would result in further delay reductions at the intersection.

The impact of the displaced crossing was assessed using two different traffic control strategies: (1) coordinated displaced PHB and (2) coordinated displaced two-stage PHB. The PHB was selected for two reasons: (1) it has a reduced impact on vehicle delay since drivers can continue after the pedestrian as crossed and (2) previous research indicates that driver compliance with PHB is very high, which increases pedestrian safety. Previous research documents driver compliance with PHB at approximately 97% (Fayyaz et al., 2019). This high compliance rate increases pedestrian safety, and research by Fitzpatrick et al. suggests that pedestrians are willing to increase their trip length to take a route that uses a PHB (2006).

The displaced pedestrian crossing was investigated at four different intersections and in each case, the benefits due to the displaced included reduced vehicle delay and reduced pedestrian delay, with the reduction in delay varying based on the volume of pedestrians, the vehicle volumes, and the extension required for the minimum green for the cross street.

Generally, average vehicle delay in the peak hour decreases with the implementation of the displaced pedestrian crossing. The reduction in delay varies depending on intersection characteristics such as turning volume and effective green time for each intersection phase. Figure 5.1 below provides an example of the benefits gained from the displaced at Ronald Reagan and Rockville in Plainfield, Indiana.

This research provides compelling evidence that designers should consider a displaced crossing strategy as an option for consideration and evaluation. Additional research is recommended to confirm the benefits of an actual field deployment of a displaced pedestrian crossing, and to confirm that the driver yield rate ensures pedestrian safety. The deployment of the displaced crossing in combination with a PHB should include appropriate signage per the MUTCD and an educational campaign to ensure safety for both pedestrians and motorists. Provided in Appendix D are signs and other enhancements to support pedestrian safety, some of which may be utilized at the displaced crossing.

In addition, future research can further examine the displaced crossing, and its impact on pedestrians, by including an expanded representation of the pedestrian generators and attractants. The methodology adopted in this study focused on pedestrian generators and attractants on the main arterial; in future research it may be appropriate to model additional pedestrian generators on the cross street in addition to those along the main arterial approaches. Accurate generation and attraction points are expected to have an impact on the overall findings, which may vary significantly

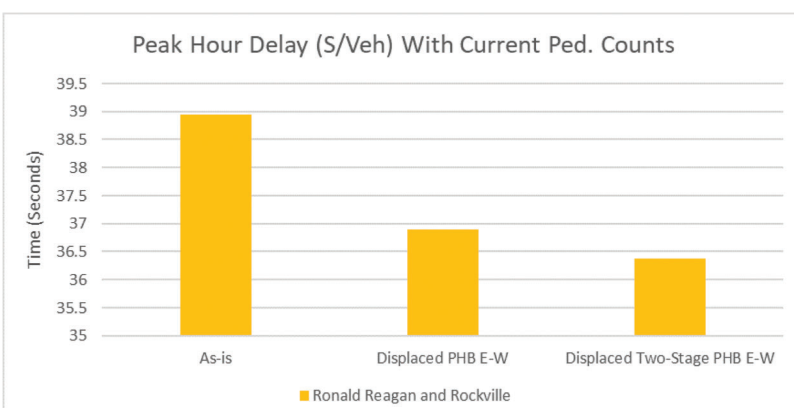


Figure 5.1 Displacement delay benefits.

depending on the specific development and pedestrian characteristics at the intersection. Future research could also examine the time required for left turns that are served concurrently with the pedestrian phase to clear without conflicts with pedestrians in the displaced crossing configuration. This would vary depending on the geometric characteristics and the volume characteristics at the individual intersection. Although outside the scope of this project, it is necessary to investigate it for a specific intersection prior to implementation.

Future work can also explore any potential limitations of modeling operations with simulation software. This may include pedestrian distribution during the traffic cycle and the implications of limiting the number of pedestrians in each simulation time frame. There were some anomalies in this research; although they occurred less than 1% of the time (three times out of the 432 different configuration for pedestrian attractions and generation points examined), they contradicted the general trend which was supportive of the displaced crossing. Future research could be conducted to provide a better understanding of limitations associated with probabilistic simulation models, and how any associated limitations can be overcome.

REFERENCES

AASHTO. (2004). *Guide for the planning, design, and operation of pedestrian facilities* (1st ed.). American Association of State Highway and Transportation Officials.

City of Laguna Beach. (n.d.). [Photograph of crosswalk sign near traffic signal light]. Retrieved August 17, 2020, from http://lagunabeachcity.net/news/displaynews.htm?NewsID=1855

Coleman, H., & Mizenko, K. (2018). *Pedestrian and bicyclist data analysis: Traffic safety facts: Research note* (DOT HS 812 205). National Highway Traffic Safety Administration.

Fayyaz, K., Schultz, G. G., & Galvez de Leon, P. (2019). *Driver compliance at enhanced pedestrian crossings in Utah* (Research Report No. UT-19.03). Utah Department of Transportation.

FHWA. (n.d.a). *Pedestrian accommodations at intersections*. Retrieved November 30, 2020, from https://safety.fhwa.dot.gov/ped_bike/univcourse/pdf/swless15.pdf

FHWA. (n.d.b). *Pedestrian hybrid beacon guide—Recommendations and case study*. Retrieved November 30, 2020, from https://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa14014/fhwasa14014.pdf

FHWA. (2009a). *Manual on uniform traffic control devices for streets and highways* (2009 ed., including revision 1). Federal Highway Administration, U.S. Department of Transportation.

FHWA. (2009b). *Pedestrian accommodations at intersections*. Federal Highway Administration. https://safety.fhwa.dot.gov/ped_bike/univcourse/pdf/swless15.pdf

Fitzpatrick, K., Turner, S., Brewer, M., Carlson, P., Ullman, B., Trout, N., Park, E. S., Whitacre, J., Lalani, N., & Lord, D. (2006). *TCRP report 112/NCHRP report 562: Improving pedestrian safety at unsignalized crossings*. Transportation Research Board of the National Academies.

Fricker, J. D., & Zhang, Y. (2019). Modeling pedestrian and motorist interaction at semi-controlled crosswalks: The effects of a change from one-way to two-way street operation. *Transportation Research Record*, *2673*(11), 433–446. https://doi.org/10.1177/0361198119850142

Google. (n.d.a). [Ronald Reagan Pkwy and Rockville Ave]. Retrieved September 2020.

Google. (n.d.b). [Google Earth image of Ronald Reagan Pkwy and US 40]. Retrieved September 2020.

Google. (n.d.c). [Google Earth image of US 31 and Home Ave]. Retrieved October 2020.

Google. (n.d.d). [Google Earth image of US 52 and Cumberland Ave]. Retrieved November 2020.

He, Q., Head, K. L., & Ding, J. (2014, September). Multi-modal traffic signal control with priority, signal actuation and coordination. *Transportation Research Part C: Emerging Technologies*, *46*, 65–82. https://doi.org/10.1016/j.trc.2014.05.001

Hubbard, S. M., Bullock, D. M., & Mannering, F. L. (2009). Right turns on green and pedestrian level of service: Statistical assessment. *Journal of Transportation Engineering*, *135*(4), 153–159.

Hubbard, S. M., Bullock, D. M., & Day, C. M. (2008). Integration of real-time pedestrian performance measures into existing infrastructure of traffic signal system. *Transportation Research Board*, *2080*(1), 37–47.

Hughes, R. (2018, March 2). *Indiana ranks 12th highest in the US in pedestrian deaths: Report*. Patch. https://patch.com/indiana/indianapolis/indiana-ranks-12th-highest-us-pedestrian-deaths-report

Jacobsen, P. L. (2015). Safety in numbers: More walkers and bicyclists, safer walking and bicycling. *Injury Prevention*, *21*(4), 271–275.

Lalani, N. (2001). Alternative treatments for at-grade pedestrian crossings. *ITE Journal*, *71*(9), 36.

Murphy, B. G., & Hummer, J. E. (2007). Development of crash reduction factors for overhead flashing beacons at rural intersections in North Carolina. *Transportation Research Record*, *2030*(1), 15–21. https://doi.org/10.3141/2030-03

NCSA. (2017a). *Bicyclists and other cyclists: 2015 Data* (Traffic Safety Facts Report No. DOT HS 812 382). National Highway Traffic Safety Administration. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812375

NCSA. (2017b, February). *Pedestrians: 2015 data*. (Traffic Safety Facts Report No. DOT HS 812 375). National Highway Traffic Safety Administration. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812375

Petritsch, T. A., Challa, S., Huang, H., & Mussa, R. (2007). *Evaluation of geometric and operational characteristics affecting the safety of six-lane divided roadways* (Project No. BD 543 RPWO 5). Florida Department of Transportation.

Redmon, T. (2014). *Pedestrian hybrid beacon guide-recommendations and case study*. Federal Highway Adminstration. https://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa14014/fhwasa14014.pdf

Retting, R. A., Ferguson, S. A., & McCartt, A. T. (2003). A review of evidence-based traffic engineering measures designed to reduce pedestrian–motor vehicle crashes. *American Journal of Public Health*, *93*(9), 1456–1463. https://doi.org/10.2105/ajph.93.9.1456

Retting, R. (2018). *Pedestrian traffic fatalities by state: 2017 preliminary data*. Governers Highway Safety Association. https://www.ghsa.org/sites/default/files/2018-02/pedestrians18.pdf

Sapp, D., Thelin, R., & Nunn, S. (2017). *Indiana crash facts 2017*. Indiana University Public Policy Institute. https://

trafficsafety.iupui.edu/crash-fact-books/Crash%20Fact%20Book_2017_Final%20Lo%20Res.pdf
Tian, Z. Z., Urbanik, T., Engelbrecht, R., & Balke, K. (2001). Pedestrian timing alternatives and impacts on coordinated signal systems under split-phasing operations. *Transportation Research Record*, *1748*(1), 46–54. https://doi.org/10.3141/1748-06
TRB. (2010). *HCM 2010: Highway capacity manual*. Transportation Research Board (TRB).
US DOT. (1995). *Nationwide personal transportation survey*. Bureau of Transportation Statistics.
World Population Review. (2018). *US states–ranked by population 2021*. Retrieved January 3, 2020, from https://worldpopulationreview.com/states

APPENDIX

Appendix A. HCS 7 Signal Timing and Phasing

Appendix B. Vehicle and Pedestrian Volumes

Appendix C. Pedestrian Origin-Destination Analysis Results

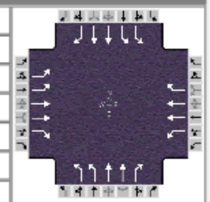
Appendix D. Signs, Markings and Other Countermeasures to Increase Pedestrian Safety

APPENDIX A. HCS 7 SIGNAL TIMING AND PHASING

Ronald Reagan Pkwy & US 40 (Plainfield, IN)

HCS 2010 Signalized Intersection Results Summary

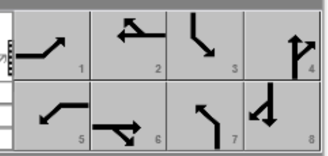
General Information				**Intersection Information**	
Agency				Duration, h	0.25
Analyst		Analysis Date	6/9/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Intersection	Ronald Reagan & US 40	Analysis Year	2020	Analysis Period	1> 7:00
File Name	Streets1.xus				
Project Description					



Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (*v*), veh/h	336	909	82	247	1065	337	167	698	213	274	515	314

Signal Information				
Cycle, s	120.0	Reference Phase	2
Offset, s	0	Reference Point	End
Uncoordinated	No	Simult. Gap E/W	On
Force Mode	Fixed	Simult. Gap N/S	On

Green	14.5	3.0	46.0	8.3	4.0	28.2
Yellow	4.0	0.0	4.0	4.0	0.0	4.0
Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	1	6	5	2	7	4	3	8

	EB	WB	NB	SB
Walk Interval, s	4.0	0.0	4.0	0.0
Pedestrian Clear Interval, s	44.0	0.0	40.0	0.0

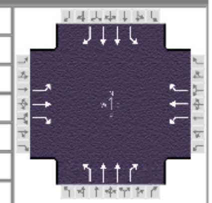
Level of Service (LOS)	E	C	C	F	D	C	E	D	D	E	D	D
Approach Delay, s/veh / LOS	40.9		D	45.4		D	52.7		D	46.8		D
Intersection Delay, s/veh / LOS	46.1						D					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	3.1	C	3.1	C	3.0	C	3.1	C

US 52 & Cumberland Ave (West Lafayette, IN)

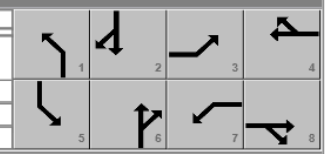
HCS7 Signalized Intersection Results Summary

General Information				Intersection Information	
Agency				Duration, h	0.25
Analyst		Analysis Date	6/28/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Urban Street		Analysis Year	2020	Analysis Period	1> 7:00
Intersection	US 52 & Cumberland	File Name	Streets1.xus		
Project Description					



Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (*v*), veh/h	106	267	161	108	272	164	241	1391	245	245	1602	241

Signal Information										
Cycle, s	120.0	Reference Phase	2							
Offset, s	0	Reference Point	End	Green	19.3	0.3	53.3	9.4	0.2	21.5
Uncoordinated	No	Simult. Gap E/W	On	Yellow	4.0	0.0	4.0	4.0	0.0	4.0
Force Mode	Fixed	Simult. Gap N/S	On	Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	3	8	7	4	1	6	5	2

	EB	WB	NB	SB
Walk Interval, s	4.0	0.0	4.0	0.0
Pedestrian Clear Interval, s	42.0	0.0	33.0	0.0

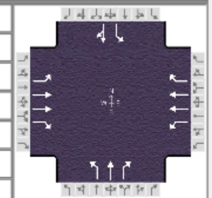
	EB			WB			NB			SB		
Level of Service (LOS)	E	D	D	E	D	D	E	D	C	E	F	C
Approach Delay, s/veh / LOS	52.2	D		52.5	D		43.9	D		71.5	E	
Intersection Delay, s/veh / LOS	57.1						E					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	3.0	C	3.0	C	2.4	B	2.4	B

US 31 & Home Ave (Columbus, IN)

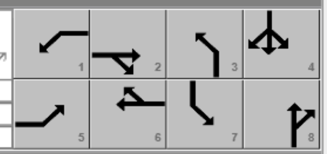
HCS7 Signalized Intersection Results Summary

General Information				Intersection Information	
Agency				Duration, h	0.25
Analyst		Analysis Date	5/5/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Urban Street	US 31	Analysis Year	2020	Analysis Period	1> 7:00
Intersection	US 31 & Home Ave	File Name	Streets1.xus		
Project Description					



Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (*v*), veh/h	44	1116	77	31	926	32	31	48	15	61	64	26

Signal Information										
Cycle, s	120.0	Reference Phase	2							
Offset, s	0	Reference Point	End	Green	4.0	0.7	57.3	4.0	1.3	36.6
Uncoordinated	No	Simult. Gap E/W	On	Yellow	4.0	0.0	4.0	4.0	0.0	4.0
Force Mode	Fixed	Simult. Gap N/S	On	Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	5	2	1	6	3	8	7	4

	EB	WB	NB	SB
Walk Interval, s	4.0	4.0	4.0	4.0
Pedestrian Clear Interval, s	33.0	32.0	38.0	38.0

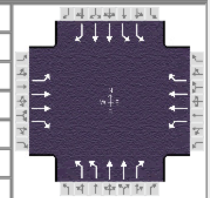
Level of Service (LOS)	E	C	B	E	C	B	E	C	C	C	C	
Approach Delay, s/veh / LOS	26.9		C	24.9		C	39.7		D	28.5		C
Intersection Delay, s/veh / LOS	26.7						C					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	2.4	B	2.3	B	3.0	C	3.0	C

Ronald Reagan Pkwy & Rockville Rd (Plainfield, IN) – Current Configuration

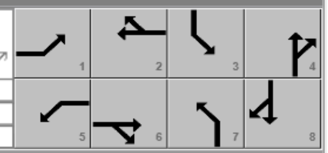
HCS7 Signalized Intersection Results Summary

General Information				Intersection Information	
Agency				Duration, h	0.25
Analyst		Analysis Date	7/19/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Urban Street	Rockville Rd	Analysis Year	2020	Analysis Period	1> 7:00
Intersection		File Name	Streets1.xus		
Project Description	Rockville Rd & Ronald Reagan Pkwy				



Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (v), veh/h	227	1074	271	285	1210	279	427	510	150	211	420	184

Signal Information										
Cycle, s	120.0	Reference Phase	2							
Offset, s	0	Reference Point	End	Green	18.3	4.0	46.6	9.9	2.1	19.1
Uncoordinated	No	Simult. Gap E/W	On	Yellow	4.0	0.0	4.0	4.0	4.0	4.0
Force Mode	Fixed	Simult. Gap N/S	On	Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	1	6	5	2	7	4	3	8

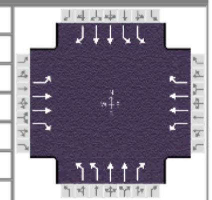
	EB	WB	NB	SB
Walk Interval, s	0.0	4.0	0.0	0.0
Pedestrian Clear Interval, s	0.0	35.0	0.0	0.0

Level of Service (LOS)	E	D	C	E	D	C	F	D	D	E	D	D
Approach Delay, s/veh / LOS	41.8		D	42.6		D	62.9		E	52.9		D
Intersection Delay, s/veh / LOS	48.2						D					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	3.1	C	3.1	C	3.0	C	3.0	C

Ronald Reagan Pkwy & Rockville Rd (Plainfield, IN) – Current Configuration – Early Left Turn

HCS7 Signalized Intersection Results Summary

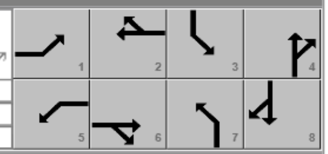


General Information				Intersection Information	
Agency				Duration, h	0.25
Analyst		Analysis Date	7/19/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Urban Street	Rockville Rd	Analysis Year	2020	Analysis Period	1> 7:00
Intersection		File Name	Streets1.xus		
Project Description	Rockville Rd & Ronald Reagan Pkwy				

Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (*v*), veh/h	181	1074	271	228	1210	279	427	510	150	211	420	184

Signal Information			
Cycle, s	120.0	Reference Phase	2
Offset, s	0	Reference Point	End
Uncoordinated	No	Simult. Gap E/W	On
Force Mode	Fixed	Simult. Gap N/S	On

Green	15.0	3.3	50.5	9.9	2.1	19.1
Yellow	4.0	0.0	4.0	4.0	4.0	4.0
Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	1	6	5	2	7	4	3	8

	EB	WB	NB	SB
Walk Interval, s	0.0	4.0	0.0	0.0
Pedestrian Clear Interval, s	0.0	35.0	0.0	0.0

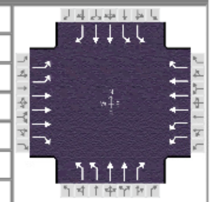
	EB			WB			NB			SB		
Level of Service (LOS)	E	C	C	E	C	C	F	D	D	E	D	D
Approach Delay, s/veh / LOS	35.5	D		36.5	D		62.9	E		52.9	D	
Intersection Delay, s/veh / LOS	44.4						D					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	3.1	C	3.1	C	3.0	C	3.0	C

Ronald Reagan Pkwy & Rockville Rd (Plainfield, IN) – Future 6-lane Configuration

HCS7 Signalized Intersection Results Summary

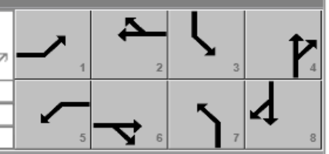
General Information				Intersection Information	
Agency				Duration, h	0.25
Analyst		Analysis Date	7/19/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Urban Street	Rockville Rd	Analysis Year	2020	Analysis Period	1> 7:00
Intersection		File Name	Streets1.xus		
Project Description	Rockville Rd & Ronald Reagan Pkwy				



Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (*v*), veh/h	227	1074	271	285	1210	279	427	510	150	211	420	184

Signal Information			
Cycle, s	120.0	Reference Phase	2
Offset, s	0	Reference Point	End
Uncoordinated	No	Simult. Gap E/W	On
Force Mode	Fixed	Simult. Gap N/S	On

Green	10.7	2.2	56.0	9.9	2.1	19.1
Yellow	4.0	0.0	4.0	4.0	4.0	4.0
Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	1	6	5	2	7	4	3	8

	EB	WB	NB	SB
Walk Interval, s	0.0	4.0	0.0	0.0
Pedestrian Clear Interval, s	0.0	35.0	0.0	0.0

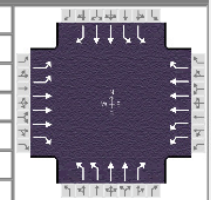
	EB			WB			NB			SB		
Level of Service (LOS)	E	C	C	D	C	C	F	D	D	E	D	D
Approach Delay, s/veh / LOS	27.4	C		27.1	C		62.9	E		52.9	D	
Intersection Delay, s/veh / LOS	38.6						D					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	3.0	C	3.0	C	3.5	C	3.5	C

Ronald Reagan Pkwy & Rockville Rd (Plainfield, IN) – Future 6-lane Configuration – Early Left Turn

HCS7 Signalized Intersection Results Summary

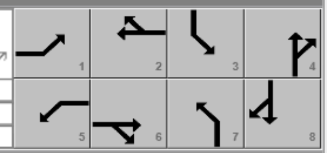
General Information				Intersection Information	
Agency				Duration, h	0.25
Analyst		Analysis Date	7/19/2020	Area Type	Other
Jurisdiction		Time Period		PHF	0.92
Urban Street	Rockville Rd	Analysis Year	2020	Analysis Period	1> 7:00
Intersection		File Name	Streets1.xus		
Project Description	Rockville Rd & Ronald Reagan Pkwy				



Demand Information	EB			WB			NB			SB		
Approach Movement	L	T	R	L	T	R	L	T	R	L	T	R
Demand (*v*), veh/h	181	1074	271	228	1210	279	427	510	150	211	420	184

Signal Information			
Cycle, s	120.0	Reference Phase	2
Offset, s	0	Reference Point	End
Uncoordinated	No	Simult. Gap E/W	On
Force Mode	Fixed	Simult. Gap N/S	On

Green	8.9	1.8	58.1	9.9	2.1	19.1
Yellow	4.0	0.0	4.0	4.0	4.0	4.0
Red	0.0	0.0	0.0	0.0	0.0	0.0



Timer Results	EBL	EBT	WBL	WBT	NBL	NBT	SBL	SBT
Assigned Phase	1	6	5	2	7	4	3	8

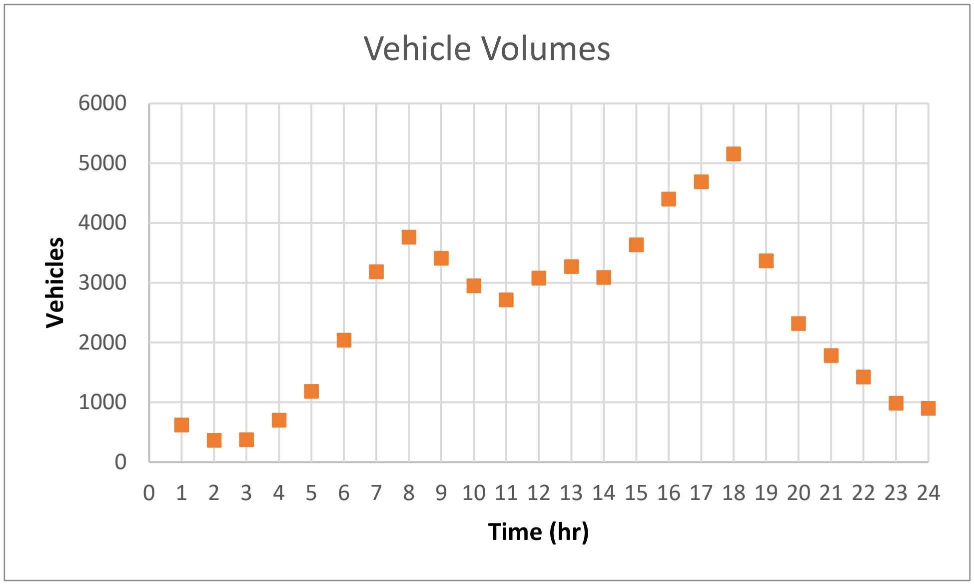
	EB	WB	NB	SB
Walk Interval, s	0.0	4.0	0.0	0.0
Pedestrian Clear Interval, s	0.0	35.0	0.0	0.0

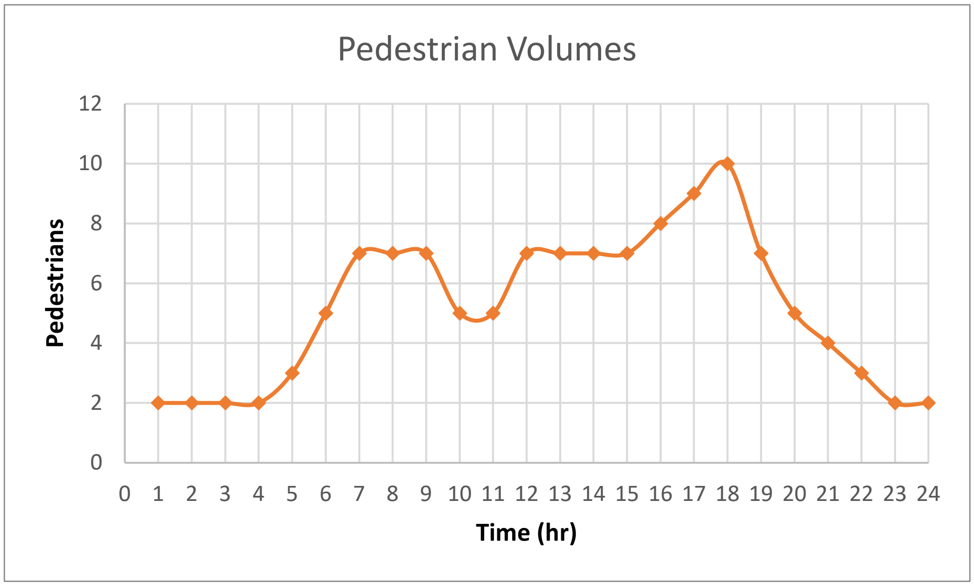
Level of Service (LOS)	E	C	C	E	C	B	F	D	D	E	D	D
Approach Delay, s/veh / LOS	25.3		C	25.3		C	62.9		E	52.9		D
Intersection Delay, s/veh / LOS	37.6						D					

Multimodal Results	EB		WB		NB		SB	
Pedestrian LOS Score / LOS	3.0	C	3.0	C	3.5	C	3.5	C

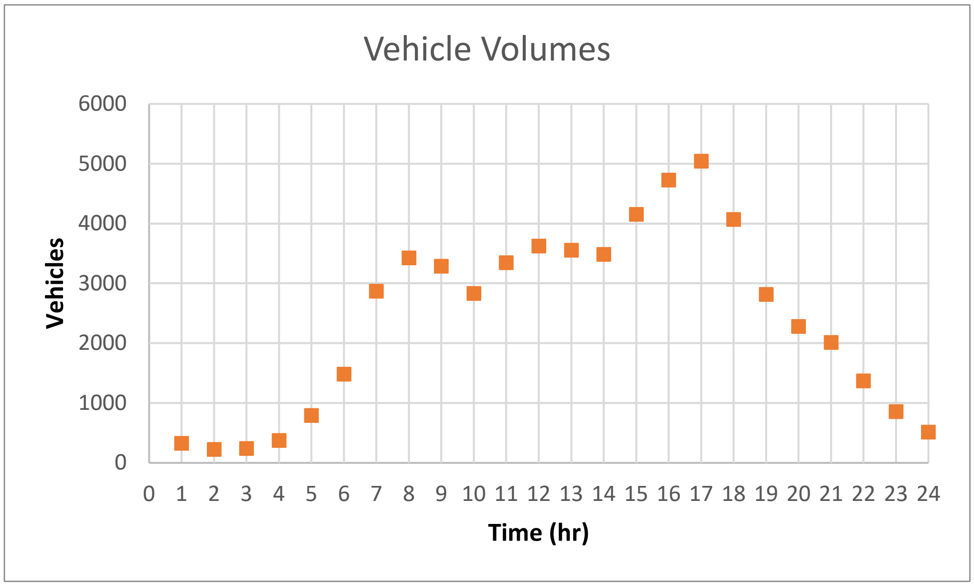
APPENDIX B. VEHICLE AND PEDESTRIAN VOLUMES

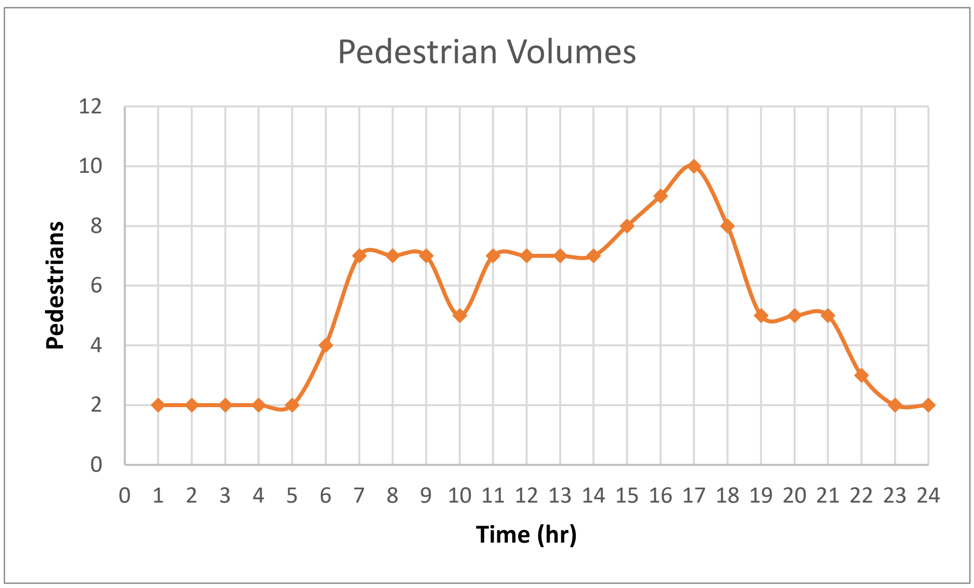
A. Ronald Reagan Pkwy & US 40 (Plainfield, IN)



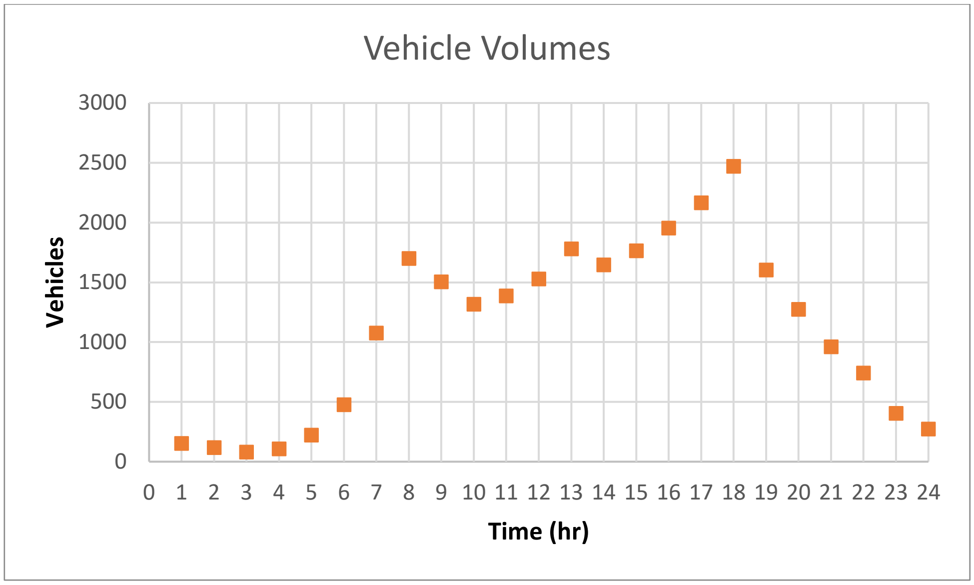


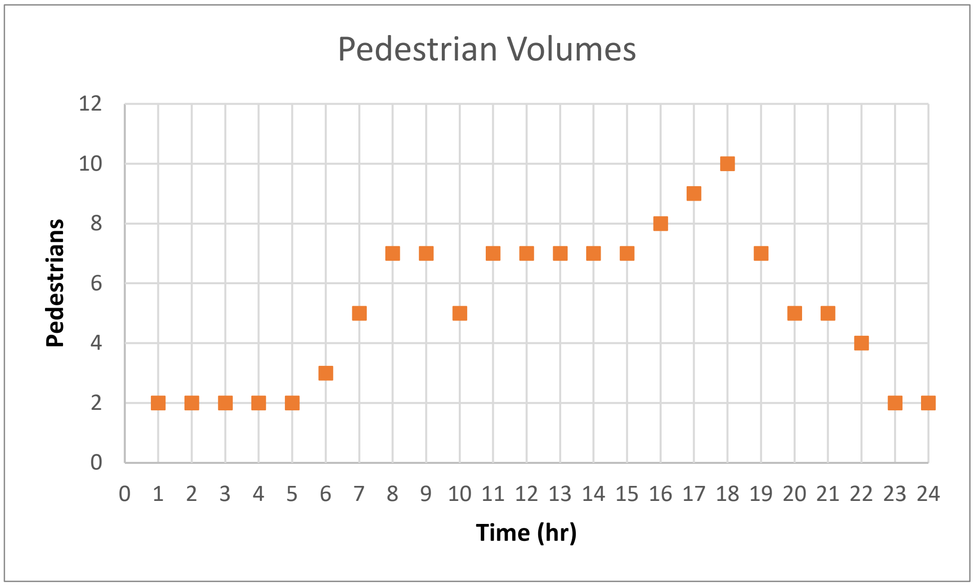
B. US 52 & Cumberland Ave (West Lafayette, IN)



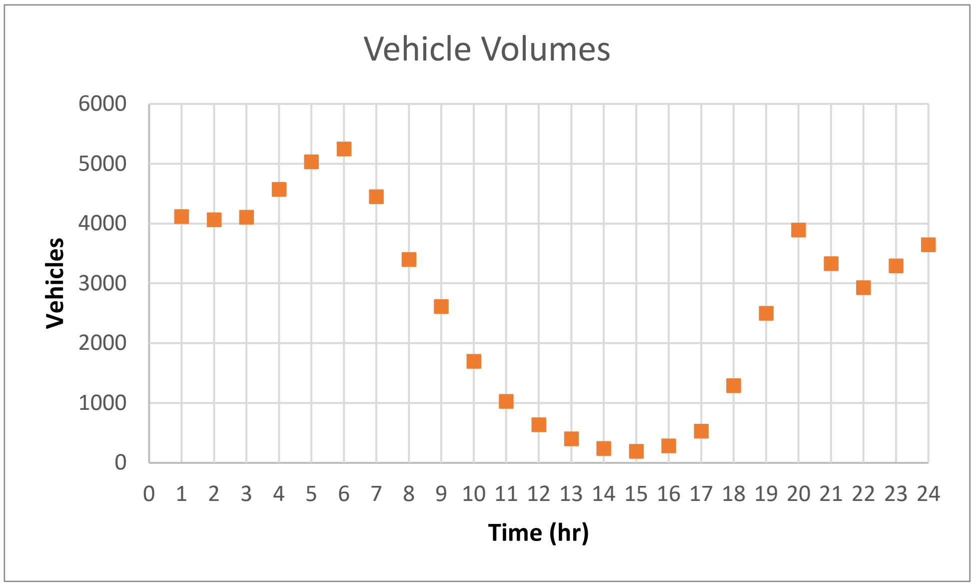


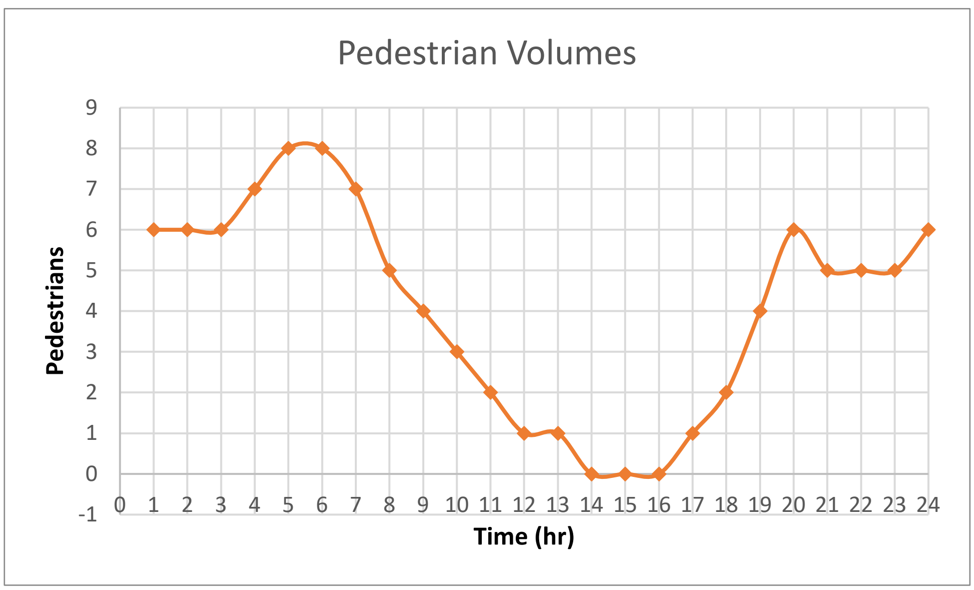
C. US 31 & Home Ave (Columbus, IN)





D. Ronald Reagan Pkwy & Rockville Rd (Plainfield, IN)





APPENDIX C. PEDESTRIAN ORIGIN-DESTINATION ANALYSIS RESULTS

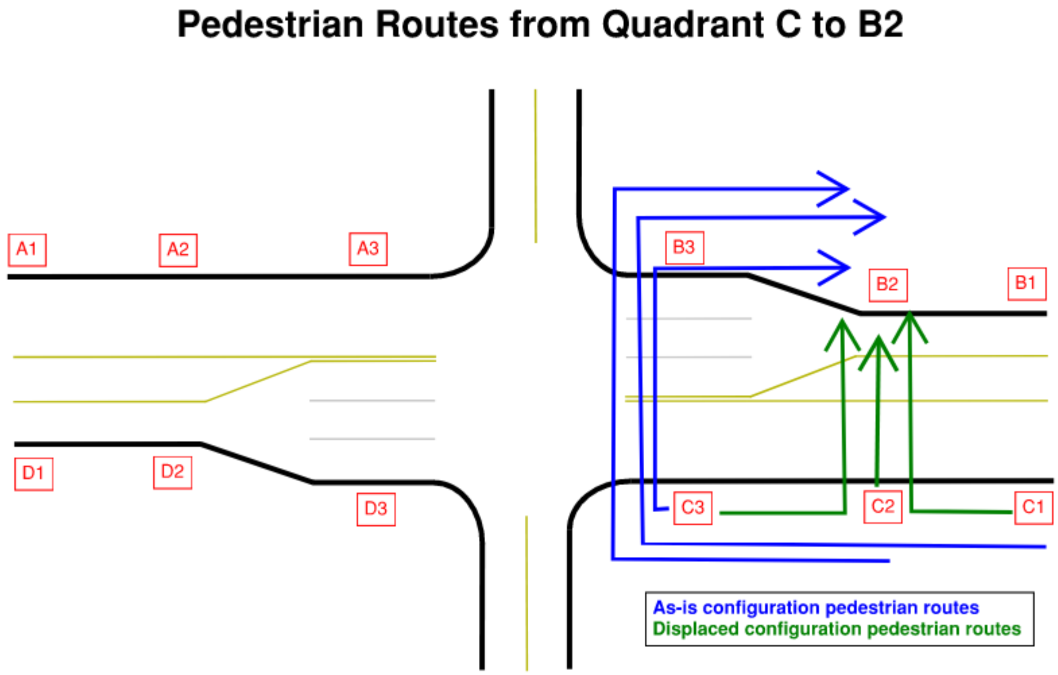


Figure C.1 Example pedestrian routes.

1. Ronald Reagan Pkwy and US 40 in Plainfield, IN (39°43'37.77"N, 86°20'13.24"W).

East-West Displaced

As-is Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	567.1	530.7	399.4	473.5	454.2	319.1
	2	533.2	497.4	370.9	441.4	418.4	289.0
	3	360.8	333.2	215.7	301.0	272.1	127.6
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	443.6	415.7	286.2	531.4	501.8	376.7
	2	404.7	375.9	252.2	506.0	469.6	339.6
	3	239.0	246.3	133.5	354.7	332.1	214.9
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	545.2	503.4	371.6	441.5	410.1	278.8
	2	501.0	470.9	333.8	415.9	382.6	251.6
	3	396.6	358.4	212.0	288.3	251.1	130.6
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	485.6	457.6	288.6	529.2	491.9	359.1
	2	449.4	421.2	260.7	502.9	456.9	334.1
	3	324.1	298.2	133.1	359.4	324.0	204.7

Displaced -PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	525.0	495.0	364.1	134.8	105.2	229.6
	2	493.8	464.5	331.1	104.0	60.8	211.9
	3	329.3	327.1	472.2	247.8	226.3	357.8
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	129.1	93.6	221.2	528.3	497.2	369.4
	2	101.2	60.9	196.2	501.9	470.6	336.8
	3	229.8	195.2	326.2	394.0	387.8	447.4
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	516.2	498.0	357.4	125.6	102.6	228.3
	2	489.5	467.4	341.2	102.9	65.4	186.9
	3	360.1	335.3	420.4	225.7	188.5	316.1
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	135.2	101.8	251.2	554.0	513.6	336.6
	2	89.5	57.5	228.8	511.2	477.5	342.3
	3	228.7	202.1	375.4	381.6	342.1	445.7

Displaced- two-stage -PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	559.3	510.2	384.7	146.8	119.4	251.3
	2	516.2	487.5	353.4	116.3	89.2	219.5
	3	326.4	325.9	466.1	268.7	242.6	375.9
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	136.5	106.9	228.3	537.6	500.9	378.2
	2	104.0	77.2	197.9	504.4	476.0	504.4
	3	241.4	202.2	314.6	408.7	383.0	470.6
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	514.0	501.0	381.5	155.8	129.3	251.8
	2	500.5	472.2	361.5	133.2	99.6	219.2
	3	359.4	337.9	495.9	254.4	222.9	334.0
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	125.3	99.9	258.1	582.7	546.4	377.2
	2	100.5	73.2	231.4	537.8	511.3	361.4
	3	238.3	211.2	365.6	411.4	365.5	485.0

North-South Displacement

As-is Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	550.5	518.1	349.0	460.2	442.7	278.5
	2	527.0	478.5	324.1	430.4	393.6	245.7
	3	397.7	361.2	210.5	337.5	301.5	129.2
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	473.5	440.6	274.1	522.0	518.4	351.3
	2	432.3	404.1	242.6	535.7	490.2	329.6
	3	322.5	285.2	136.6	389.6	375.3	218.3
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	561.8	501.1	454.2	462.9	444.6	317.9
	2	523.3	494.2	397.6	434.2	414.8	295.4
	3	356.2	344.7	235.8	280.0	249.4	134.7
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	478.7	452.2	318.3	532.3	497.7	383.5
	2	425.2	402.3	280.6	517.3	458.4	350.9
	3	276.6	255.3	131.6	337.4	312.3	206.2

Displacement-PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	115.0	95.9	191.4	526.6	483.9	357.0
	2	93.7	77.8	180.7	473.0	456.8	304.2
	3	188.3	174.2	296.1	371.2	351.6	424.8
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	121.1	108.9	209.8	517.4	498.8	361.0
	2	92.0	81.2	167.3	485.5	463.5	345.6
	3	206.9	173.4	277.2	391.8	361.1	425.4
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	511.9	515.0	405.4	122.5	97.9	242.4
	2	495.3	478.2	376.3	99.6	70.5	208.5
	3	344.8	324.6	429.4	255.0	221.6	354.2
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	539.1	500.9	384.7	132.8	103.3	240.9
	2	498.1	464.7	358.5	97.2	69.3	216.8
	3	350.1	329.1	453.3	243.6	211.3	359.9

Displaced- Two-stage -PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	122.8	93.9	189.9	488.0	446.0	356.6
	2	87.5	62.9	168.7	443.2	442.8	313.4
	3	180.3	170.7	282.1	359.2	327.7	435.0
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	124.7	92.1	196.9	485.1	455.6	353.1
	2	88.0	72.0	167.4	456.0	429.5	324.8
	3	208.2	174.3	271.0	360.5	326.9	425.8
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	476.9	479.2	368.4	125.4	102.2	217.7
	2	451.1	434.7	344.5	111.8	76.5	189.0
	3	335.9	315.3	425.0	212.6	177.2	276.1
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	480.2	460.2	356.7	138.3	103.7	212.0
	2	476.9	433.6	329.9	106.9	74.7	181.7
	3	336.9	311.8	414.0	216.1	186.7	290.1

2. US 52 and Cumberland Ave in West Lafayette, IN (40°27'37.41"N, 86°55'59.27"W).

As-is Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	654.3	668.3	491.2	686.9	646.5	411.9
	2	622.2	600.6	460.7	636.1	593.6	362.2
	3	391.4	343.2	220.3	392.3	367.7	139.9
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	467.2	456.7	300.6	646.1	609.8	369.3
	2	442.2	406.7	275.6	612.8	583.4	357.6
	3	303.2	275.3	139.1	500.6	459.7	228.2
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	659.4	588.8	366.9	479.1	447.6	305.3
	2	590.5	560.2	350.6	424.9	394.3	272.5
	3	481.5	442.2	217.8	285.3	270.0	142.0
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	679.8	658.5	427.7	681.0	641.1	505.4
	2	630.6	616.8	389.0	638.3	599.0	466.1
	3	390.3	372.3	139.9	379.0	355.7	216.9

Displaced-PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	712.1	713.1	505.0	149.0	114.6	351.9
	2	585.9	563.3	483.4	134.7	94.9	313.1
	3	327.5	362.3	528.7	359.6	306.0	492.8
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	113.0	122.6	303.4	710.7	595.0	408.4
	2	106.5	92.5	232.7	600.2	585.4	381.5
	3	248.0	231.8	350.5	495.8	459.7	532.1
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	716.5	631.0	315.6	148.5	105.3	201.5
	2	599.5	489.2	318.5	132.7	92.8	204.4
	3	618.4	481.8	478.1	182.5	235.5	329.3
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	226.9	109.5	287.7	639.7	587.0	489.8
	2	124.8	89.7	312.2	691.1	572.9	530.9
	3	287.4	284.3	472.7	387.5	371.1	474.8

Displaced- Two-stage -PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	712.1	697.4	552.0	224.9	202.1	425.2
	2	585.9	685.5	531.1	134.7	94.9	313.1
	3	327.5	453.0	573.0	359.6	306.0	492.8
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	241.9	200.8	336.2	706.4	699.5	480.0
	2	203.5	172.4	300.5	600.2	585.4	381.5
	3	345.9	231.8	435.9	495.8	459.7	532.1
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	697.2	588.8	366.9	221.4	197.8	337.3
	2	689.7	489.2	436.2	132.7	92.8	204.4
	3	566.8	538.2	575.8	182.5	235.5	329.3
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	226.9	185.2	414.0	639.7	587.0	489.8
	2	196.1	162.8	395.4	691.1	572.9	530.9
	3	419.5	385.8	472.7	379.0	355.7	216.9

3. US 31 and Home Ave in Columbus, IN (39°13'49.28"N, 85°54'40.01"W).

As-is Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	341.4	321.0	274.1	297.8	242.5	202.3
	2	246.2	290.8	337.9	264.5	246.1	177.3
	3	180.1	232.6	261.0	205.5	187.5	123.0
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	239.4	239.6	191.7	356.1	314.9	258.9
	2	235.0	193.3	166.1	339.3	289.1	245.5
	3	199.1	159.1	125.7	284.4	267.6	210.9
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	369.1	328.0	277.4	247.6	230.5	186.9
	2	335.7	297.4	246.3	220.4	199.2	160.8
	3	284.7	245.8	205.5	183.1	159.3	120.8
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	293.2	260.0	221.4	314.0	238.6	216.6
	2	238.6	216.6	176.8	302.1	264.4	246.9
	3	207.5	168.7	141.3	254.4	218.2	190.0

Displaced-PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	321.2	293.5	259.5	114.7	78.0	131.7
	2	299.9	277.3	227.8	84.3	70.4	118.5
	3	233.6	222.1	251.9	132.3	112.9	157.3
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	102.0	91.8	126.9	310.0	299.9	237.1
	2	90.6	67.9	104.6	299.3	270.8	214.2
	3	128.3	101.9	134.8	237.2	225.2	247.5
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	318.6	279.5	249.2	108.6	94.1	124.6
	2	289.5	268.7	216.3	84.6	65.8	97.4
	3	237.8	208.3	247.0	121.8	88.4	135.3
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	101.9	85.2	132.5	293.9	296.4	252.6
	2	73.4	55.4	104.3	283.0	266.1	209.8
	3	129.1	98.4	160.4	252.8	206.9	247.0

Displaced- Two-stage Midblock-PHB Pedestrian Travel Time (Seconds)							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	333.7	322.9	286.8	125.0	102.2	143.0
	2	307.9	300.0	246.5	95.9	78.5	121.6
	3	236.0	228.2	264.5	140.8	126.3	170.1
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	106.0	103.4	138.4	322.7	297.4	247.6
	2	92.6	73.4	110.4	332.7	285.0	219.3
	3	133.8	106.4	138.7	271.0	251.9	276.5
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	329.9	307.7	262.2	124.8	102.2	132.3
	2	304.2	290.0	219.0	94.6	74.7	103.0
	3	275.3	240.7	268.7	122.7	106.3	147.4
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	112.9	98.9	143.8	299.5	310.2	246.1
	2	77.1	68.5	108.1	286.9	260.7	218.5
	3	143.2	103.8	174.5	247.7	202.4	248.2

	Distance (ft)	
	As-is	**Displaced**
Average	627.5	468.4
Standard deviation	5.1	4.6

4. Ronald Reagan Pkwy and Rockville Rd in Avon, IN (39°45'49.37"N, 86°20'12.41"W).

As-is Pedestrian Travel Time (Seconds) – Current Configuration							
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
A	**1**	727.3	666.5	581.7	349.0	350.9	252.7
	2	668.0	593.6	586.6	380.4	351.9	235.0
	3	482.9	458.8	466.5	258.9	236.3	138.6
		C1	**C2**	**C3**	**D1**	**D2**	**D3**
B	**1**	440.3	312.9	267.5	656.3	648.3	517.0
	2	328.8	271.8	218.3	713.1	693.9	553.5
	3	241.2	226.8	170.2	604.4	494.5	514.6
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
C	**1**	785.2	704.7	671.6	397.9	353.1	284.0
	2	612.2	570.7	667.6	304.5	307.5	216.5
	3	584.1	563.9	443.7	236.1	221.8	147.2
		A1	**A2**	**A3**	**B1**	**B2**	**B3**
D	**1**	402.6	387.0	225.4	621.7	616.7	511.0
	2	403.6	369.2	237.8	613.5	634.6	583.3
	3	295.6	251.8	138.4	543.4	716.3	504.5
		A1	**A2**	**A3**	**B1**	**B2**	**B3**

Displaced-PHB Pedestrian Travel Time (Seconds) – Current Configuration							
		C1	C2	C3	D1	D2	D3
A	1	518.7	471.3	368.0	146.1	126.1	258.3
	2	486.8	436.9	342.6	125.0	302.9	208.9
	3	381.0	363.4	440.0	238.2	200.8	308.1
		C1	C2	C3	D1	D2	D3
B	1	154.8	128.4	205.5	491.3	465.5	334.8
	2	137.1	493.3	177.7	459.0	437.0	314.7
	3	216.5	181.1	257.0	409.3	383.6	380.7
		A1	A2	A3	B1	B2	B3
C	1	469.9	480.6	395.6	156.3	124.0	193.4
	2	454.2	450.9	347.4	124.0	277.9	173.4
	3	368.3	353.3	429.7	197.0	169.9	252.7
		A1	A2	A3	B1	B2	B3
D	1	138.5	118.1	228.1	517.9	494.8	408.7
	2	115.6	180.4	200.4	464.3	451.2	372.3
	3	219.5	195.0	299.0	343.6	316.5	382.8

Displaced- Two-stage -PHB Pedestrian Travel Time (Seconds) – Current Configuration							
		C1	C2	C3	D1	D2	D3
A	1	512.8	457.2	362.8	136.2	106.3	214.5
	2	478.4	434.2	341.8	111.3	99.9	187.3
	3	388.4	355.1	422.1	220.2	190.0	292.3
		C1	C2	C3	D1	D2	D3
B	1	151.8	120.6	198.2	513.8	468.7	337.1
	2	119.0	97.5	163.2	460.3	432.0	302.7
	3	194.1	165.3	235.7	408.8	387.3	365.9
		A1	A2	A3	B1	B2	B3
C	1	511.4	480.0	400.9	146.5	111.6	193.3
	2	474.7	441.1	363.7	115.5	90.8	160.0
	3	385.4	356.1	433.1	190.5	155.7	226.8
		A1	A2	A3	B1	B2	B3
D	1	151.5	115.6	224.1	510.5	504.4	427.3
	2	115.6	182.7	197.0	474.0	458.4	401.0
	3	216.3	193.4	307.5	334.2	314.8	383.0

As-is Pedestrian Travel Time (Seconds) – Future 6-lane Configuration							
		C1	C2	C3	D1	D2	D3
A	1	699.8	646.5	604.2	408.6	371.3	279.0
	2	806.5	662.0	556.3	359.3	307.4	232.5
	3	657.4	613.5	515.5	287.5	230.1	150.8
		C1	C2	C3	D1	D2	D3
B	1	388.2	342.1	273.2	895.3	824.0	738.0
	2	328.9	289.5	221.7	680.7	667.0	553.9
	3	269.6	231.5	164.2	734.1	672.4	570.9
		A1	A2	A3	B1	B2	B3
C	1	834.3	650.7	634.9	368.0	328.1	260.9
	2	757.7	670.9	609.7	327.1	291.5	221.0
	3	670.3	582.3	541.8	256.7	223.9	152.9
		A1	A2	A3	B1	B2	B3
D	1	398.5	381.0	282.9	739.0	648.5	612.4
	2	362.8	316.8	231.2	621.2	681.3	581.4
	3	277.7	235.0	148.8	538.5	599.0	488.4

Displaced-PHB Pedestrian Travel Time (Seconds) – Future 6-lane Configuration							
		C1	C2	C3	D1	D2	D3
A	1	556.6	517.3	425.3	203.6	165.8	253.0
	2	499.3	455.6	376.7	166.4	117.3	196.2
	3	439.6	388.1	436.5	252.0	203.8	282.6
		C1	C2	C3	D1	D2	D3
B	1	216.0	166.5	229.1	524.3	479.1	415.8
	2	163.1	126.0	192.1	497.7	452.4	380.1
	3	232.9	191.4	249.8	439.4	401.1	438.4
		A1	A2	A3	B1	B2	B3
C	1	527.7	512.4	418.5	168.2	133.0	198.1
	2	493.5	445.8	379.3	130.7	97.9	165.2
	3	437.5	388.5	482.0	197.6	168.5	238.8
		A1	A2	A3	B1	B2	B3
D	1	191.5	144.2	217.2	508.8	470.8	408.2
	2	146.3	97.1	174.7	452.1	423.6	369.1
	3	221.5	172.8	252.5	371.4	347.0	444.8

Displaced- Two-stage -PHB Pedestrian Travel Time (Seconds) – Future 6-lane Configuration							
		C1	C2	C3	D1	D2	D3
A	1	441.7	420.4	362.7	193.3	139.7	218.1
	2	412.9	378.9	309.3	127.2	86.0	169.9
	3	346.8	302.9	348.1	201.8	160.9	261.3
		C1	C2	C3	D1	D2	D3
B	1	178.8	131.5	197.0	465.7	422.4	341.8
	2	122.5	91.1	158.9	436.7	388.0	306.5
	3	183.4	152.2	217.6	345.7	300.3	365.2
		A1	A2	A3	B1	B2	B3
C	1	441.9	413.8	325.1	155.9	123.8	187.5
	2	426.2	383.4	288.5	114.4	83.0	150.1
	3	382.0	324.1	336.4	178.4	146.3	209.0
		A1	A2	A3	B1	B2	B3
D	1	211.1	149.2	233.8	473.9	434.5	365.3
	2	150.4	97.4	179.8	416.6	388.3	315.5
	3	223.0	172.9	266.2	328.0	300.9	348.6

	Distance (ft)	
	As-is	**Displaced**
Average	689.4	386.5
Standard deviation	323.6	240.2

APPENDIX D. SIGNS, MARKINGS AND OTHER COUNTERMEASURES TO INCREASE PEDESTRIAN SAFETY

This appendix presents strategies and in-use practices that may be used to increase pedestrian safety, some these strategies/practices may be appropriate at a displaced crosswalk. The first section presents all the countermeasures identified as part of FHWA's Safe Transportation for Every Pedestrian (STEP) initiative, which is part of FHWA's Every Day Counts (EDC) program. The second section presents a discussion of signs and markings that may be used to support pedestrian safety, including signs in the Manual on Uniform Traffic Control Devices (MUTCD). The third section presents a number of photos that illustrate applications, including those specified in the MUTCD as well as innovative applications that are not in the MUTCD. Some of the material presented in this appendix was released after the draft final report for this project was drafted (e.g., details about the STEP countermeasures), so the report narrative may not fully reflect the content of this appendix.

A. Countermeasures to Increase Pedestrian Safety in FHWA STEP Initiative

FHWA's STEP initiative identifies seven countermeasures that can be used to increase pedestrian safety (2020a).

1. Road diet
2. Pedestrian hybrid beacon (PHB)
3. Raised crosswalk
4. Rectangular rapid flashing beacons (RRFB)
5. Crosswalk visibility enhancements
6. Pedestrian refuge island
7. Leading pedestrian interval (LPI)

Each of the countermeasures is described below, followed by a brief discussion as to the expected applicability for a displaced pedestrian crossing. Additional information can be found in FHWA STEP resources (2020b).

1. **Road Diets.** Road diets reduce the roadway width by reducing the number of traffic lanes and/or the width of each lane. This increases pedestrian safety because it provides a shorter crossing distance for pedestrians (Figure D.1). Road diets also increase safety by reducing vehicle speeds. In some cases, road diets provide extra space for pedestrians in the space that was taken away from the original roadway. Road diets may be especially effective in suburban areas where they may reduce total crashes by 47%; in urban areas they may reduce crashes by 19% (FHWA, 2018a). An example of a road diet is shown below.
   - **Applicability for a displaced pedestrian crossing.** The displaced crossing is consistent with this concept since it allows the pedestrians to cross a reduced roadway width that does not include turn lanes since the displaced crossing is implemented upstream of the left and right turn lanes. It is probably not practical to reduce the number of through lanes on most arterials due to capacity needs for vehicles.

Figure D.1 Road diet (FHWA, 2018a).

2. **Pedestrian hybrid beacons** (PHBs) require vehicles to stop for pedestrians and are an intermediate option between RRFBs and a full pedestrian signal. PHB may be used in areas where pedestrian volumes are not high enough to warrant an installation of a full pedestrian signal. PHB can reduce pedestrian crashes by 55% (FHWA, 2018b). A PHB is shown in Figure D.2 below.
    - **Applicability for a displaced pedestrian crossing.** The displaced crossing is compatible with a PHB. The timing of the PHB for pedestrians can be coordinated with the arterial traffic signal timing to minimize disruption to corridor progression.

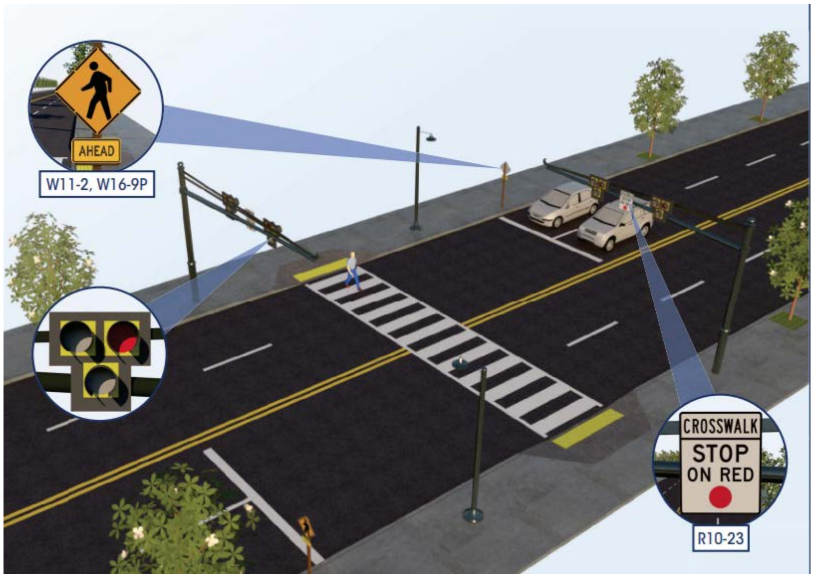


Figure D.2a Pedestrian hybrid beacon (FHWA, 2018b).

Figure D.2b Example of Pedestrian Hybrid Beacon in Phoenix AZ (pedbikeimages.org/Mike Cynecki).

3. **Raised crosswalks** may increase pedestrian conspicuity and reduce vehicle speeds, both of which support pedestrian safety. Raised crosswalks also allow pedestrians to cross at the same grade as the sidewalk. Raised crosswalks may reduce pedestrian crashes by 45% (FHWA, 2018c). A raised crosswalk is shown in Figure D.3 below.
    - **Applicability for a displaced pedestrian crossing.** A raised pedestrian crosswalk could potentially be implemented in conjunction with a displaced crossing. It would be important to carefully consider the benefits to pedestrians as well as the negative impact on vehicle speeds (and potentially corridor progression). A raised crosswalk that reduces vehicle speeds would affect vehicle speeds throughout the day, and may not be appropriate where arterial vehicle capacity and service are important considerations. Due to the negative impact on vehicles throughout the day, a raised crosswalk may not be appropriate at displaced crossings where pedestrian volumes are very low.

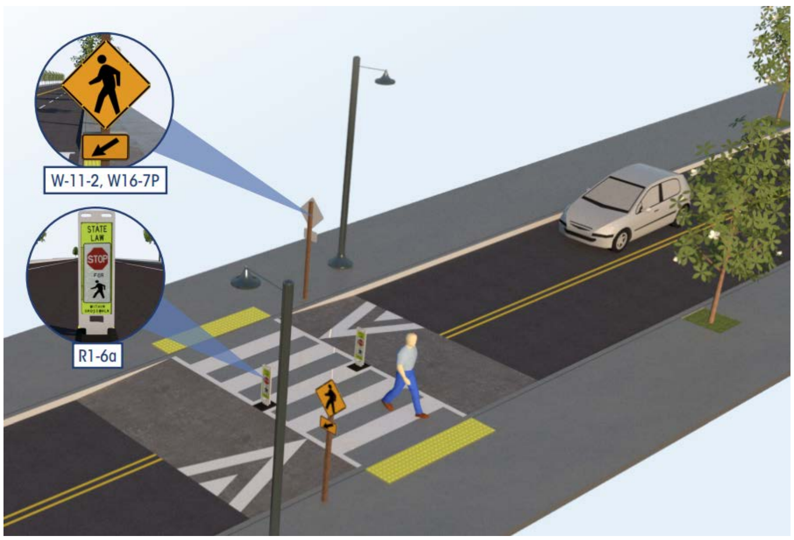


Figure D.3a Raised crosswalk (FHWA, 2018c).


Figure D.3a Raised crosswalk in Salt Lake City UT (bikepedimages.org/Dan Burden).

4. **Rectangular Rapid Flashing Beacons (RRFB)** are amber lights (usually LEDs) with an irregular flash patter for uncontrolled pedestrian crossing locations (e.g., midblock and/or trail crossings). RRFB may be activated by the user via a pedestrian push button or by automated detection. RRFB increase pedestrian safety since they significantly increase driver yielding behavior. RRFB can reduce pedestrian crashes by 47% (FHWA, 2018d). Note the use of warning signs and pavement markings to enhance driver compliance. An RRFB is shown in Figure D.4 below.
   - **Applicability for a displaced pedestrian crossing.** An RRFB could be used with a displaced crossing. FHWA has provided guidance for conditions where the PHB should be considered instead of the RRFB in *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations* (Blackburn et al., 2018). An RRFB may be a good choice at displaced crossings such as midblock intersections with trails.

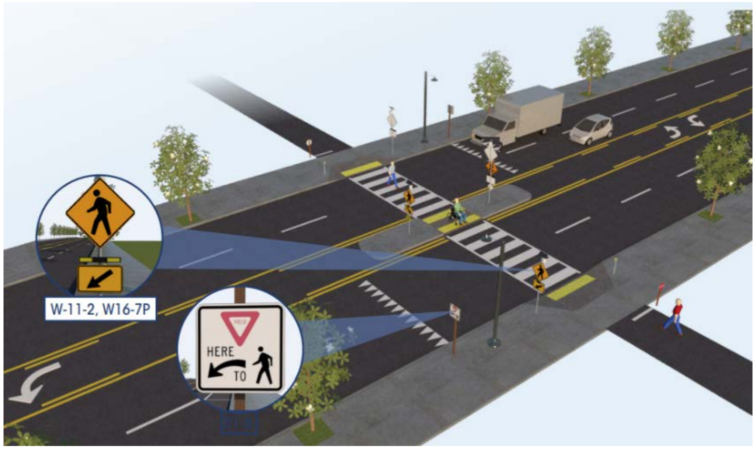


Figure D.4a Rectangular rapid flashing beacon (RRFB) (FHWA, 2018d).

Figure D.4b Rectangular rapid flashing beacon (RRFB) in Seattle WA (bikepedimages.org/Toole Design Group).

5. **Crosswalk visibility enhancements** include crosswalk lighting and enhanced signing and marking; these enhancements provide additional visual cues of the pedestrian crossing and remind drivers that pedestrians may be present. These visibility enhancements may be especially helpful for pedestrians crossing at night. Crosswalk visibility enhancements may reduce crashes by 23% to 48% (FWHA, 2018e). Crosswalk visibility enhancements are shown in Figure D.5a and Figure D.5b below.
   - **Applicability for a displaced pedestrian crossing.** Visibility enhancements such as crosswalk lighting, signing and marking are compatible and recommended for implementation with displaced pedestrian crossings. Lighting can increase pedestrian safety and comfort, as well as enhance the environment. Although costs will vary depending on a variety of factors, and average cost for in-pavement lighting is approximately $20,000 (range $6,000 to $40,000) and an average cost for street lighting is approximately $5,000 (range $500 to $15,000) (FHWA, n.d.a).

Figure D.5a Crosswalk visibility enhancements (FHWA, 2018e).

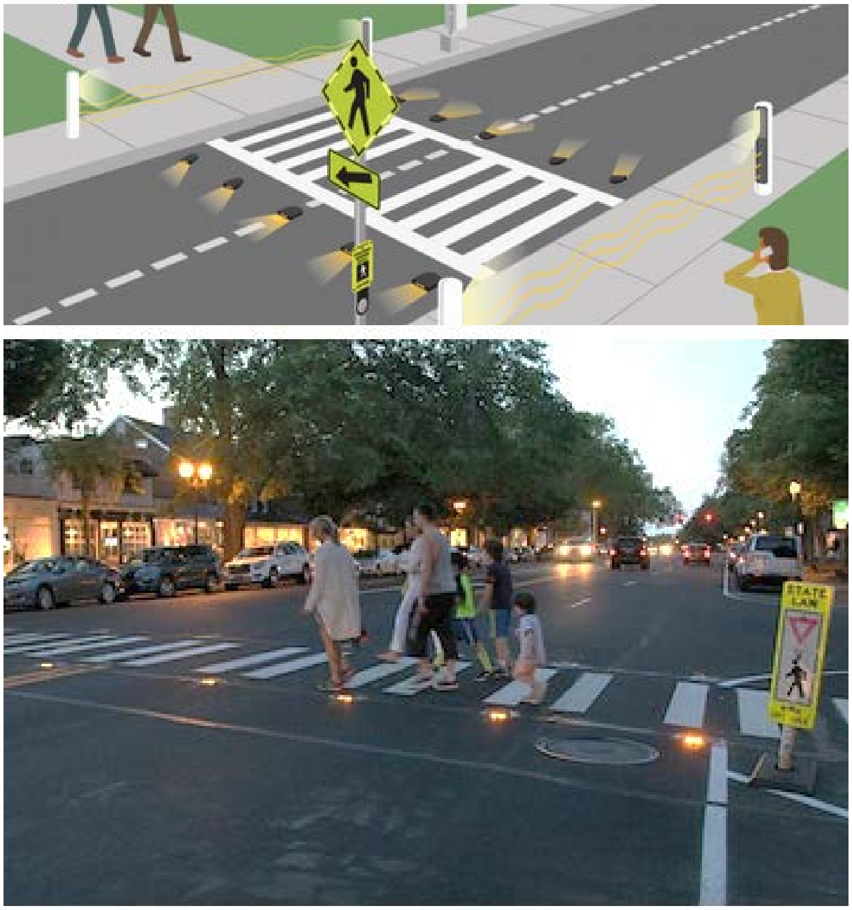


Figure D.5b Example of lighted crosswalk (Lightguard Systems, 2019).

Figure D.5b Example of street lighting to improved pedestrian safety at night (pedbikeimpages.org/Dan Burden).

6. **Pedestrian refuge islands** provide a safe place for pedestrians to stop, allowing the roadway to be crossed in two segments. This is especially helpful for large arterials and for pedestrians with limited mobility. Pedestrian refuge islands may reduce pedestrian crashes by 32% and are especially desirable for roads with four or more travel lanes, and where AADT is 9,000 or higher (FHWA, 2018f). A pedestrian refuge island is shown in Figure D.6 below (note the in-street pedestrian sign shown is only to be used at an unsignalized crosswalk). A median that forces pedestrians to face on-coming traffic also supports pedestrian situational awareness and increases the visibility of pedestrians for oncoming drivers.
   - **Applicability for a displaced pedestrian crossing.** Pedestrian refuge islands are recommended for implementation with a displaced crossing. Use of a displaced crossing may make a refuge island more feasible, since the roadway cross section for vehicles is reduced because it is upstream of the turning lanes. In this regard, the pedestrian refuge island may be synergistic with the road diet countermeasure. The pedestrian refuge island also enables a two-stage pedestrian crossing, which may support better corridor progression for vehicles.

Figure D.6 Pedestrian refuge island (FHWA, 2018f).

- **Refuge Island with Danish Offset.** At the refuge island, a Danish Offset ensures pedestrians are facing the next half of the traffic (lanes to be crossed). This countermeasure was found to address problems including pedestrians trapped between opposing lanes, pedestrian failure to yield to traffic, and pedestrian do NOT wait for acceptable gaps (Nambisan, & Dangeti, 2008).

Figure D.7 Pedestrian refuge island with Danish offset layout (Nambisan & Dangeti, 2008).

7. **Leading Pedestrian Intervals (LPIs)** provide pedestrians with a walk signal before the adjacent concurrent traffic turning left or right gets a green indication. The LPI is a low-cost adjustment to signal timing and often provides pedestrians exclusive use of the crosswalk for 3 to 4 seconds. The LPI increases pedestrian safety because it increases pedestrian visibility, reduces conflicts with turning traffic and improves the likelihood of driver yielding to pedestrians. An LPI can reduce pedestrian crashes by 13% (FHWA, 2019a). An LPI is shown in Figure D.7; although not shown, it may be appropriate to restrict right turns on red into the crosswalk or provide supplemental signs reminding drivers to yield to pedestrians.
   - **Applicability for a displaced pedestrian crossing.** The displaced crossing eliminates conflicts with turning vehicles by moving the crosswalk away from the intersection so an LPI would not be needed in many cases. If there is a driveway with a traffic signal adjacent to the displaced crossing, an LPI could be used.

Figure D.8 Leading pedestrian interval (LPI) (FHWA, 2019a).

B. Signs and Markings to Increase Pedestrian Safety

Signs and markings are a valuable tool to increase driver awareness and provide a warning of a displaced pedestrian crossing.

Signs

Standards for pedestrian signs are provided in the MUTCD. Although not mandatory, each of the STEP countermeasure illustrations (Figures D.1 through D.7) included warning signs. The W-11-2 is a diamond warning sign with a pedestrian symbol; this can be implemented for both directions of traffic and may be supplemented with a placard such as W16-9P or W16-7P, as shown in Figure D.8. W11-2 and W-119 are considered non-vehicular warning signs; W11-1, W11-15, W11-15P and W11-15a and considered vehicular warning signs and plaques. While warning signs are useful to increase driver awareness of pedestrians in areas that pedestrians are not expected, the unnecessary use of warning signs should be avoided since it may result in less respect for all signs.

Signs for unsignalized pedestrian crosswalks are shown in Figure D.9. All warning signs are yellow with black borders and legends; a fluorescent yellow-green may also be used, and the background color of the placard must match the background color of the warning sign that it supplements. For the unsignalized pedestrian crosswalk signs (e.g., R1-6, R1-6a, R1-9 and R1-9a), the STATE LAW legend is optional.

Traffic signs that may be used with traffic signals are shown in Figure D.10, pedestrian signs and plaques are shown in Figures D.11, and regulatory signs for bicycle facilities are shown in Figure D.12. Figure D.13 illustrates signs that could be used at the intersection to direct pedestrians to the displaced crosswalk. Additional example applications of standard MUTCD and innovative signs and markings are shown in the subsequent section, Example Applications.

W-11-2

W11-9

W11-1

W11-15 with optional placard W11-15P

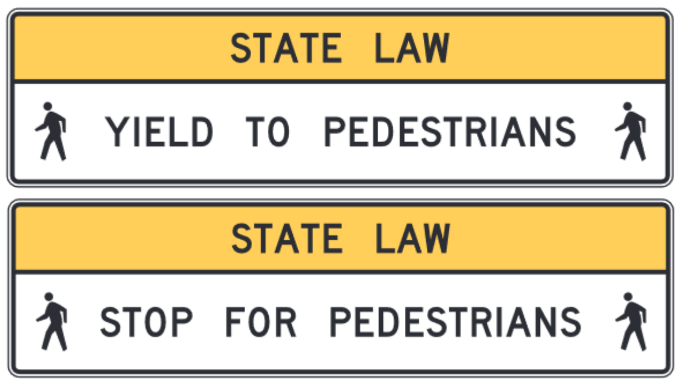
W11-15a

W16-7P (top) and W16-9P (bottom)

Figure D.9 Warning signs and placards (FHWA, 2019b).

R1-5, R1-5a, R1-5b and R1-5c (from left to right)

R1-6 (left) and R1-6a (right)



R1-9 (top) and R1-9a (bottom)

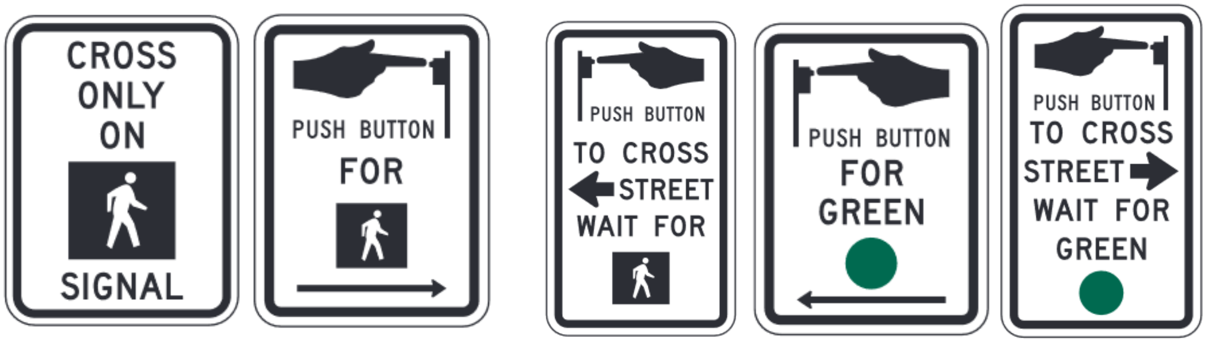
Figure D.10 Unsignalized pedestrian crosswalk signs (FHWA, 2019b).

R10-15

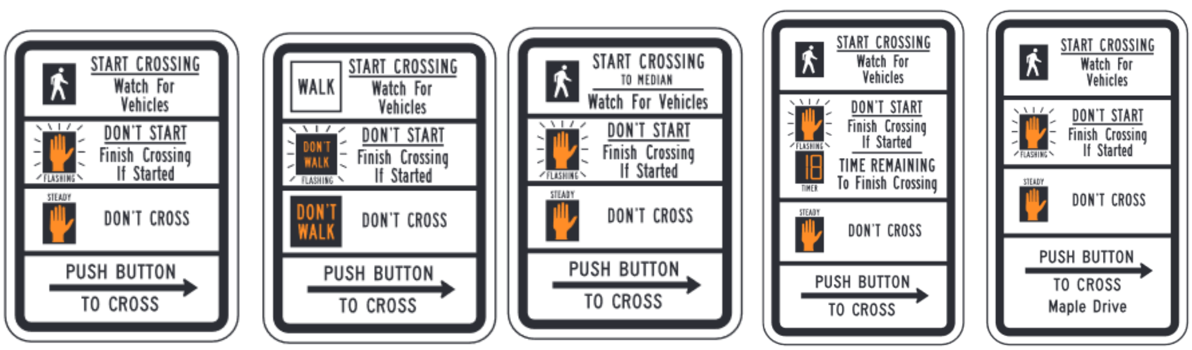
R10-23

Figure D.11 Traffic signal signs (FHWA, 2019b).

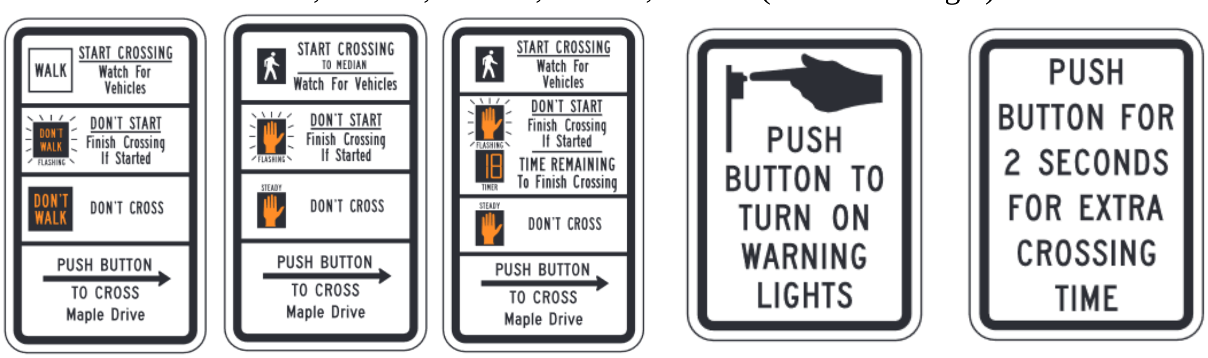
R9-2 R9-3 R9-3a R9-3bP-23



R10-2 (left) and 10-3 (right) R10-3a (left), R10-4 (center) and R10-4a (right)

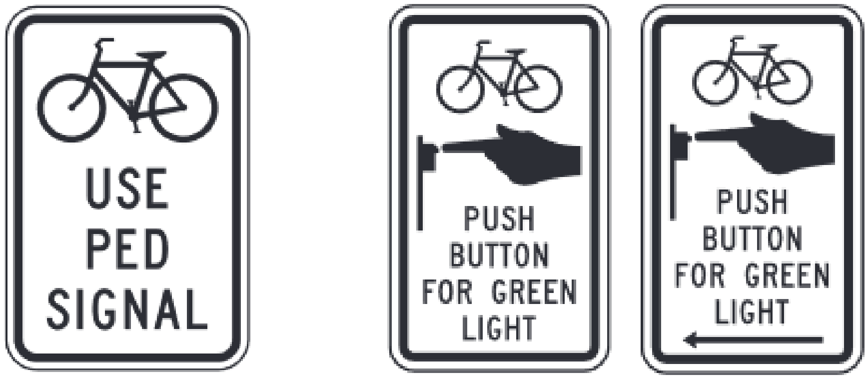


R10-3b, R10-3c, R10-3d, R10-3e, R10-3f (from left to right)



R10-3g (left), R10-3h (center), R10-3i (right) R10-25 R10-32P

Figure D.12 Pedestrian signs and plaques (FHWA, 2019b).



R9-5 R10-24 (left) and R10-26 (right)

Figure D.13 Regulatory signs for bicycle facilities (FHWA 2019b).

Figure D.14 Signs posted at the intersection may be used to direct pedestrians to a displaced crossing; this sign is in North Las Vegas NV (pedbikeimages.org/Dan Burden).

C. Pavement Markings

Pavement markings may also be used to support pedestrian safety. Pavement markings may include the white crosswalk markings and advance yield and stop lines for vehicles. An advance yield or stop line is the standard stop bar or "sharks teeth" yield markings placed 20 to 50 feet in advance of a marked crosswalk. Advance yield or stop markings are a low cost (perhaps $500) but effective solution. Combined with signs R1-6, R1-6a, R1-9, and R1-9a (the "STOP Here for Pedestrians" or "YIELD Here to Pedestrians" signs shown in Figure D.9), these advance yield or stop lines provide additional guidance to drivers and can greatly reduce the likelihood of a crash at an unsignalized midblock crossings (Zegeer et al., 2017). Increasing the distance between stopped vehicles increases pedestrian comfort and also increases safety since it increases visibility. As illustrated in Figure D.14a, on a roadway with multiple lanes, a vehicle stopped close to the crosswalk may limit the visibility of a pedestrian in the crosswalk for vehicles in adjacent lanes, resulting in a vehicle-pedestrian crash. The danger is exacerbated on roadways with higher speeds, since higher speeds are more likely to result in a pedestrian fatality or severe injury. Similarly, increasing the distance to the stop or yield line increases the capability of pedestrians to see oncoming vehicles, and take evasive action, if needed. Previous research has shown that the addition of an advance stop or yield line may reduce crashes by 25%, and may reduce conflicts between pedestrians and vehicles by 90%; a warning sign alone may reduce conflicts between pedestrians and vehicles by 67% (Zegeer et al., 2017). Advance stop and advance yield markings can also be combined with PHB and RRFB. An example of advance yield markings is shown in Figure D.14b.

D. Example Applications

The previous sections provided standard treatments including those endorsed by the MUTCD; this section presents example applications including signs and markings from the MUTCD, as well as alternative treatments, both innovative treatments in the US and international treatments, that have been implemented for pedestrian and bicycle facilities.

In some cases, states or cities may choose to request permission for approval to experiment with new pedestrian signs or markings. For example, FHWA approved a California experiment of a yellow LED boarder to standard pedestrian signal head to enhance motorist awareness of the presence of a pedestrian waiting to cross (FHWA, 2011). In other cases, cities or states may implement treatments in conjunction with the signs and markings in the MUTCD, or may find that explicit approval for an innovative treatment is not required.

A domestic scan of pedestrian safety features identified some of these examples, including the crosswalk treatments in Figure D.15, which use color and texture to increase conspicuity of the crosswalk. Figure D.16 illustrates use of textured pavement and colored pavers to enhance conspicuity. When considering textured pavements, it is important to consider the potential impact of wheelchair or users who may have problems with textured pavement. It may be useful to consider innovative treatments for bicycle facilities, as well, since bicycles and pedestrians share some of the same challenges in the roadway environment (e.g., they travel at lower speed, they are vulnerable road users since they are not protected by a vehicle, they may not be visible to drivers, and drivers may fail to yield the right-of-way).

Figures D.17, D.18 and D.19 illustrate the use of colored pavement to increase conspicuity and raise driver awareness. The pavement markings in Figure D.19 were installed with a private sector partner as part of a community pride effort.

Figure D.20 illustrates an innovative regulatory sign that emphasizes the need for vehicles to yield to bicycles when turning across the bike lane. The blue pavement marking in Figure D.15 is useful to illustrate the bike lane in these signs.

Figure D.21 illustrates the importance of tailoring signs to the user group, in this case, blind and Spanish speaking pedestrians. This may be appropriate based on the demographics of the neighborhood or a traffic generator serving the crosswalk.

Figures D.22 and D.23 illustrate signs targeted for pedestrians using symbols and text, respectively, to encourage awareness and safety. The sign in Figure D.24 reminds pedestrians to stop and look for oncoming traffic, and the sign in Figure D.25 provides a sobering reminder for pedestrian caution at this location.

Figures D.26 and D.27 illustrate pavement markings and signs warning drivers of the raised crosswalk; these examples are from Singapore and Washington State, respectively. Figures D.28 and D.29 illustrate the use of flags to increase driver awareness of pedestrians. Flags may be placed on the sign to capture driver attention (Figure D.28) or may be provided for pedestrians to carry while they cross the street (Figure D-29).

Figure D.30 illustrates the use of a curb extension to reduce the pedestrian crossing distance. The red and white bollards are an effective way to delineate the space for pedestrians. Bollards could be used in other applications to increase driver awareness. Signs such as those shown in Figures D.31, D.32 and D.33 can also be used to increase driver awareness of pedestrians; signs may use text and symbols to communicate the presence of pedestrians.

Similarly, Figures D.34, D.35, D.36, and D.37 illustrate the use of pavement markings, both text and symbols, to warn drivers and pedestrians of the potential for conflicts ahead. Similarly, Figure D.38 illustrates the use of signs to warn drivers and pedestrians of the potential for conflicts between turning traffic and pedestrians.

The examples are not intended to be proscriptive, however, they are intended to illustrate the broad range of ways that signs and pavement markings may be used to enhance pedestrian safety by increasing the conspicuity of a crosswalk and providing additional warnings to drivers and pedestrians.

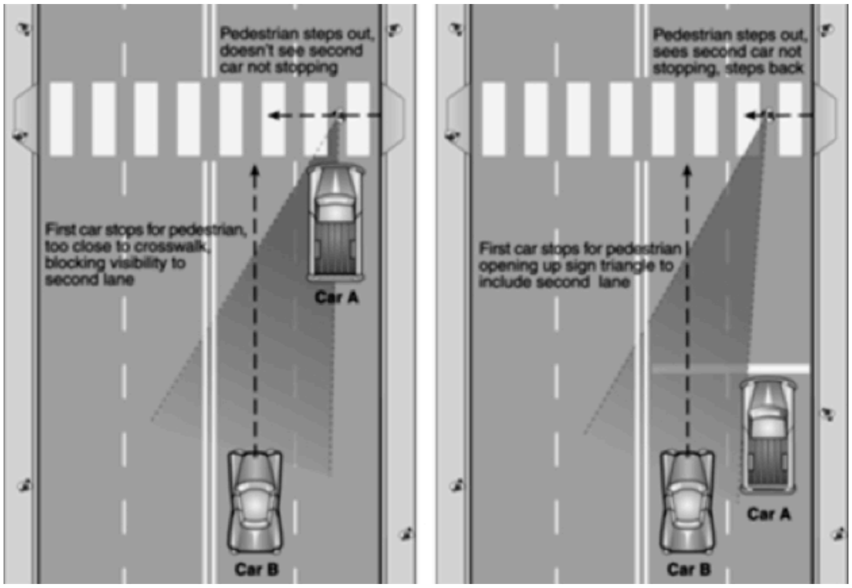


Figure D.15a Advance stop line increases visibility of pedestrians (FHWA, n.d.b).

Figure D.15b Advance yield markings at a midblock crosswalk (pedbikeimages.org/Toole Design Group).

Figure D.16 Innovative sidewalk treatment: Raised textured crosswalk (left) and brick crosswalk (right) in Charlotte, NC (Warren et al., 2006).

Figure D.17 Textured pavement, and colored paver design warns drivers of pedestrian and bike crossing in Delft, Netherlands (pedbikeimages.org/Laura Sandt).

Figure D.18 Blue pedestrian crossing (top left), Blue Bike lane in Portland, OR (bottom left) and green bike lane in Taipei, China; (pedbikeimages.org/Dan Burden; Warren et al., 2006; and pedbikeimages.org/Shawn Turner, respectively).

Figure D.19 Pink and green crossings in Chapel Hill NC and floral crosswalk in Decatur GA (pedbikeimages.org/Kristen Brookshire and pedbikeimages.org/Brandon Whyte)

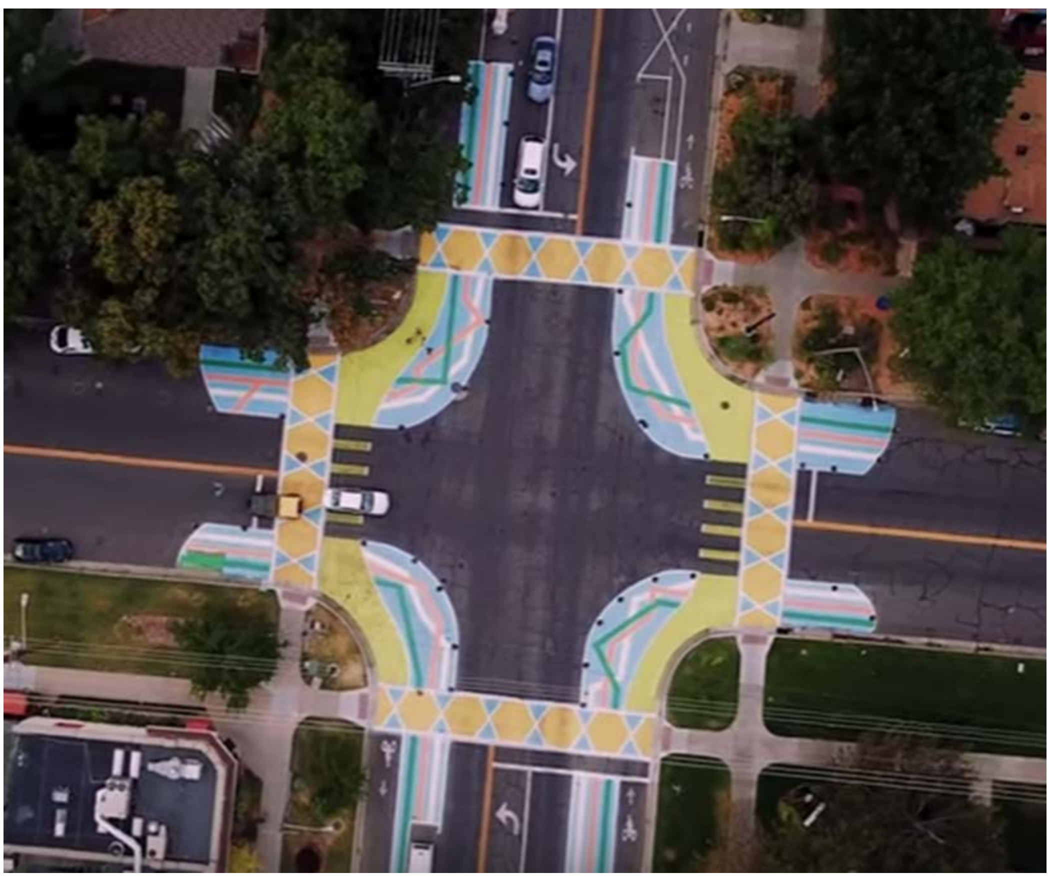


Figure D.20 Crosswalk markings in Salt Lake City, UT (Spin, 2019).

Figure D.21 Yield to bikes regulatory signs in Portland, OR (Warren et al., 2006).

Figure D.22 Pedestrian signs in Braille (left) and Spanish (top center and right) ensure service for blind and Spanish speaking pedestrians in Charlotte, NC (Warren et al., 2006).

Figure D.23 Sign to warn pedestrians of street traffic in Freiburg, Germany (pedbikeimages.org/Ryan Snyder).

Figure D.24 Sign encouraging pedestrians to use crosswalks in Memphis, TN (pedbikeimages.org/Dan Burden).

Figure D.25 Sign to warn pedestrians of street traffic in University Place, WA (pedbikeimages.org/Dan Burden).

Figure D.26 Sign to warn pedestrians of previous collision and phone number to provide information in London, UK (pedbikeimages.org/Laura Sandt).

Figure D.27. Raised crosswalk with pavement markings and offset (on the far side of the crosswalk in the right lane) increase pedestrian safety in Singapore (pedbikeimages.org/Larry Schaeffer).

Figure D.28 Pavement markings warn drivers of pedestrian crossing in Olympia, WA (pedbikeimages.org/Dan Burden).

Figure D.29 Sign and flag warn drivers of pedestrian crossing in Bellevue, WA (left) (pedbikeimages.org/Dan Burden).

Figure D.30 Flags for pedestrians to carry in crosswalk to increase visibility in Kirkland, WA (right) and US (pedbikeimages.org/Jan Moser and Dan Burden).

Figure D.31 Curb extension reduces pedestrian crossing distance (pedbikeimages.org/Michael King).

Figure D.32 Sign warns drivers of pedestrian crossing in Austin, WA (pedbikeimages.org/Dan Burden).

Figure D.33 Pavement markings warn drivers of pedestrian crossing in Mill Creek, WA (pedbikeimages.org/Dan Burden).

Figure D.34 Sign to warn drivers of pedestrian crossing in Redmond, WA (pedbikeimages.org/Carl Sundstrom).

Figure D.35 Pavement markings may be used to warn drivers (left) and trail users (right) of upcoming pedestrian crossings (two different locations) (pedbikeimages.org/Dan Burden).

Figure D.36 Pavement markings may be used to help differentiate bike lanes on paths with high volumes (Rails-to-Trails, n.d.).

Figure D.37 Pavement markings warn drivers of pedestrian crossing in Arcadia CA (pedbikeimages.org/Dan Burden).

Figure D.38 Pavement markings warn drivers of pedestrian crossing used by school children in Santa Rosa CA (pedbikeimages.org/Dan Burden).

Figure D.39 Signs warn turning traffic of pedestrians in New Center, MI (left) and pedestrians of turning traffic in Boston, MA (right) (pedbikeimages.org/Dan Burden and Laura Sand).

Appendix D References

Blackburn, L, Zegeer, C., & Brookshire, K. (2018, July). *Guide for improving pedestrian safety at uncontrolled crossing locations* (Report No. FHWA-SA-17-072). Retrieved February 22, 2021, from http://pedbikesafe.org/PEDSAFE/documents/STEP_Guide.pdf

FWHA. (2011, December 12). *FHWA's response letter approving the request to experiment.* Federal Highway Administration. Retrieved February 22, 2021, from https://mutcd.fhwa.dot.gov/documents/html/4_09_13_ex1.htm

FHWA. (2020a, March 19). *Safe transportation for every pedestrian (STEP)* [Webpage]. Federal Highway Administration. Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/

FHWA. (2020b, October 19). Safe transportation for every pedestrian (STEP)–resources. Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/resources/

FHWA. (2018a, June). *Road diet countermeasure tech sheet* (Report No. FHWA-SA-18-066). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/docs/techSheet_RoadDiet2018.pdf

FHWA. (2018b, June). *Pedestrian hybrid beacon (PHB) countermeasure tech sheet* (Report No. FHWA-SA-18-064). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/resources/docs/fhwasa18064.pdf

FHWA. (2018c, June). *Raised crosswalk countermeasure tech sheet* (Report No. FHWA-SA-18-063). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/docs/techSheet_RaisedCW2018.pdf

FHWA. (2018d, June). *Rectangular rapid-flashing beacon (RRFB) countermeasure tech sheet* (Report No. FHWA-SA-18-065). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/docs/techSheet_RRFB_2018.pdf

FHWA. (2018e, June). *Crosswalk visibility enhancements countermeasure tech sheet* (Report No. FHWA-SA-18-061). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/docs/techSheet_VizEnhancemt2018.pdf

FHWA. (2018f, June). *Pedestrian refuge island countermeasure tech sheet* (Report No. FHWA-SA-18-062). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/docs/techSheet_PedRefugeIsland2018.pdf

FHWA. (2019a, October). *Leading pedestrian interval (LPI) countermeasure tech sheet* (Report No. FHWA-SA-19-040. Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/ped_bike/step/resources/docs/fhwasa19040.pdf

FHWA. (2019b, June 12). *Manual on uniform traffic control devices (MUTCD) for streets and highways* (2009 version with changes 1 and 2 incorporated, May 2012). Retrieved February 22, 2021, from https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm

Nambisan, S. S., & Dangeti, M. R. (2008, September 15). *Pedestrian safety engineering and intelligent transportation system-based countermeasures program for reduced pedestrian fatalities, injuries, conflicts, and other surrogate measures* (Miami–Dade Site. Phase 2 Final Report). Retrieved February 28, 2021, from https://safety.fhwa.dot.gov/ped_bike/tools_solve/ped_scdproj/lasvegas/pedsafety_lasvegas.pdf

FHWA. (n.d.a). *Lighting and illumination*. PEDSAFE Pedestrian Safety Guide and Countermeasures. Retrieved February 23, 2021, from http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=8

FHWA. (n.d.b). *Advance yield/stop lines*. PEDSAFE Pedestrian Safety Guide and Countermeasures. Retrieved February 23, 2021, from http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=13

Lightguard Systems. (2019, February 6). *How to get a lighted crosswalk in your community*. Retrieved February 22, 2021, from https://www.lightguardsystems.com/how-to-get-a-lighted-crosswalk-in-your-community/

pedbikeimages. (n.d.). [An open source photo collection of pedestrian and bicycling scenes]. Pedestrian and Bicycle Information Center. Retrieved February 24, 2021, from pedbikeimages.org

Rails-to-Trails Conservancy. (n.d.) *Trail building toolbox* [Webpage]. Retrieved February 22, 2021, from https://www.railstotrails.org/build-trails/trail-building-toolbox/

Spin. (2019, October 3). *The spin space: Salt Lake City* [Photo screenshot]. YouTube. https://www.youtube.com/watch?reload=9&v=9Z7ouWAR-R8&feature=youtu.be

Warren, H., Chappell, D., & Chen, S.-R. (2006, September 1). *Innovative intersection safety improvement strategies and management practices: A domestic scan* (FHWA-SA-06-016). Retrieved February 22, 2021, from https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa06016/fhwasa06016.pdf

Zegeer, C., Srinivasan, R., Lan, B., Carter, D., Smith, S., Sundstrom, C., Thirsk, N. J., Zegeer, J., Lyon, C., Ferguson, E., & Van Houten, R. (2017). *Development of crash modification factors for uncontrolled pedestrian crossings treatments* (National Cooperative Highway Research Program Report 841). National Academies of Sciences, Engineering and Medicine. https://doi.org/10.17226/24627

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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