

**DEVELOPING GUIDANCE ON LEADING
PEDESTRIAN INTERVALS AND CURB
EXTENSIONS TO IMPROVE
PEDESTRIAN SAFETY AT SIGNALIZED
INTERSECTIONS**

Final Report

SPR 877



Oregon Department of Transportation

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by

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16. Abstract Improving pedestrian safety continues to be critically important to ODOT's mission to provide a safe and reliable multimodal transportation system. This research provides ODOT with refined tools to improve pedestrian safety at signalized intersections by developing enhanced guidance on when and where to implement Leading Pedestrian Intervals (LPI) either solely or in conjunction with complementary treatments such as Curb Extensions (CE). The guidance was informed by four major tasks: a literature review, a conflict-based field study, a driving simulator study, and development of an LPI suitability assessment tool. This research found that CEs decrease vehicle turning speed and shift conflicts from high/medium to low severity. For conflicts involving speed, both CEs & LPIs reduced conflicts, with the addition of the CE providing additional conflict reduction. The findings from this research support ODOT's Strategic Action Plan as well as ODOT design and practice documents.			
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SI* (Modern Metric) Conversion Factors
Approximate Conversions to SI Units

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	n	inches	25.4	millimeters	mm
Length	ft	feet	0.305	meters	m
Length	yd	yards	0.914	meters	m
Length	mi	miles	1.61	kilometers	km
Area	in ²	square inches	645.2	square millimeters	mm ²
Area	ft ²	square feet	0.093	square meters	m ²
Area	yd ²	square yard	0.836	square meters	m ²
Area	ac	acres	0.405	hectares	ha
Area	mi ²	square miles	2.59	square kilometers	km ²
Volume	fl oz	fluid ounces	29.57	milliliters	mL
Volume	gal	gallons	3.785	liters **	L
Volume	ft ³	cubic feet	0.028	cubic meters	m ³
Volume	yd ³	cubic yards	0.765	cubic meters	m ³
Mass	oz	ounces	28.35	grams	g
Mass	lb	pounds	0.454	kilograms	kg
Mass	T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)	oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	oC
Illumination	fc	foot-candles	10.76	lux	lx
Illumination	fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
Force and Pressure or Stress	lbf	poundforce	4.45	newtons	N
Force and Pressure or Stress	lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Measurement

** Volumes greater than 1000 L shall be shown in m³

SI* (Modern Metric) Conversion Factors
Approximate Conversions from SI Units

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	mm	millimeters	0.039	inches	in
Length	m	meters	3.28	feet	ft
Length	m	meters	1.09	yards	yd
Length	km	kilometers	0.621	miles	mi
Area	mm ²	square millimeters	0.0016	square inches	in ²
Area	m ²	square meters	10.764	square feet	ft ²
Area	m ²	square meters	1.195	square yards	yd ²
Area	ha	hectares	2.47	acres	ac
Area	km ²	square kilometers	0.386	square miles	mi ²
Volume	mL	milliliters	0.034	fluid ounces	fl oz
Volume	L	liters	0.264	gallons	gal
Volume	m ³	cubic meters	35.314	cubic feet	ft ³
Volume	m ³	cubic meters	1.307	cubic yards	yd ³
Mass	g	grams	0.035	ounces	oz
Mass	kg	kilograms	2.202	pounds	lb
Mass	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)	oC	Celsius	1.8C+32	Fahrenheit	oF
Illumination	lx	lux	0.0929	foot-candles	fc
Illumination	cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
Force and Pressure or Stress	N	newtons	0.225	poundforce	lbf
Force and Pressure or Stress	kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

For More Information see: <https://www.fhwa.dot.gov/publications/convtbl.cfm>

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1.0 INTRODUCTION AND MOTIVATION

In Oregon, there were 703 pedestrians injured and 125 pedestrians killed in 2022 (ODOT, 2024). Nationally, there were approximately 7,522 pedestrians killed, and 67,336 pedestrians injured. At the national scale, 85% of pedestrian fatalities occurred in urban areas, and 16% of them occurred at intersections (NHTSA, 2024). Additionally, failure to yield the right of way was a factor in 53% of pedestrian fatalities in 2022 (NHTSA, 2025). These pedestrian crash outcomes are the worst since 1981 when 7,837 pedestrians were killed. This alarming increase in pedestrian injuries and fatalities has prompted renewed emphasis on operational and geometric countermeasures, especially those specific to pedestrians, such as Leading Pedestrian Intervals (LPIs) and Curb Extensions (CEs).

The Oregon Department of Transportation (ODOT) implements both of these treatments at intersections in Oregon. However, there is limited guidance on how to implement these options (separately or in combination with other treatments) to maximize their efficacy. While the safety impacts of LPIs are well established, questions remain regarding whether curb extensions or no turn on red (NTOR) signs should be implemented in conjunction with LPIs and what the combined effects are. Questions also remain regarding where LPIs should be implemented; when right turns on red should be restricted; as well as what the appropriate LPI duration is, particularly for wider intersections. The use of LPIs reduces the available green time for other modes and users, which may have operational and safety issues that need to be quantified and interpreted. This study explores the integration of curb extensions' spatial advantages with LPIs' temporal benefits to promote pedestrian safety.

Improving pedestrian safety continues to be critically important to ODOT's mission to provide a safe and reliable multimodal transportation system. The objective of this research is to provide ODOT with refined tools to improve pedestrian safety at signalized intersections by developing enhanced guidance on when and where to implement Leading Pedestrian Intervals (LPI) either solely or in conjunction with complementary treatments such as Curb Extensions (CE). Additionally, ODOT needs a tool to quantitatively assess signal inventory to produce a priority list of signals suitable for LPI in order of greatest expected benefit. The guidance provided in this research was developed in a way that can be integrated into agency design and practice documents, and an effort was made for the LPI suitability assessment tool to be as comprehensive as possible based on a synthesis of the literature and the findings obtained from this research. Overall, this research supports the ODOT Strategic Action Plan's priority of a modern transportation system and the Strategic Action Plan's goal of safety. This research was informed by four major tasks: a literature review, a conflict-based field study, a driving simulator study, and an LPI suitability assessment tool. Chapters 2 to 5 provide an overview of the methodology and results from each of these tasks. Chapter 6 provides the conclusions, limitations, and future work for each task, as well as recommendations for practice derived from this research.

2.0 LITERATURE REVIEW

This chapter provides insights gained from a literature review conducted on 1) the relationship between LPIs and CEs on signalized intersection safety, 2) agency practices related to LPIs and CEs, 3) factors that impact LPI duration and effectiveness, and 4) recommended LPI supplements. The literature review revealed that both LPIs and CEs are known for giving pedestrians a head start at intersections. While LPIs are known for providing pedestrians with a head start “in time”, curb extensions are known for providing pedestrians with a head start “in space” (Saeidi-Razavi & Furth, 2023). They both share similar safety benefits and demonstrate great potential for improving pedestrian safety at signalized intersections. To gain a better understanding on existing guidance related to LPIs and CEs across the United States, policy and guidelines from 10+ cities and state DOTs were reviewed. Factors such as corner radius, street furniture in sight triangle, lane configuration, crosswalk setback, approach and turning speeds, as well as signal operation scheme, were identified as factors that may impact the duration and effectiveness of an LPI. Finally, research and guidance on recommended LPI supplements such as APS and NTOR were also reviewed. Ultimately, the insights gained from the literature review helped inform the methodology of the field and simulator studies, as well as the development of the LPI suitability assessment tool.

2.1 LEADING PEDESTRIAN INTERVALS

To this day, many traffic signals are timed to give turning vehicles a right turn permitted signal indication at the same time that pedestrians in the parallel crosswalk are given the walk signal. This operation may present conflicts between pedestrians and turning vehicles, particularly when motorists fail to yield. A Leading Pedestrian Interval (LPI), also known as a “head start” is an operational countermeasure that addresses this issue by allowing pedestrians to begin crossing the signalized intersection 3-7 seconds before turning vehicles get the green (Albee & Bobitz, 2021). Figure 2.1 illustrates an example of the functioning of an LPI.

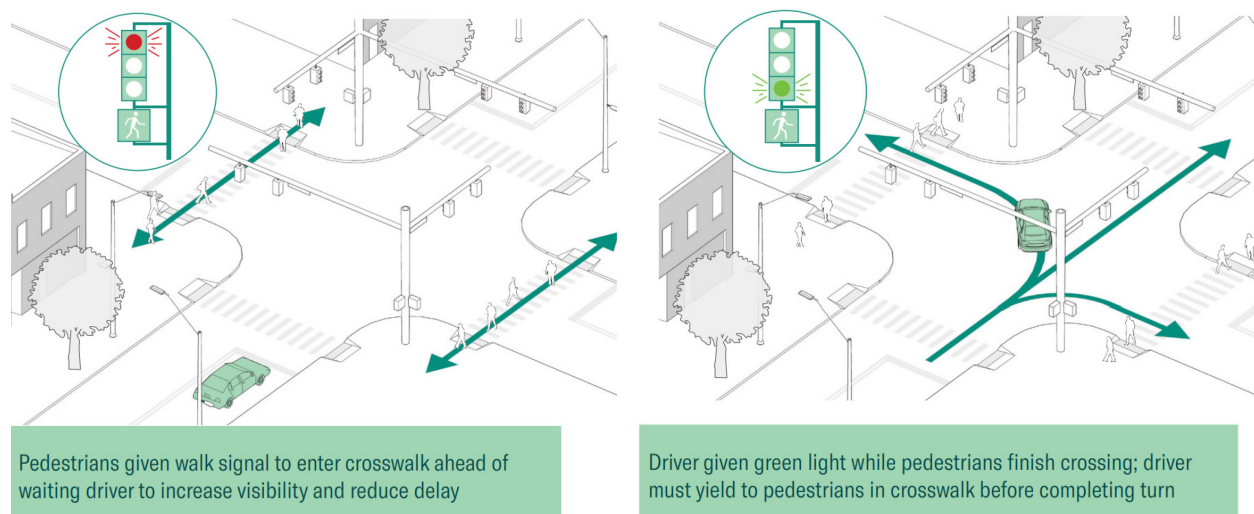


Figure 2.1. Leading Pedestrian Interval (City of Detroit, 2021)

According to Fayish & Gross (2010), LPIs have been described in the Manual on Uniform Traffic Control Devices (MUTCD) as early as 1961. This finding was confirmed during this literature review. Section 3F-7 of the 1961 Edition of the MUTCD, describes a pedestrian signal interval similar to that of LPIs, known as a “Leading Pedestrian Phase”, which is described as a “*signal phasing wherein an exclusive pedestrian phase, in advance of the minor-street vehicular phase, is provided for pedestrians crossing the main street only*” (MUTCD, 1961). However, the term “Leading Pedestrian Interval” was not used until the 1971 Edition of the MUTCD, where section 4D-7 describes the LPI as a “*signal phasing wherein an exclusive pedestrian interval, in advance of the vehicular indication shall be steady WALK*” (MUTCD, 1971). Additionally, specific guidance such as minimum required duration, suitable location, among other specific recommendations pertaining to LPIs were not directly described until the 2009 Edition of the MUTCD. Since then, LPIs have become more commonly known and implemented nationwide because of their proven safety benefits and low implementation costs. Described below are examples of those benefits.

2.1.1 Benefits

Pedestrians waiting at a corner of an intersection may sometimes fall on the blind spot of a turning vehicle whose sight may be compromised by the vehicle’s A-pillar (the roof structure that supports the windshield). By providing pedestrians with a head start, LPIs help increase their visibility by allowing them to establish themselves safely beyond the blind spot of the turning vehicle (GHSA, 2023). LPIs also assist pedestrians with slower crossing speeds when timed to allow them to cross at least one moving lane of traffic before the onset of conflicting vehicles (Staplin et al., 2001). Supported by multiple research studies, LPIs have shown to be effective in reducing pedestrian-vehicle conflicts (Zadey et al, 2025; Raha et al, 2025; Arun et al., 2023; Shangguan et al., 2023; Goughnour et al., 2021; Fayish & Gross, 2010; Van Houten et al., 2000). The Crash Modification Factor (CMF) for the LPI is 0.87, with a 13% reduction in vehicle-pedestrian crashes (Goughnour et al., 2018). Lastly, LPIs are considered a cost-effective alternative to decrease pedestrian crashes. The study by Goughnour et al. (2018) obtained a benefit-cost (B/C) ratio ranging from 1:207 to 1:517.

2.2 CURB EXTENSIONS

A common issue experienced at intersections with on-street parking is parked vehicles that block the view of both pedestrians and moving traffic. This visibility issue creates room for vehicle-pedestrian conflicts and is one of the major issues that curb extensions seek to address. Curb extensions (CEs), also known as bulb outs, bump outs, neck downs, or corner extensions are geometric improvements that increase ped visibility while visually and physically narrowing the road by extending a section of the sidewalk into the parking lane (AASHTO, 2018; NACTO, 2013). CEs are recommended at intersections with on-street parking, one-way streets, long crossing distances, visibility issues, speed limits of ≤ 40 mph, high pedestrian volume, near land-use contexts or facilities that attract pedestrians, or at intersections with known issues such as high turning speeds, crash history, or non-yielding behaviors (ODOT, 2025a; Arlington County, 2025; ODOT, 2024b; TxDOT, 2024; NYCDOT, 2024; City of Philadelphia, 2024; City of Columbus, 2023; KYTC, 2022; PBOT, 2022; T&ES Alexandria, 2022; GDOT, 2021; City of Minneapolis, 2021; MnDOT, 2021; City of Fairfax, 2021; City of Detroit, 2021; MDOT SHA, 2020; Seattle DOT, 2020; Thomas et al., 2016; and HDOT, 2013; SF Planning, 2010). Figure 2.2 shows a sample curb extension.

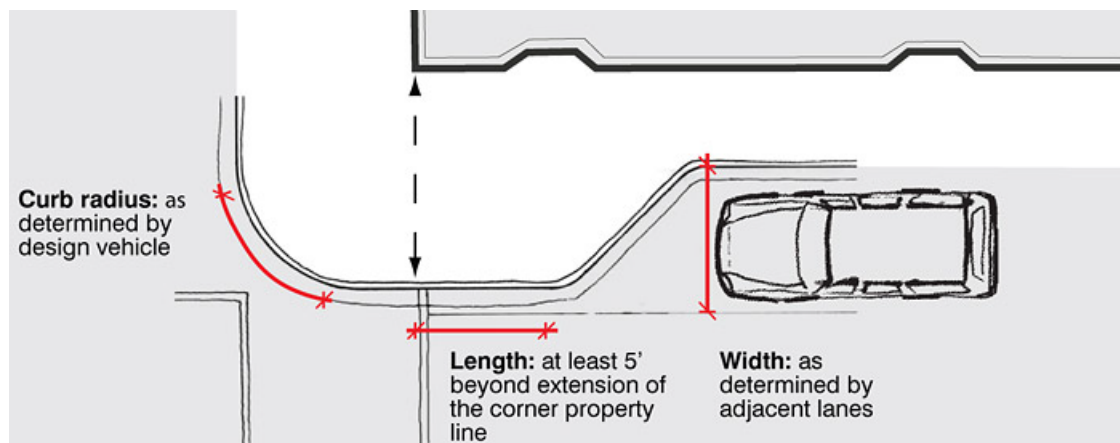


Figure 2.2. Curb Extension (SF Planning, 2010)

The dimensions of CEs may vary by project, intended purpose, or jurisdiction. However, after reviewing guidance documentation from 15+ jurisdictions, some common trends emerged. Listed below are some of the typical dimensions recommended for CEs.

Width – The width of the CE is typically recommended to be equal to the full width of the parking lane. However, to prevent the curb extension and associated gutter pan from intruding into a bike lane or travel lane, some jurisdictions recommend leaving a 1-2 ft offset from the edge of the parking lane (NYCDOT, 2025; TxDOT, 2024; City of Philadelphia, 2024; City of Columbus, 2023; T&ES Alexandria, 2022; KYTC, 2022; PBOT, 2022; MnDOT, 2021; City of Detroit, 2021; City of Minneapolis, 2021; Seattle DOT, 2020; SF Planning, 2010).

Length – At minimum, many jurisdictions recommend the length of the CE to be equal to the full width of the crosswalk (NYCDOT, 2025; TxDOT, 2024; T&ES Alexandria, 2022; Seattle DOT, 2020). However, the length could be longer, depending on the intended purpose of the CE

(e.g. enforce parking restrictions per local code, create space for ADA compliant curb ramps, sight line improvements, transit loading, stormwater management, etc.). Section 7.3.12.2 of the 7th Edition of the AASHTO Green Book says “where CEs are utilized at intersections, the extended curb should extend down the roadway to the point where legal parking is resumed. This helps deter motorists from parking too close to the intersection”.

Taper – The taper is the segment that connects the edge of the original curb with the edge of the CE. The steepness of this taper can vary depending on the needs and priorities of the jurisdiction. For example, MnDOT (2021) uses taper rates of 1:3 to 1:5 to accommodate snowplows and ease maintenance, however, they mention that with a flatter taper, vehicles may still attempt to park along the taper. SF Planning (2010) mentions that flatter tapers result in less space for pedestrians and landscaping, greater parking loss, and less sharply defined CEs. Where enforcing parking restrictions or making use of extra space is a major priority, steeper taper rates such as 1:1 or 1:2 are often used (City of Columbus, 2023; MnDOT; 2021; SF Planning, 2010). TxDOT (2024) recommends designers to consult with local jurisdictions regarding the operating characteristics of their maintenance equipment.

Curb Radius – A design memo on CEs from City of Columbus (2023) states that CEs should maximize pedestrian safety and comfort by minimizing the actual curb radius (curvature along the curb line) for the design vehicle, while providing adequate effective radius (curvature drivers follow when turning) for the check vehicle in accordance with local policy.

2.2.1 Benefits

By extending a portion of the sidewalk into the parking lane, CEs help to shorten the crossing distance, thus aiding pedestrians with slower crossing speeds and reducing exposure to conflicts (Anderson et al., 2022). Research studies have found that CEs help reduce pedestrian injuries and increase the likelihood of vehicles yielding to pedestrians (Stipancic et al., 2020; Thomas et al., 2016; Mead et al., 2014; Van Hengel, 2013; Johnson, 2005; King, 2000). CEs are listed in the 7th Edition of the AASHTO Green Book as a recommended measure to reduce vehicle–pedestrian crashes and increase pedestrian comfort at intersections. A study conducted by Ewing (1999) found that “narrowing”, which Ewing describes as a “speed control measure that uses a psycho-perceptive sense of enclosure to discourage speeding” (neckdowns highlighted as the most common type of street narrowing), resulted in a 2.6 mph speed reduction (this was most likely an approach speed). According to Ewing (1999), Hallmark et al. (2007), and the FHWA Traffic Calming ePrimer (FHWA, 2017), the effect of CEs, referred to as “neckdowns”, on vehicle speeds is limited because of the absence of either a pronounced vertical or horizontal deflection. However, Ewing argues that by tightening curb radii at the corner, pedestrian crossing distance is reduced and the speeds of turning vehicles are reduced. The FHWA Traffic Calming ePrimer (FHWA, 2017) suggests that CEs can be combined with a vertical speed control device (e.g. raised crosswalk) to achieve a greater reduction in vehicle speed.

2.3 RELATIONSHIP BETWEEN LPIS AND CURB EXTENSIONS

Both LPIs and CEs are known for giving pedestrians a head start at intersections. While LPIs are known for providing pedestrians with a head start “in time”, CEs are known for providing pedestrians with a head start “in space” (Saeidi-Razavi & Furth, 2023). They both share similar

safety benefits and demonstrate great potential for improving pedestrian safety at signalized intersections. Table 2.1 summarizes the safety benefits of both LPIs & CEs.

Table 2.1. Summary of Safety Benefits of LPIs and Curb Extensions

Safety Benefits	LPIs	Curb Extensions
Increases Pedestrian Visibility	Yes	Yes
Reinforces Pedestrian Right-of-Way	Yes	Yes
Shortens Crossing Distance	No	Yes
Delays Signal Operation for Vehicles	Yes	No
Reduces Vehicle Turning Speeds	No	Yes
Prevents Parking Near the Intersection	No	Yes
Decreases Pedestrian Exposure to Conflict Zone	Yes	Yes

2.3.1 Implementation Costs

2.3.1.1 *Curb Extension*

According to Module 3, Section 3.2 of the FHWA Traffic Calming ePrimer (FHWA, 2017), if drainage is not an issue, the typical cost for four corner extensions (a.k.a. curb extensions) ranges between \$8,000 and \$12,000. However, if drainage alteration is required, cost can increase to \$40,000. According to NHTSA's Report No. DOT HS 813 479 (Dunlap and Associates, Inc. et al., 2023) as well as FHWA's Safe Transportation for Every Pedestrian (STEP) Studio (FHWA, 2020), the average cost per curb is estimated at \$13,000. According to the FHWA's Pedestrian Facilities Users Guide, some examples of factors that may influence the cost of a curb extension include: the curb extension design (e.g., size), site conditions, drainage requirements, utility pole/controller box relocation, etc. (Zegee et al., 2002).

2.3.1.2 *Leading Pedestrian Interval*

According to Florida DOT's Statewide Guidelines for Implementing LPIs, the cost of implementing LPIs is very low as it mostly requires time and effort, assuming that the existing signal can be easily re-timed without the need for controller or signal upgrades (Lin et al., 2017). In a study by Goughnour et al. (2018), New York City, NY estimated that installing an LPI at a single intersection would cost \$1,200, primarily due to staff time (collecting ped & vehicle counts, conducting field investigation, performing traffic capacity analysis, preparing NYC's database for LPIs, and implementing the LPI timing in the field). This does not include the cost of controller or signal upgrades, Accessible Pedestrian Signals (APS), No Turn on Red (NTOR) signs, or Yield to Pedestrian signs. In the same study, Charlotte, NC reported that their costs range widely due to their policy of

accompanying an LPI conversion with installing APS to meet accessibility requirements. Their low-end cost was \$200 (staff time) and high-end cost was \$50-100k (major upgrades). According to the 2024 NYC DOT APS Program Status Report, the cost of installing APS at an intersection can range greatly depending on complexity. However, for 2023 installations in New York City, the cost per intersection averaged approximately \$66,600 (NYCDOT, 2024).

2.3.2 Similarities

One of the similarities that both LPIs and CEs share is that they both reduce the amount of time that a pedestrian is exposed to conflicting traffic. Both of these countermeasures also increase the visibility of pedestrians by allowing them to safely establish themselves within the crosswalk, thus reinforcing their right-of-way during a crossing maneuver. They both reduce pedestrian-vehicle conflicts, and they both benefit pedestrians who may need more time to cross or a shorter crossing distance at an intersection. Lastly, LPIs and CEs are both recommended by the National Association of City Transportation Officials (NACTO) as pedestrian safety countermeasures, and as potential complements to each other (NACTO, 2013). As previously mentioned, the cost of implementing LPIs and CEs is highly dependent on the existing conditions of the intersection. Both provide similar safety benefits, but the main difference is how they help reduce pedestrian-vehicle conflicts. One does so through geometric design, while the other does so through signal timing.

2.3.3 Differences

One of the main differences between LPIs and CEs is the type of protection they provide. As previously mentioned, LPIs provide a head start “in-time” while CEs provide a head start “in space” (Saeidi-Razavi & Furth, 2023). LPIs are helpful in preventing pedestrian-vehicle conflicts by delaying the green signal indication for conflicting turning vehicles. They may provide pedestrians with additional time to position themselves within the crosswalk, but they do not geometrically shorten the distance that pedestrians need to cross. On the other hand, CEs shorten the length of the crosswalk, but if no LPI is present, turning vehicles will turn concurrently with the pedestrian walk indication, and the driver’s yielding behavior would be based on the visibility of the pedestrian and the yielding compliance. Additionally, the geometric configuration of a CE may reduce the turning speed of vehicles by decreasing the curb radii, while the LPI may have little to no impact on the vehicle’s turning speed. Nevertheless, the turning needs of emergency, maintenance, and heavy vehicles need to be considered when implementing CEs. Overall, LPIs are less costly than CEs and quicker to implement provided that the controller and other hardware can support it.

2.4 AGENCY PRACTICES RELATED TO LPIs & CURB EXTENSIONS

Across the nation, many agencies have developed guidelines, policies, and best practices regarding the implementation of LPIs and CEs. Table 2.2 shows a summary of guidelines, policies, and practices used in different states and cities across the United States. Note: other jurisdictions not included in the table may also have LPI or CE guidelines in place and are referenced in other sections of this report. However, only 10 states with documentation for both LPIs & CEs that were easy to locate were summarized in the table.

Table 2.2. LPI & Curb Extension Guidelines, Policies, and Practices by State

State	Leading Pedestrian Intervals	Curb Extensions
Oregon	LPI Guidelines: Factors considered include conflict history, poor visibility, T intersections, one-way streets, pedestrian and vehicle volumes, impacts to operations and delay for all modes, and illumination conditions, according to 2024 ODOT Traffic Signal Policy & Guidelines, section 5.1 (ODOT, 2024c). LPI Policies: “Where LPIs are incorporated, regions should install APS to provide a non-visual cue that a walk phase has begun”, according to section 5.3.2 of the 2024 ODOT Traffic Signal Policy & Guidelines (ODOT, 2024c). “Regions may implement LPI using region signal operations engineer authority and shall notify state traffic operations engineer’s office of LPI deployments”, according to section 5.1 of the 2024 ODOT Traffic Signal Policy & Guidelines (ODOT, 2024c). LPI Practices: The LPI is the Portland Bureau of Transportation’s (PBOT) default practice at new or upgraded traffic signals on the High Crash Network, as mentioned in section 3.3.3. of the 2025 PBOT Traffic Design Manual (PBOT, 2025). This research was proposed to support ODOT’s & PBOT’s implementation.	CE Guidelines: Factors considered include areas with on-street parking, slower speed compact areas such as Special Transportation Areas (STAs), downtown or commercial business districts, according to section 506.17 of the 2025 ODOT Highway Design Manual (ODOT, 2025a). CE Policies: “CE design at proposed locations must meet process and criteria outlined in ORS 366.215 and must meet freight mobility needs.” And CEs can be used to enforce ORS 811.550.17 and ORS 811.550.18., according to section 506.17 of the 2025 ODOT Highway Design Manual (ODOT, 2025a), and section 310.3 of the 2024 ODOT Traffic Manual (ODOT, 2024b). CE Practices: Sections 506.17, 703.4.2, and 830.2 of the 2025 ODOT Highway Design Manual (ODOT, 2025a), and section 4.5 of the 2025 PBOT Traffic Design Manual (PBOT, 2025) provide design guidance.
California	LPI Guidelines: Factors considered include collision history, pedestrian crossing volumes, vulnerable populations, T-intersections, one-way streets, and intersection visibility, according to the 2021 CalTrans LPI Implementation Guidelines (CalTrans, 2021). LPI Policies: According to section 21450.5 of the CA Vehicle Code (CA VEH, 2025), “Upon first placement or replacement of a state-owned or operated traffic-actuated signal, a traffic-actuated signal shall be installed and maintained to have an LPI, and shall include the installation, activation, and maintenance of an APS and detector that complies with sections 4E.08 to 4E.13 of the CA MUTCD”. And according to section 21456 of the CA Vehicle Code (CA VEH, 2025), “Except as otherwise	CE Guidelines: Factors considered include urban conventional highways and rural main streets with posted speeds of 35 mph or less, according to section 303.4 of the 2025 CalTrans Highway Design Manual (CalTrans, 2025). CE Policies: According to section 303.4 of the 2025 CalTrans Highway Design Manual, “CEs are considered pedestrian facilities and as such, compliance with DIB 82 – Pedestrian Accessibility Guidelines for Highway Projects, is required”... “CEs are not to extend into Class II Bikeways (Bike Lanes)”... And the corner curb radii

State	Leading Pedestrian Intervals	Curb Extensions
	directed by a bicycle control signal described in Section 21456.3, the operator of a bicycle facing a pedestrian control signal displaying a “WALK” or approved “Walking Person” symbol may proceed across the roadway in the direction of the signal but shall yield the right-of-way to any vehicles or pedestrians lawfully within the intersection”. LPI Practices: California Senate Bill 671 (Chapter 326) was passed on 10/03/25 to amend section 21450.5 of the CA Vehicle Code. The bill provides additional requirements on LPI & APS implementation and requires local agencies to report LPIs at locations where local agencies are operating state-owned signals so that they can be included in the CalTrans TMS inventory database.	should be the minimum needed to accommodate the design vehicle” (CalTrans, 2025). CE Practices: The 2017 CalTrans DIB 82 Pedestrian Accessibility Guidelines for Highway Projects mention the following statement: “Consider designing a CE, see HDM Index 303.4, where right-of-way is limited to accommodate a standard curb ramp” (CalTrans, 2017).
Washington	LPI Guidelines: Factors considered include intersections with high volumes of turning vehicles, high pedestrian volumes, and a high number of children, older pedestrians, pedestrians with physical disabilities (WSDOT, 2024). LPI Policies: “If bicyclists in a bike facility adjacent to the sidewalk will also use the LPI at an intersection, install a “bikes use ped signal” sign (R9-5), near the pedestrian countdown signal” (WSDOT, 2024). LPI Practices: Seattle (SDOT, 2019) and Bellevue (City of Bellevue, 2023) have also developed LPI guidelines & policy. The City of Bellevue says that when implementing LPIs, APS buttons should exist or be added. SDOT says that LPIs may not be installed if existing leading protected / permissive left turn phasing does not warrant being converted to lagging protected/permissive phasing; if other treatments exist such as protected turns, restricted turns, or all-way walk; and if LPI requires increasing the signal cycle length.	CE Guidelines: Factors considered include intersections and midblock crosswalks; roadways with on-street parking (WSDOT, 2024). CE Policies: “CEs may double as physical barriers to restrict parking near crossings” (WSDOT, 2024). CE Practices: “Select and place site features such as landscaping, cabinets, poles, benches, planters, bollards, newspaper stands, and sandwich boards so they don’t obstruct the vision of pedestrians or drivers within curb extension areas” (WSDOT, 2024).
New York	LPI Guidelines: Factors considered include intersections with long pedestrian crossings or complex phasing needs, high pedestrian or cyclist activity, and corridors with high ridership bus routes, according to the 2025 NYC DOT Street Design Manual (NYCDOT, 2025)	CE Guidelines: Factors considered include within a curbside parking lane; marked crosswalks in retail districts, schools; ped safety issues; wide streets; high foot traffic (NYCDOT, 2025).

State	Leading Pedestrian Intervals	Curb Extensions
	LPI Policies: “On 12/27/21, the United States District Court, Southern District of New York issued a decision in the case of American Council of the Blind of New York, Inc. v. City of New York (18Civ. 5792) mandating the City of New York (City) to equip at least 10,000 signalized intersections with APS by the end of 2031. The court prioritized the installation of APS at signalized intersections with outstanding external/public requests, LPIs, exclusive pedestrian phases, and a group of 424 intersections newly signalized on or after 06/27/15 which did not include APS” (NYCDOT, 2024). “A person operating a bicycle while crossing an intersection shall follow pedestrian control signals except where otherwise indicated by traffic control devices, and provided that such person shall yield to pedestrians in the crosswalk” (NYC Administrative Code, 19-195.1). LPI Practices: From 2010-2021, NYC DOT installed 5,000+ LPIs. A before/after injury analysis from 2010 to 2016, revealed an 18.1% reduction in pedestrian injuries (NYCDOT, 2022). NYC’s “Vision Zero View Map” shows an inventory of NYC’s LPIs (NYC, 2025).	CE Policies: According to the 2025 NYC DOT Street Design Manual, “CEs discourage truck turns onto streets with No Truck regulations and discourages or prevents vehicles from taking banned turns (review rules related to truck routes in the Rules of the City of New York, Title 34, Chapter 4, Section 4-13)”...“Permits, revocable consents, and/or maintenance agreements may be required for certain furniture elements”...and... “Feasibility is evaluated based on engineer review of design vehicle turning movements” (NYCDOT, 2025). CE Practices: “When a CE conflicts with design vehicle turning movements, the CE should be reduced in size rather than eliminated” (NYCDOT, 2025).
Washington DC	LPI Guidelines: Factors considered include intersections with high volumes of both pedestrians and turning cars, according to the 2025 DDOT Safety Treatment Toolbox (DDOT, 2025a) LPI Policies: “People biking can also use the LPI phase to move through an intersection more safely than waiting for the green traffic light” (DDOT, 2025a). “When an LPI is implemented, an APS is often installed as well” (DDOT, 2025a). LPI Practices: “The LPI reinforces District law for drivers to stop for pedestrians in a crosswalk”. DDOT has installed LPIs at approximately 75% of all signalized intersections in the district (DDOT, 2025a).	CE Guidelines: Factors considered include drainage, intersection geometry, bus stops, parking configurations, according to the 2025 DDOT Safety Treatment Toolbox (DDOT, 2025a). CE Policies: “DDOT supports installation of murals in CEs because they are retired from vehicle use. CEs also bring on-street parking up to DDOT standards by removing street parking 25 ft from the crosswalk (DEM 45.1.4)” (DDOT, 2025b). CE Practices: DDOT is currently conducting research evaluating intersections with concrete CEs, tactical CEs, and tactical CEs with art (DDOT, 2025c).

State	Leading Pedestrian Intervals	Curb Extensions
Florida	LPI Guidelines: Factors considered include field observations, citizen complaints, crash history, near misses, or risk analysis indicate conflicts between turning vehicles on green and pedestrians; marked school crossings; drivers’ view of pedestrians is blocked due to obstructions or poor sight distance (intersection geometry, lighting problems, sun angle); and approaches where the time needed to serve vehicular demand is less than the associated WALK and flashing DON’T WALK interval, according to section 3.11.5.1 of the 2025 FDOT Traffic Engineering Manual (FDOT, 2025). LPI Policies: “Consider using APS (MUTCD 4K.01-4K.05) with LPI applications, as vision-impaired pedestrians use the sound of moving traffic to decide when to start crossing” (FDOT, 2025). LPI Practices: With an actuated pedestrian phase, the optimal max LPI duration is 10 seconds. If more time is needed, either based on Formula 3.11.5.2-1 or due to sight distance concerns, consider geometry updates such as CEs to shorten the distance pedestrians need to cross to get through one through lane (FDOT, 2025).	CE Guidelines: Factors considered include on-street parking at intersections or midblock locations where there is a crosswalk, provided there is adequate width for existing traffic movements, according to the 2026 FDOT Design Manual (FDOT, 2026). CEs must consider the needs of transit, emergency vehicles, commercial trucks, drainage, and bicyclists (FDOT, 2026). CE Policies: “Do not use street furniture on curb extensions” (FDOT, 2026). CE Practices: “CEs at intersections should be designed using a CADD-based vehicle turning path (e.g., AutoTurn) to verify the appropriate design and control vehicles are accommodated” (FDOT, 2026).
Pennsylvania	LPI Guidelines: Factors considered include citizen complaints; crash data; land-use context (pedestrian generator locations such as playgrounds, parks, schools, recreation centers, urban areas, hospitals, retirement/assisted-living communities, transit stops); T-intersections, one-way streets; visibility issues (sun angle, lighting, intersection geometry); and controller capabilities, according to the 2021 PennDOT LPI Policy (PennDOT, 2021). LPI Policies: “At locations where LPI is used without APS (Sections 4E.09–4E.13 of the MUTCD), the minimum required time for the walk interval shall be provided in addition to the time provided for the LPI, as vision-impaired pedestrians use the sound of moving traffic to start crossing” (PennDOT, 2021).	CE Guidelines: Factors considered include intersections with max speed limit of 40 mph; all street types with on-street parking; any number of travel lanes; urban, suburban, rural town settings, according to the 2025 PennDOT Contextual Roadway Design Manual (PennDOT, 2025). CE Policies: “CEs can be used in conjunction with separated bicycle facilities, where CE includes an opening for the bike facility along the curb or a bypass lane for bicyclists (PennDOT, 2025).

State	Leading Pedestrian Intervals	Curb Extensions
	LPI Practices: Consider blank-out signs at locations with inconsistent pedestrian volumes, low/non-illuminated crosswalks, locations with high volumes that could see capacity issues with continual right-turn prohibitions. If right turns on red are not prohibited, consider R10-15R sign (PennDOT, 2021).	CE Practices: At transit stops, CEs should be long enough to accommodate simultaneous loading and unloading from front and rear doors (PennDOT, 2025).
North Carolina	LPI Guidelines: Factors considered include moderate to high pedestrian activity; several nearby pedestrian generators; K-12 schools or college/university campuses, pedestrian crash history, trail crossings, light rail, BRT or high-frequency transit stop locations; vulnerable pedestrians; atypical locations with limited sight distance; one-way and T-intersections; heavy turning movements in shared thru/left or thru/right lanes; and public request, according to the 2025 NCDOT Guidelines for LPI Implementation (NCDOT, 2025a). LPI Policies: “APS is not a current requirement for installation of LPI in the MUTCD; however, public requests for APS will be considered. Public requests are reviewed by the Division & Regional Traffic Engineer staff for potential improvements. If a city requests to install APS at NCDOT-maintained signal, NCDOT will accept that request as part of the signal plan review” (NCDOT, 2025a). “LPI may be used by bicyclists -referred to as Leading Bicycle Interval- is where bicycle traffic does not justify a bicycle signal phase, but bicyclists would benefit from entering the intersection before parallel vehicle traffic. In this application of LPI, signs should direct bicyclists to use the pedestrian signal, and timing should be set considering speeds of bicyclists and pedestrians” (NCDOT, 2025a). LPI Practices: The 2025 NCDOT Guidelines for LPI Implementation (NCDOT, 2025a) provide considerations related to signal phasing (protected-permitted left turn, FYA, lead-lag phasing, split phasing, single ped crossing on major approach, two-stage ped crossing); controller software; coordination, time of day operation; recall; and intersection geometry (dual left turn, dual right turn).	CE Guidelines: Factors considered include permanent parking lane; pedestrian-oriented areas; and transit stops where full-time on-street parking exists, according to the 2007 City of Charlotte Urban Street Design Guidelines (City of Charlotte, 2007). “CE should not encroach into the bike lane” (City of Charlotte, 2007). CE Policies: CEs are inappropriate on boulevards, parkways, local industrial streets (City of Charlotte, 2007). “CEs should be designed to accommodate both large and small vehicles; tight curb radii can accommodate low speed turning movements by large vehicles if the intersection is designed properly” (City of Charlotte, 2007). “Street furniture or plants on the CE should not impede motorist or pedestrian sightline” (City of Charlotte, 2007). CE Practices: “Various geometric design features may be considered for bicycle boulevards, including raised islands, curb extensions, raised crossings, and other traffic calming features”, according to the 2025 NCDOT Roadway Design Manual (NCDOT, 2025b).

State	Leading Pedestrian Intervals	Curb Extensions
Minnesota	LPI Guidelines: Factors considered include intersections with relatively high crossing volumes, relatively high turning vehicle volumes, patterns of pedestrian or bicycle conflict with vehicles, according to the 2021 Minnesota’s Best Practices for Pedestrian & Bicycle Safety (MnDOT, 2021). LPI Policies: “An alternative approach for a leading bicycle interval that does not require a request to experiment is to implement an LPI in conjunction with a “Bikes use ped signal” sign (R9-5). R9-5 signs and LPIs are both included in the MnMUTCD, and there is nothing that precludes their use together” (MnDOT, 2021). LPI Practices: “LPIs can be enhanced with CEs at the intersection to further improve pedestrian visibility” (MnDOT, 2021).	CE Guidelines: Factors considered include urban settings with on-street parking lane or a shoulder where CEs will not impede bicycle travel, according to the 2021 Minnesota’s Best Practices for Pedestrian & Bicycle Safety (MnDOT, 2021). CE Policies: “CEs reinforce the no-parking distance that the MN MUTCD requires for advanced stop bars”, according to the 2024 MnDOT Facility Design Guide (MnDOT, 2024). “For sidewalks narrower than 8 ft, use a CE to widen sidewalk at the intersection corner” (MnDOT, 2024). CE Practices: Add delineators or markers on the CE to help guide snowplows (MnDOT, 2021).
Georgia	LPI Guidelines: Factors considered include crash trends between peds and turning vehicles; evidence of conflicts or near misses between peds and turning vehicles; less than ½-mile walk from any school or along an identified path to school; and T-intersections, according to the 2021 GDOT Pedestrian & Streetscape Guide (GDOT, 2021). LPI Policies: “APS is recommended to accompany LPI implementation if time used in the walk or pedestrian change interval is used for the LPI interval” (GDOT, 2021). LPI Practices: To increase LPI effectiveness and improve visibility at high-conflict intersections, install a CE. No Turn on Red prohibitions may be considered. At intersections with bicycle signal faces, an LBI may be provided with LPI to reduce bicycle-vehicle conflicts (GDOT, 2021).	CE Guidelines: Factors considered include streets with speed limits of 40 mph or less; streets with on-street parking; not appropriate for high volume truck routes, according to the 2021 GDOT Pedestrian & Streetscape Guide (GDOT, 2021). CE Policies: “If used for a ped crossing, applicable ADA measures should be implemented” (GDOT, 2021). CE Practices: “CEs may be opportunities to incorporate green stormwater infrastructure into the street” (GDOT, 2021).

As seen in Table 2.2, many different states have developed guidelines and best practices regarding the implementation of LPIs and CEs. Described below are some of the commonalities found among different states.

2.4.1 Curb Extensions

Although different states and cities have their own design manuals with recommended best practices, they share similar recommendations when it comes to CEs. For example, many cities agree that the recommended location for curb extensions are areas with on-site parking. CEs are commonly described as a recommended measure for shortening the length of crosswalks, increasing pedestrian visibility, and encouraging slower vehicle turning speeds. Many mention the potential of CEs in helping to provide additional surface area to help meet the accessibility needs of curb ramps, especially at constrained locations. Many also see the potential of CEs in creating opportunities for stormwater management features such as bioswales or rain gardens. However, many recommend doing so in a way that does not impede motorist or pedestrian sightlines. Additionally, many states recommend considering the turning needs of emergency, maintenance, and heavy vehicles when designing CEs. While Crash Modification Factors (CMFs) are not yet available for CEs, these geometric improvements continue to be widely implemented across the nation due to their direct benefits in shortening crosswalk widths and increasing pedestrian visibility.

2.4.2 Leading Pedestrian Intervals

The Manual on Uniform Traffic Control Devices (MUTCD) provides guidance and recommendations for the implementation of Leading Pedestrian Intervals (LPIs). A common trend is that many states have often referred to or directly replicated the guidance provided in the MUTCD. For example, many cities agree with the MUTCD's guidance of implementing LPIs at intersections with high pedestrian volumes and high conflicting turning vehicle volumes. The MUTCD also recommends a minimum LPI duration of 3 seconds or long enough to allow pedestrians to cross at least one lane of traffic. This recommendation is consistent with the LPI guidelines and policies developed in states like Florida and Pennsylvania. Additionally, the MUTCD also recommends the installation of Accessible Pedestrian Signals in conjunction with LPIs, as well as prohibiting turns across the crosswalk during the Leading Pedestrian Interval. The Federal Highway Administration (FHWA) lists the LPI as a "Proven Safety Countermeasure" under the FHWA's Proven Safety Countermeasures initiative (PSCi), which provides a collection of 28 countermeasures and strategies effective in reducing roadway fatalities and serious injuries (Albee and Bobitz, 2021). With the widespread implementation of LPIs, many transportation agencies have sought to develop guidelines to help standardize the LPI implementation process. One example is the state of Florida. Shown in Table 2.3 is a summary of the eight LPI Warrants developed in 2017 by the USF Center for Urban Transportation Research for research sponsored by the Florida Department of Transportation. These warrants helped inform the LPI suitability assessment tool developed for the Oregon Department of Transportation.

Table 2.3: LPI Warrants (Lin et al., 2017)

Warrant	Description
Warrant 1: Approach Crash Frequency	Average Crash Frequency between turning vehicles on green and pedestrians legally crossing the street on the associated crosswalk with the pedestrian “Walk” signal indication on the approach of the intersection ≥ 1 per year (in last 3 years).
Warrant 2: Reported Visibility Issue	A visibility issue of blocked driver view of pedestrians on the crosswalk due to obstructions or poor sight distance at an approach of an intersection is reported and then verified by an engineering study.
Warrant 3: Vehicle Non- Yielding Behavior	Vehicle non-yielding behavior to pedestrians is reported, and one of the following is satisfied: A) Average number of conflicts between pedestrians and turning vehicles ≥ 3 per day on the studied approach based on field observations of 3 days; or B) Percentage of compromised pedestrians at onset of the “Walk” signal at the crosswalk of the studied approach $\geq 10\%$.
Warrant 4: Vehicle Peak Hour	An engineering study finds that one of the following is satisfied: A) For vehicle peak hour of an average day, approach turning vehicle volume $\geq 130/\text{hr}$, pedestrian volume at crosswalk $\geq 25/\text{hr}$; or B) If either turning vehicle volume $\geq 130/\text{hr}$ or pedestrian volume at crosswalk $\geq 25/\text{hr}$, but not both, is satisfied, and through traffic volume of cross street $\geq 500/\text{hr}/\text{lane}$ is also satisfied.
Warrant 5: Pedestrian Peak Hour	An engineering study finds that one of the following is satisfied: A) For pedestrian volume peak hour of an average day, approach turning vehicle volume $\geq 100/\text{hr}$, pedestrian volume at crosswalk $\geq 50/\text{hr}$; or B) If either turning vehicle volume $\geq 100/\text{hr}$ or pedestrian volume at crosswalk $\geq 50/\text{hr}$, but not both, is satisfied, and through traffic volume of cross street $\geq 400/\text{hr}/\text{lane}$ is also satisfied.
Warrant 6: Four-Hour Vehicular & Pedestrian Volume	An engineering study finds that one of the following is satisfied for each of any 4 hours of an average day: A) Approach turning vehicle volume $\geq 105/\text{hr}$, pedestrian volume at crosswalk $\geq 30/\text{hr}$; or B) If either turning vehicle volume $\geq 105/\text{hr}$ or pedestrian volume at crosswalk $\geq 30/\text{hr}$, but not both, is satisfied, and through traffic volume of cross street $\geq 400/\text{hr}/\text{lane}$ is also satisfied.
Warrant 7: Eight-Hour Vehicular & Pedestrian Volume	An engineering study finds that one of the following is satisfied for each of any eight hours of an average day: A) Approach turning vehicle volume $\geq 100/\text{hr}$, pedestrian volume at crosswalk $\geq 25/\text{hr}$; or B) If either turning vehicle volume $\geq 100/\text{hr}$ or pedestrian volume at crosswalk $\geq 25/\text{hr}$, but not both, is satisfied, and through traffic volume of cross street $\geq 400/\text{hr}/\text{lane}$ is also satisfied.
Warrant 8: School Crossing	An engineering study finds that the following condition is satisfied at an intersection with a school crossing: Approach turning vehicle volume $\geq 50/\text{hr}$ (consider LPI for the period 1 hr before and 30 minutes after school start time, and the period 30 min before and 1 hr after school end time).

2.5 FACTORS THAT IMPACT LPI DURATION & EFFECTIVENESS

The effectiveness of LPI in reducing pedestrian-vehicle conflicts and crashes is well supported by multiple research studies (Arun et al., 2023; Goughnour et al., 2018; Fayish & Gross, 2010; Van Houten et al., 2000). The Crash Modification Factor (CMF) for the LPI is 0.87, with a 13% reduction in vehicle-pedestrian crashes (Goughnour et al., 2018). Although the safety benefits of LPIs are well established, the duration and potential effectiveness of an LPI may often be impacted by the existing conditions of an intersection. Described in this section are examples of a couple of factors that may impact the duration and potential effectiveness of an LPI, including factors such as corner radius, number of turn lanes, crosswalk setback, street furniture in sight triangle, approach speed and turning speed, signal operation scheme, etc. The insights gained regarding each of these factors helped inform the LPI suitability assessment tool developed in this research.

2.5.1 Corner Radius

As mentioned in the 11th Edition of the Manual on Uniform Traffic Control Devices (MUTCD), the minimum required duration of an LPI is 3 seconds. It should be timed to “allow pedestrians to cross at least one lane of traffic or, in the case of a large corner radius, to travel far enough for pedestrians to establish their position ahead of the turning traffic before the turning traffic is released” (FHWA, 2023). This recommendation suggests that the duration of an LPI may increase depending on the corner radius of an intersection. According to NACTO (2013), the standard corner radius for urban streets is 10-15 ft. However, many cities use corner radii as small as 2 ft. According to the FHWA Pedestrian Facilities Users Guide, an appropriate corner radius for arterial streets with a substantial volume of turning buses and/or trucks is 15-25 ft (Zegeer et al., 2002). Figure 2.3 shows the relationship between corner radius and crossing distance at an intersection.

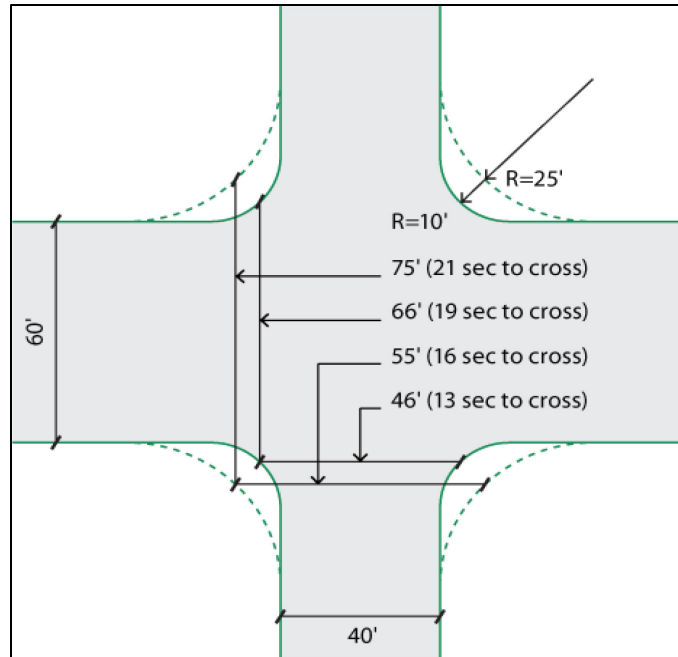


Figure 2.3. Relationship Between Corner Radius & Crossing Distance (NACTO, 2013)

As shown in Figure 2.8, as the corner radius increases, the length of the crosswalk increases, and thus the amount of time that it takes pedestrians to cross. Per MUTCD recommendations, an LPI should be timed in a way that allows pedestrians to cross at least one lane of traffic. If the minimum length of 3 seconds is not enough to do so, the length of the LPI would need to be longer. However, because all traffic is held during the LPI, a longer LPI could mean more loss in vehicular capacity (Furth & Saeidi-Razavi, 2019). In addition to increasing LPI duration, large corner radii may present other challenges towards pedestrian safety. A recent study found that intersections with large corner radii showed a tendency for drivers to be less likely to stop and a tendency for pedestrians to feel the need to yield to right-turning vehicles (Singleton, 2023). Other studies found that as corner radius increases, turning speed increases (Hurwitz et al., 2023; Fitzpatrick et al., 2022; Chai et al., 2024). These findings show the impact that corner radius can have not only on LPI duration but also turning speeds and yielding behaviors, which may need to be considered when evaluating the effectiveness of the LPI. Table 2.4 shows average turning speeds related to curb radius and crosswalk setbacks collected from a driving simulator study.

Table 2.4: Vehicle Turning Speed in miles per hour (mph) Due to Curb Radius & Crosswalk Setbacks (Hurwitz et al., 2023)

Setback (S) & Radius (R) in Feet	S10 & R15	S10 & R30	S10 & R45	S20 & R15	S20 & R30	S20 & R45	S30 & R15	S30 & R30	S30 & R45
Median	14.2	15.1	16.1	15.3	15.3	18.2	15.3	15.9	18.3
Mean	14.8	15.4	16.3	15.2	15.5	18.1	16.0	16.7	18.3
Standard Deviation	2.9	2.7	2.8	2.4	2.9	3.1	3.0	3.0	2.9

Note: No pedestrians present.

2.5.2 Street Furniture in Sight Triangle

One objective of the LPI is to increase the visibility of pedestrians at an intersection. However, obstructions may impact the effectiveness of the LPI if the provided LPI duration is not long enough to fix the visibility problem caused by the obstruction. According to NACTO, fixed objects, such as trees, buildings, signs, and street furniture, should not be removed without the prior consideration of alternative safety mitigation strategies such as reduction in traffic speeds, geometric improvements that help increase visibility (e.g., curb extensions), or supplementary warning signs. Figure 2.4 shows an example of the sight triangles for two types of intersections (one with no CEs and one with CEs).

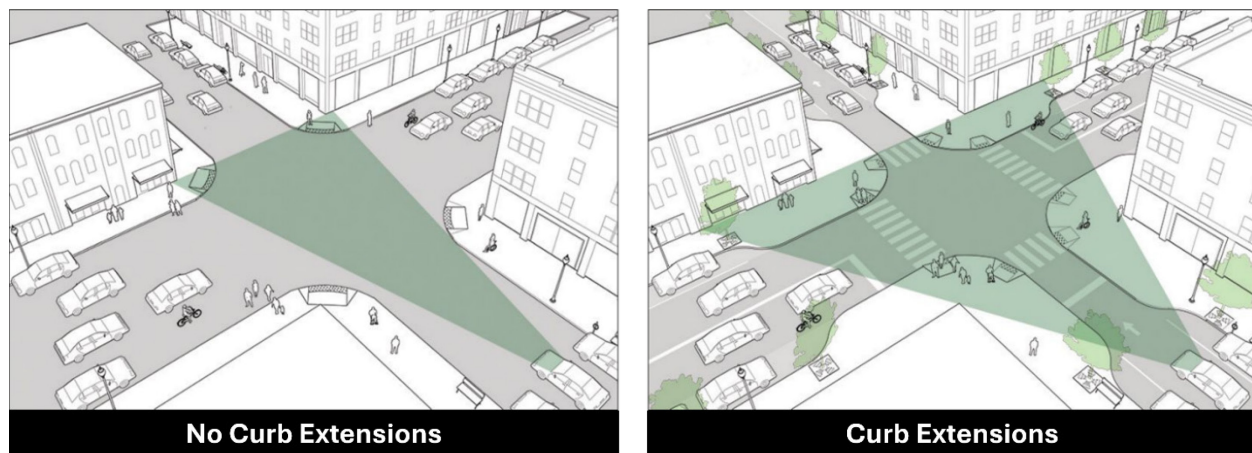


Figure 2.4. Sight Triangles Example (NACTO, 2013)

As shown in the two examples presented in Figure 2.4, the presence of curb extensions can help widen the sight triangle, providing all users with a better view of potential conflicts. A conceptual study suggests that when an intersection provides pedestrians with a head start in space through the use of geometric improvements such as curb extensions, the LPI could accomplish its goal with a shorter duration (Saeidi-Razavi & Furth, 2023). This implies that if obstructions cannot be easily removed, the duration of the LPI may need to be longer, or

geometric improvements such as curb extensions could be implemented to help improve visibility while minimizing the need for a longer LPI duration.

2.5.3 Lane Configuration

Lane configuration is an example of another factor that could impact the duration and overall effectiveness of an LPI. Factors such as shared lanes, exclusive lanes, the number of turn lanes/receiving lanes are worth considering when evaluating the existing conditions of an intersection. Described below are some of the ways in which each of these configurations could impact the duration and overall effectiveness of an LPI.

2.5.3.1 Shared Lane

According to Furth & Saeidi Razavi (2019), as the proportion of right-turners increases in a lane shared by through and right-turning vehicles, the incremental lost time caused by the LPI decreases. They claim that when there is no pedestrian blockage, the incremental lost time for the LPI is simply the duration of the LPI itself. However, when there is pedestrian blockage and the proportion of right turning vehicles is high, many of the vehicles held by the LPI would have been delayed by the pedestrians anyway, which in turn reduces the impact of the LPI. Using a deterministic simulation model, the researchers tested what the incremental lost time for a 7 second LPI would be using a 10 second pedestrian blockage, 28% right turns, and no informal flare (a condition where an intersection has space for a right-turning vehicle to wait at the crosswalk without blocking through traffic). This test resulted in an incremental lost time of only 2.8 seconds, which suggests that within shared lanes, negative impacts on capacity caused by the LPI decrease as the proportion of right-turning vehicles increases and as pedestrian blockage increases.

2.5.3.2 Exclusive Turn Lane

Because all traffic is held during the LPI, the LPI duration may need to be limited to avoid losses in vehicular capacity. At intersections with exclusive turn lanes, Leading Through Intervals (LTI) have been mentioned as a treatment alternative that has less impact on capacity compared to LPIs. Research by Furth & Saeidi-Razavi (2019) suggests that at intersections where turning traffic has its own exclusive turn lane, LTIs have less capacity impacts than LPIs because LPIs hold traffic in all lanes whereas LTIs hold traffic only for turning movements in one lane while through traffic is allowed to run in the adjacent lanes. At intersections with exclusive turn lanes, LTIs could be considered or the duration of the LPI could be limited to avoid impacts on capacity for through movements. However, factors such as vehicle volumes and closely spaced signals (e.g., downtown areas) may need to be considered when assessing whether losses in vehicular capacity are considered significant. Additionally, initiatives such as Vision Zero (Vision Zero Network, 2025) are shifting the focus on vehicular capacity and placing emphasis on pedestrian safety. This shift in thinking prioritizes the safety impacts of LPIs over impacts on vehicular capacity.

2.5.3.3 Number of Turn Lanes/Receiving Lanes

Although no research has evaluated the impact of the number of turn lanes on LPI, it can be inferred that as the number of turn lanes increase, pedestrians are more exposed to potential conflicts with turning vehicles. One study instead considered the effect of the number of receiving lanes on LPI duration. Saeidi-Razavi & Furth (2023) developed a model for determining the duration of an LPI as a function of intersection geometry. Within their model, the conflict zone is defined as “the intersection of the crosswalk and the swept path of the right-turning vehicle headed for the lane of the receiving roadway furthest from the pedestrian’s starting point.” This choice was informed by the fact that if a receiving roadway has multiple lanes, a vehicle could be on a trajectory aiming for any of them, and because of the vehicle’s greater speed, the critical case happens when the vehicle is aiming for the lane most distant from the pedestrian’s starting point (Saeidi-Razavi & Furth, 2023). Additionally, when multiple turn lanes are present, there could be a vehicle shadowing effect, where one vehicle obscures the sight triangle of the adjacent vehicle to a crossing pedestrian. Figure 2.5 shows a visualization of the critical conflict zone for both nearside and farside pedestrians, where d_p = pedestrian distance from the curb to the middle of the conflict zone, and d_v = driving distance to the conflict zone.

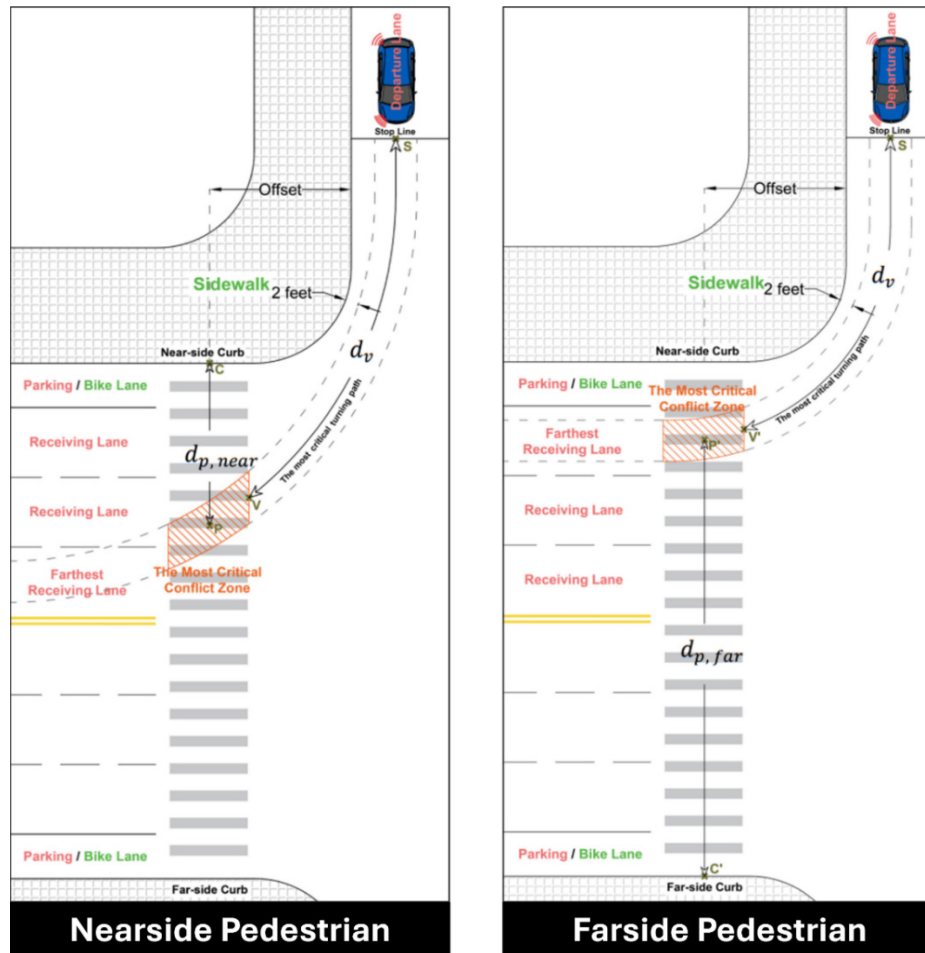


Figure 2.5. Critical Conflict Zone (Saeidi-Razavi & Furth, 2023)

Saeidi-Razavi & Furth (2023) developed the following equation to determine the necessary length of an LPI as a function of intersection geometry.

$$LPI = \max \left\{ 0, \quad t_{p-r} + \frac{d_p}{v_p} - t_{d-r} - t_v \right\} \quad (2.1)$$

LPI = duration of the leading pedestrian interval (s),
 d_p = pedestrian distance from the curb to the middle of the conflict zone,
 t_{d-r} = driver reaction time (s),
 t_{p-r} = pedestrian reaction time (s),
 v_p = pedestrian design speed (ft/s),
 t_v = driving time from start of acceleration to when the vehicle reaches the conflict zone.

As seen in Figure 2.5, as the number of receiving lanes increases, the pedestrian distance from the curb to the middle of the conflict zone (d_p) will increase, and thus, the required LPI duration will increase. This suggests that when there are fewer receiving lanes or when pedestrians are provided with a head start in space through geometric improvements such as curb extensions, (d_p) will be smaller, and therefore the LPI duration will be smaller.

2.5.4 Crosswalk Setback

Another factor that could impact the duration and overall effectiveness of an LPI is the crosswalk setback (a.k.a. recessed crosswalk). Crosswalk setbacks are correlated with crossing distance (Jacquemart, 2012). Figure 2.6 shows how a crosswalk setback reduces the crossing distance, which in turn reduces the amount of time that it would take a pedestrian to cross. A driving simulator study that examined the relationship between crosswalk setbacks and intersection safety observed how crosswalk setbacks decreased drivers' visual attention on pedestrians since pedestrians would clear the receiving lane by the time the drivers would reach the intersection apex for the turning movement (Hurwitz et al., 2023). Similar to other geometric improvements such as curb extensions, crosswalk setbacks may provide pedestrians with a head start in space by increasing the amount of time that it takes a vehicle to reach a conflicting pedestrian and by shifting the pedestrian into the forward view of the driver.

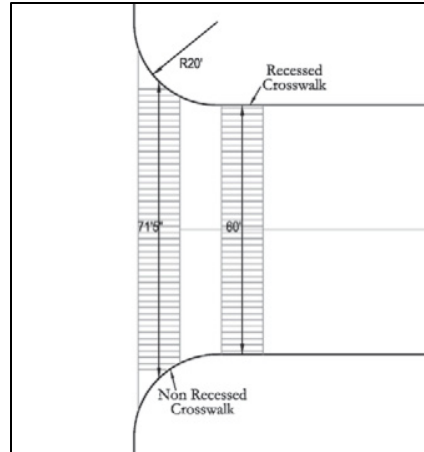


Figure 2.6. Crosswalk Setback (Jacquemart, 2012)

Saeidi-Razavi & Furth (2023) considered impacts on LPI duration by the “relative setback” which they described as the distance between the pedestrian stop line (i.e., curb) and the vehicle stop line (pictured in Figure 2.7). They suggest that the further back the vehicle stop line is positioned relative to the pedestrian stop line, the shorter the necessary LPI. As previous research suggests, shortening the crossing distance or delaying the amount of time that it takes a turning vehicle to reach the conflict zone could impact the required LPI duration. Because of this, crosswalk setbacks may need to be considered when determining the desired length of an LPI at an existing or new intersection.

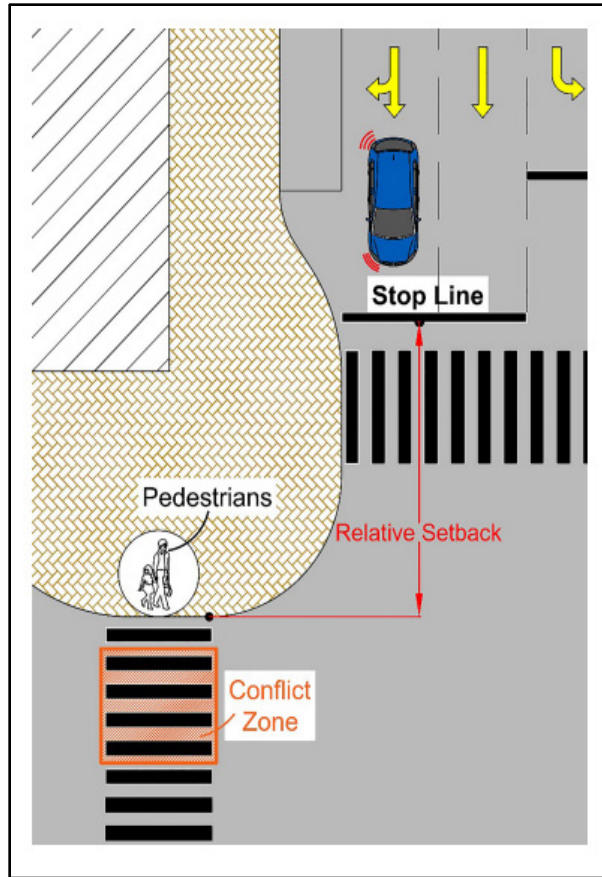


Figure 2.7. Relative Setback (Saeidi-Razavi & Furth, 2023)

2.5.5 Approach Speed & Turning Speeds

A study by Ghomi & Hussein (2023) developed a model to predict what pedestrian-focused countermeasure combinations worked best and where to reduce pedestrian crashes. This study found that LPIs were effective in neighborhoods with high population density, high subway station density, high commercial density, and high institutional/office density, especially when integrated with speed limit reduction and community zones (Ghomi & Hussein, 2023).

According to NACTO, the peripheral vision of drivers narrows severely when speed increases. Figure 2.8 shows an example of this phenomenon.



Figure 2.8. Relationship Between Speed & Driver's Peripheral Vision (NACTO, 2013)

With higher speeds, drivers have less time to hit the brakes or swerve. According to Jashami et al. (2024a), Turner et al. (2017), and the 2020 City Limits Guide by NACTO, the likelihood of fatality increases as the posted speed limit increases. Figure 2.9 shows this relationship.

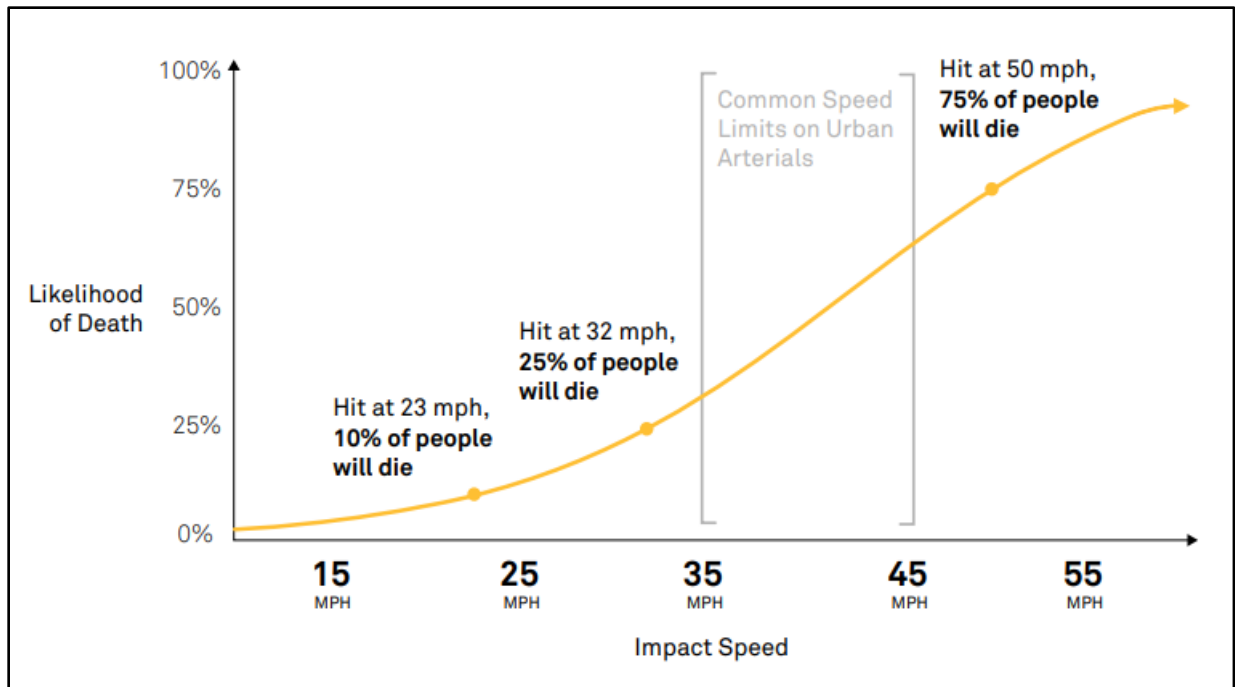


Figure 2.9. Relationship Between Speed & Likelihood of Fatality (NACTO, 2020)

Although no field studies have directly evaluated the impact of approach speed and turning speed on LPI effectiveness, the safety implications of higher turning speeds suggest that speed could potentially impact the effectiveness of LPIs when vehicles turn on red at relatively high speeds and fail to yield to pedestrians during the LPI. In order to prevent this non-yielding behavior from happening at intersections with LPIs, the MUTCD and multiple jurisdictions recommend the implementation of No Turn on Red (NTOR) in conjunction with LPIs (NCDOT, 2025; TxDOT, 2024; FHWA, 2023; City of Bellevue, 2023; PennDOT, 2021; CalTrans, 2021; MDOT SHA, 2020; FHWA, 2019; Saneinejad & Lo, 2019; Lin et al., 2017). In order to encourage slower turning speeds, geometric improvements such as smaller curb radius or CEs are also recommended (Arlington County, 2025; GDOT, 2021; MnDOT, 2021; MDOT SHA, 2020; Gilpin et al., 2020; NACTO, 2013; Zegeer, 2002).

2.5.6 Signal Operation Scheme

Because LPIs delay the onset of vehicle traffic at intersections, a common drawback of LPIs is their potential impact on capacity and vehicle lost time. A marginal benefit–cost study claims that an LPI treatment is economically efficient when the safety benefit for pedestrians exceeds the delay cost levied on vehicle traffic (Sharma et al., 2017). Impact on capacity is highly dependent on the duration of the LPI. However, other aspects of the intersection, such as signal operation scheme (e.g., actuated, pre-timed, semi-actuated, coordinated, presence of overlaps, etc.), may need to be considered when evaluating the overall effectiveness and impacts on capacity caused by the LPI. Lin et al. (2017) recommends examining the utilization efficiency of implemented LPIs to ensure that they are working effectively.

2.5.6.1 *Actuated*

At intersections with push-button actuated LPIs, a concern raised is when pedestrians press the push button but fail to make use of the LPI by either crossing the intersection before the LPI activates or leaving the intersection. According to Lin et al. (2017), this behavior could cause potential driver complaints because of the unnecessary travel delay experienced by motorists when pedestrians do not make use of the LPI. A benefit provided by actuated signals is that the LPI is activated only when it is needed, which in turn reduces impacts on capacity. Push-button actuated LPIs can be effective when used correctly. Based on conversations with numerous traffic engineers with experience designing and operating signalized intersection In Oregon, motorist complaints related to LPI at signalized intersections have been rare.

2.5.6.2 *Pre-Timed*

Lin et al. (2017) analyzed the utilization efficiency for 9 intersections in Florida that implemented LPIs. The results obtained showed that the LPI was effectively used at most tested approaches with a percentage of utilization above 85%. However, one of the intersections that was pre-timed during the daytime experienced a significant number of unused LPIs, for which the researchers recommended that the signal be programmed with actuated control. Another option when working with pre-timed signals could be to provide the LPI only during specific hours of the day (e.g., whenever pedestrian volumes are higher). According to Sharma et al. (2017), providing the LPI only during specific hours of the day can help increase the benefit-cost ratio by reducing vehicle delay. However, doing so could cause user expectation issues.

2.5.6.3 *Semi-Actuated*

Another potential way to configure the LPI within an intersection is through the use of semi-actuated controls. According to Saneinejad & Lo (2019), if vehicular volumes are low on the minor road, the LPI for crossing the major road would not add to the total cycle time nor increase pedestrian wait time at semi actuated signals of minor and major road intersections. Instead, the vehicle maximum time for the minor traffic would be reduced by the LPI duration. Since the LPI would not add to the total cycle time or increase pedestrian wait time, the recommendations provided by Saneinejad & Lo (2019) suggest that semi-actuated LPI controls could be suitable for locations where the minor approach experiences low vehicular volumes.

2.5.6.4 *Coordinated*

Saeidi-Razavi & Furth (2023) claim that adding or eliminating an LPI will often have no effect on cycle length at intersections that are already in excess of their necessary cycle length because they belong to a coordinated system with a common cycle length that is determined by the needs of a different “critical” intersection. In cases like this, they suggest LPIs will help reduce vehicle capacity and unused green time, which in turn may reduce speeding. They also suggest considering longer LPIs for cases where cycle length will not be affected by an LPI. These recommendations suggest that coordinated signals

could be suitable for LPI implementation as they would allow for longer LPI durations, which could help provide pedestrians with increased protection.

2.5.6.5 *Presence of Overlaps*

While sharing examples of signalization techniques that help provide full or partial crossing protection, Furth & Saeidi-Razavi (2019) mentioned the use of an ‘overlap,’ in which right turns run concurrently with a parallel left-turn movement. The separation in time provided by this technique comes at the price of increased delay for pedestrians, bikes, and turning traffic. However, the phases are all shortened compared with traditional concurrent phasing. Because this signalization technique already provides some level of protection to pedestrians, LPIs may not be as applicable to this signal operation scheme.

2.6 RECOMMENDED LPI SUPPLEMENTS

To improve accessibility, vehicle and pedestrian compliance, and the overall safety performance of LPIs, additional supplements such as Accessible Pedestrian Signals (APS), No Turn on Red (NTOR) Signs, Yield to Pedestrian Signs, Right Turn Flashing Yellow Arrows (RTFYA), and In-Street Educational Signage are recommended.

2.6.1 Accessible Pedestrian Signals (APS)

When crossing at signalized intersections, an orientation and mobility (O&M) technique that pedestrians who are blind typically use is to listen for the surge of parallel traffic, which provides them with an auditory cue to help them decide when to cross (Barlow et al., 2005). Figure 2.10 helps to illustrate this technique. Audible push buttons, also known as APS, communicate the start of the WALK signal using auditory and vibrotactile information.

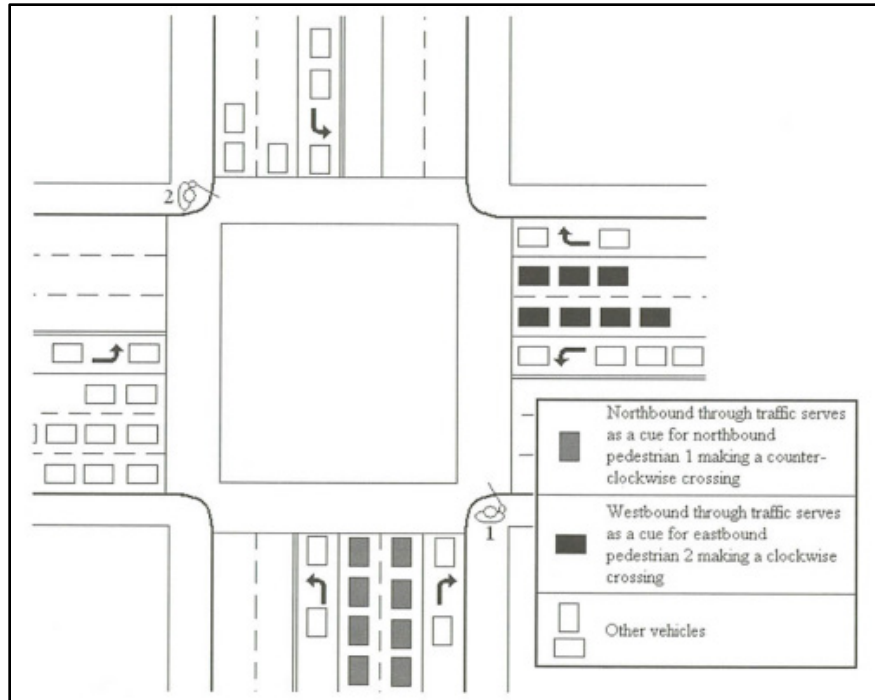


Figure 2.10. Example of O&M Technique (Barlow et al., 2005)

Because LPIs delay the onset of parallel traffic, they may present potential challenges to pedestrians who are blind. A recent study that evaluated the effects of LPIs on blind pedestrians mentions that LPIs could create situations in which blind pedestrians begin and/or end crossings against the pedestrian signal. This study found that at crosswalks with LPI, blind pedestrians can be expected to cross after the WALK sign has expired 15 to 38% of the time and end their crossing 40 to 82% of the time when the visual display says DON'T WALK (Bourquin et al., 2023).

The primary purpose of an LPI is to provide pedestrians with a head start in relation to traffic. However, as mentioned by Bourquin et al. (2023), when blind pedestrians rely only on the auditory cue provided by oncoming traffic, LPIs could further delay the time when blind pedestrians begin to cross. This decreases the amount of time that they have to cross and increases their likelihood of beginning to cross just as vehicles begin to turn, which is counterintuitive to the main problem that LPIs seek to address. To fix this, the installation of APS is proposed (Bourquin et al., 2023). Figure 2.11 shows an example of the ideal placement of APS. And NHCPR Reports 117A (Harkey et al., 2007) and 117B (Harkey et al., 2007) provide guidelines and best practices for APS implementation.

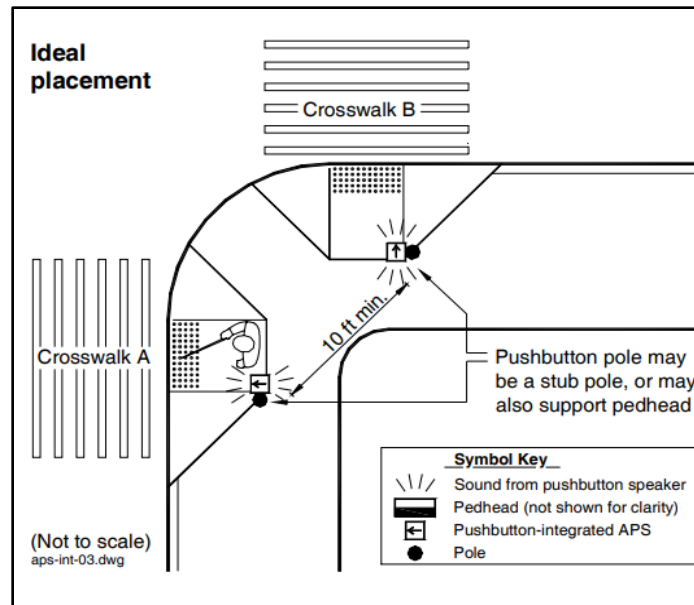


Figure 2.11. Ideal Placement of APS (Harkey et al., 2007)

By communicating the start of the walk signal in non-visual formats, APS not only ensures that pedestrian crossings at signalized intersections are accessible to blind pedestrians, but it also improves safety. For example, Scott et al. (2008) conducted research on crossings by 56 blind pedestrians at complex intersections before and after the installation of APS. The study found that after APS installation, delay in starting to cross was reduced by approximately 2 seconds, and there was significant improvement in independently determining a safe time to cross, beginning to cross during the “Walk” signal, and completing crossings before the onset of perpendicular traffic. Routhier et al. (2023) conducted an exploratory study of blind or visually impaired pedestrians’ sense of safety, preferences, and expectations. This study surveyed 32 blind or visually impaired participants. Findings from the study suggest that an exclusive phasing with directional audible pedestrian signals configuration is perceived to be the safest option by the participants, and overall, the addition of APS to pedestrian signals heightens the sense of safety of blind or visually impaired pedestrians. Finally, NCHRP Report 117A (Harkey et al., 2007) mentions that in addition to the benefits that APS provides to blind pedestrians, sighted pedestrians also begin crossing faster at intersections with APS. This suggests that for all pedestrians, APS improves alertness and reduces delay in starting to cross.

The installation of APS in conjunction with LPIs is consistent with recommendations provided by the MUTCD (FHWA, 2023), research from Bourquin et al. (2023); Harkey et al. (2007); Barlow et al. (2005); and Lin et al. (2017), as well as many jurisdictions across the United States (see Table 2.2).

The final rule of the Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way (PROWAG) states that “*All new and altered pedestrian signal heads installed at crosswalks must include “accessible pedestrian signals”*” (U.S. Access Board, 2023). Under a section titled “Alterations that Trigger Installation of APS”, the rule states the following:

“In the NPRM, the Board indicated that the alteration of a signal controller and software, or the replacement of a signal head, would trigger the requirement to install an accessible pedestrian signal (NPRM R209.2). Upon consideration of public comments, the Access Board acknowledges the diverse nature of alterations that affect pedestrian signals and declines in the final guidelines to list specific actions that trigger the requirement to install accessible pedestrian signals. Rather, pedestrian signals are subject to the same alteration requirements as other pedestrian facilities. The entity making the alteration will assess, according to requirements in the guidelines as adopted by USDOT and DOJ, whether installation of an accessible pedestrian signal is required. The Board notes that USDOT and DOJ may provide further specifics as to alterations triggering installation of APS in their rulemakings adopting these guidelines” (U.S. Access Board, 2023).

Within PROWAG, the following statement is also included:

“The National Committee on Uniform Traffic Control Devices (NCUTCD) recommended requiring installation of accessible pedestrian signals when traffic signal equipment modification or timing changes affect the ability of a pedestrian with a disability to be aware of the change. See NCUTCD, Public Comment, ATBCB–2011–0004–0477, available at www.regulations.gov. NCUTCD cited reduction of walk time or pedestrian clearance, and installation of modified turn phasing as examples of such changes that should warrant conversion to an accessible pedestrian signal” (U.S. Access Board, 2023).

Because LPIs are not directly mentioned within PROWAG, it is up to the entity making the alteration to assess whether an LPI would trigger the installation of an APS. However, given the notable impacts that LPIs have on delaying the onset of traffic surges, which in turn delay the auditory cue that blind pedestrians use to know when to cross, the installation of an APS is recommended as it can help communicate the start of the LPI by providing blind pedestrians with an auditory cue as soon as the LPI activates. Given the impact that LPIs could have on blind pedestrians, and the fact that PROWAG is silent on LPIs, USDOT and DOJ need to provide further specifics on whether LPIs would fall under the list of alterations that would trigger the installation of APS within their rulemakings adopting the PROWAG guidelines.

Although PROWAG is silent on whether an LPI would trigger the installation of APS, and APS is not a current requirement for installation of LPI in the MUTCD, lawsuits involving APS have highlighted the importance of providing APS in conjunction with LPIs. For example, in 2021, the City of Chicago was held in violation of the Americans with Disabilities Act (ADA) for providing APS in fewer than 1% of their signalized intersections. Within the lawsuit, LPIs were identified as something that makes intersections even “more dangerous than before for people who are blind”, because “they deprive blind pedestrians of the extra seconds of crossing time provided to sighted pedestrians”. Additionally, “drivers may get a false sense that no more pedestrians will cross when the traffic light turns green because sighted pedestrians will have already stepped into the crosswalk” (Department of Justice, 2021). Another example is the lawsuit against the City of New York in 2021, where it was mandated for the city to equip at least 10,000 signalized intersections with APS by the end of 2031. In this lawsuit, the court prioritized the installation of APS at signalized intersections with outstanding external/public

requests, LPIs, exclusive pedestrian phases, and a group of 424 intersections newly signalized on or after 06/27/15 which did not include APS” (NYCDOT, 2024). Finally, jurisdictions like the State of California are taking proactive steps regarding APS & LPI implementation. For example, the CalTrans (2021) LPI Implementation Guidelines mention that it is preferable for intersections to have crosswalk markings, APS, and pedestrian countdown signals before LPIs are implemented. And on 10/03/25, California passed legislation related to LPI & APS implementation at state-owned signals through California Senate Bill 671 (Chapter 326).

2.6.2 No Turn on Red (NTOR)

Although LPIs are intended to reinforce pedestrian right-of-way by providing them with a head start, a common concern that is often raised for intersections that do not prohibit right turn on red, is when drivers fail to yield right-of-way to pedestrians during the LPI. A study by Jashami et al. (2024a) analyzed 5 years of crash data in Oregon (2012-2016) to investigate the underlying factors that contribute to right-turn crashes at signalized intersections. A random parameters binary logit model was developed to predict the likelihood of whether a crash resulted in an injury or fatality. A total of 14 variables were found to be statistically significant contributors to crash severity. These included factors like time of day, lighting condition, weather condition, road surface condition, posted speed limit, crash type, driver characteristics, and reported driver-level crash cause. Results from the model showed that 3 reported driver-level crash causes (driver sped too fast for conditions, driver did not yield right-of-way, and driver disregarded the traffic control device) all led to an increase in probability of a fatal or injury crash. The marginal effects from each of these factors were 0.124, 0.202, and 0.075, respectively.

Field observations from an LPI study conducted by Lin et al. (2017) revealed that drivers continued to turn on red when allowed, and if pedestrians had not started to walk, drivers tended to turn quickly at the onset of the walk phase. To prevent these non-yielding behaviors and enhance pedestrian safety at signalized intersections, researchers (Day et al., 2025; Day et al., 2024; Day et al., 2023; Wolfgram et al., 2022; Sharma et al., 2017; Lin et al., 2017), the MUTCD (FHWA, 2023), FHWA (2019), and multiple jurisdictions (NCDOT, 2025; TxDOT, 2024; City of Bellevue, 2023; PennDOT, 2021; CalTrans, 2021; MDOT SHA, 2020) recommend prohibiting right turns on red during the LPI, through complementary treatments such as static or blank-out NTOR signs. There is some concern that rigid NOTR requirements could result in reduced LPI implementation, and should therefore be carefully considered.

The MUTCD recommends installing NTOR “Static” signs when “an engineering study finds that one or more of the following conditions exists: A) Inadequate sight distance to vehicles approaching from the left (or right, if applicable); B) Geometrics or operational characteristics of the intersection that might result in unexpected conflicts; C) An exclusive pedestrian or bicycle phase; D) An unacceptable number of conflicting pedestrian movements with right-turn-on-red maneuvers, especially involving children, older pedestrians, or persons with disabilities; E) More than three right-turn-on-red crashes reported in a 12-month period for the particular approach; or F) The skew angle of the intersecting roadways creates difficulty for drivers to see traffic approaching from their left (or right, if applicable)” (FHWA, 2023). R10-11, R10-11b signs are recommended when a right turn on a circular red signal indication is to be prohibited, and R10-11a signs are recommended when the approach is controlled by both circular red and red arrow indications. Figure 2.12 shows an example of these NTOR “Static” signs.



Figure 2.12. No Turn on Red “Static” Signs (FHWA, 2023)

NTOR “Static” signs have commonly been implemented at signalized intersections where pedestrian safety is a priority. However, some studies suggest that static NTOR signs might have some negative operational impacts on the intersection, such as reduced right-turn vehicle throughput and longer right-turn queue lengths, which can lead to more severe conflicts due to potential driver impatience, peer pressure to clear the queue, or lack of visibility caused by vehicles blocking views of the signal and pedestrians (Singleton et al., 2023). In order to prevent the negative impacts of NTOR, a recommended solution for intersections that experience higher right-turning volumes is to prohibit RTOR only during certain times (e.g., when pedestrians activate the pushbutton, when pedestrian volumes are higher, etc.), which can be achieved through the use of blank-out signs (Day et al., 2025; Cunningham et al., 2020; Singleton et al., 2023; Lin et al., 2017). Figure 2.13 shows an example of a blank-out sign. Cunningham et al. (2020) recommends documenting the effectiveness of the treatment through a before-and-after study.

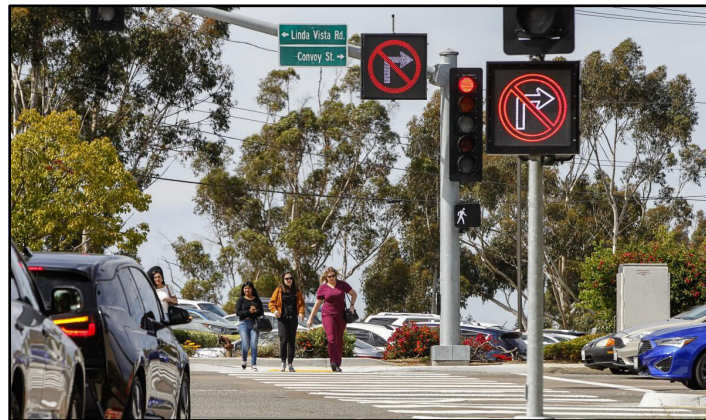


Figure 2.13. NTOR Blank-Out Sign in San Diego, CA (Garrick, 2020)

2.6.3 Yield to Pedestrian Signs

If right turns on red are not prohibited, installation of an R10-15R sign is often recommended at intersections with LPIs, a dedicated turn lane, or a free-flow channelized turn lane (FDOT, 2025; NCDOT, 2025; PennDOT, 2021; MDOT SHA, 2020). Lin et al. (2019) recommends yield to pedestrian blank out signs in conjunction with LPIs. And PennDOT (2021) mentions that R10-15L can be helpful for protected/permissive left turns that don’t end concurrently. Figure 2.14 shows an example of each of these signs (images sourced from MUTCD, 2023; City of Santa Clarita, 2022; and Evangeline Specialties, 2025; respectively).



Figure 2.14. Yield to Pedestrian Signs

2.6.4 Right Turn Flashing Yellow Arrow

Another strategy could be the use of a Right-Turn Flashing Yellow Arrow (RT FYA). The findings from a study conducted by Jashami et al. (2019) found that the RT FYA improves driver-yielding behavior and pedestrian safety at signalized intersections with high volumes of permissive right turns from exclusive right-turn lanes. Although no studies have evaluated the use of an LPI in conjunction with a RT FYA, these two strategies could potentially be combined by having the red arrow be displayed during the LPI, and having the flashing yellow arrow displayed as soon as the LPI is over to help provide further protection to pedestrians at the end of the LPI. This strategy could also help decrease the capacity impacts of a RT FYA, as the red turn arrow could be displayed only for the duration of the LPI instead of the entire walk interval.

Cunningham et al. (2020), studied ten RT FYA and fourteen LPI stand-alone treatment locations across North Carolina. However, no data was collected for the combination of both treatments. From the data that was collected, researchers found that LPIs seem to provide better yielding to pedestrians compared to RT FYAs, with yield rates of 84% compared to 49%, respectively. Although no data for the combination of RT FYAs and LPIs was collected, the researchers mentioned that Charlotte DOT, along with other municipalities and NCDOT Divisions have implemented RT FYA at multiple sites in conjunction with LPIs. As this combination becomes more commonly implemented, it is worth evaluating the combination of these two treatments in future studies.

2.6.5 In-Street Educational Signage

At intersections with push button actuated LPIs, a common concern raised is when pedestrians press the push button but fail to make use of the LPI by either crossing the intersection before the LPI activates or leaving the intersection. According to Lin et al. (2017), this behavior could cause potential driver complaints because of the unnecessary travel delay experienced by motorists when pedestrians do not make use of the LPI. A behavioral pedestrian study by Wyman et al. (2024) found that pedestrians generally attended to traffic signals and push button signage to make efficient crossing decisions. The study also found that separating push buttons on different poles (something that CEs could help accommodate) was associated with the most positive push button behavior outcomes. The findings of this study highlight the important role that engineering modifications to pedestrian infrastructure (e.g. signage and push button pole location) could play in promoting pedestrian behavioral change at signalized intersections.

To help communicate to pedestrians that a signalized intersection has been upgraded with an LPI (and to potentially encourage pedestrians to press the push button and make proper use of the LPI), multiple jurisdictions in Canada and a couple in the US have added in-street educational signage at pilot LPI locations. Figure 2.17 shows some examples of the signage implemented and listed below (same order shown in image) is the name of the jurisdiction that implemented the signage.

1. District of Saanich, British Columbia, Canada (District of Saanich, 2025)
2. City of New Westminster, British Columbia, Canada (McManus, 2022)
3. City of Langford, British Columbia, Canada (City of Langford, 2024)
4. Arlington County, Virginia, United States (Arlington County, 2023)
5. City of Bellevue, Washington, United States (Carlson, 2022)
6. City of Mississauga, Ontario, Canada (Finucane, 2022)
7. Town of West Hartford, Connecticut, United States (Town of West Hartford, 2025)
8. City of Mission, British Columbia, Canada (City of Mission, 2025)

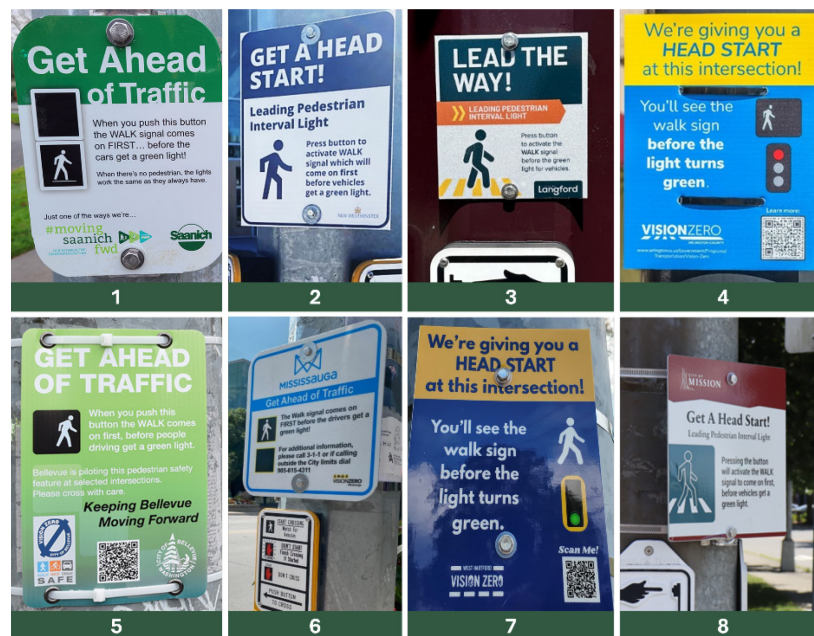


Figure 2.15. In-Street Educational Signage

2.7 COMBINATION OF LPI & CURB EXTENSIONS

Although no research studies have evaluated the effects of LPIs used in conjunction with CEs through field empirical or laboratory experimentation, the idea of combining both of these treatments has been mentioned by NACTO (2013) and in research studies by Saeidi-Razavi & Furth (2023); Gates et al. (2022); and Saneinejad & Lo (2019). Some of the potential benefits of combining both of these treatments include improved visibility, shorter crossing distances, and slower turning speeds.

2.7.1 Improved Visibility

NACTO (2013) recommends installing CEs to help increase the effectiveness of an LPI and improve visibility of pedestrians at high-conflict intersections. CEs may provide increased protection for pedestrians by preventing parked vehicles from blocking pedestrians waiting to cross, while further increasing the visibility of pedestrians and reinforcing their right-of-way within the intersection. Additionally, the presence of CEs can help provide additional space for pedestrians waiting to cross, while also helping to improve the sight distance and sightlines for both pedestrians and motorists, thus providing all users with a better view of potential conflicts.

2.7.2 Shorter Crossing Distances

A Synthesis of National Best Practices on Pedestrian and Bicycle Design, Guidance, and Technology Innovations by Gates et al. (2022) mentions the idea of implementing LPIs in conjunction with CEs to reduce crossing distances at the intersection. Singleton et al. (2023) suggests that shorter crossing distances are important for avoiding pedestrian crashes with right-turning vehicles. Monsere et al. (2020) list CEs as one of three countermeasures to shorten the crossing distance and exposure time of older pedestrians. According to Saeidi-Razavi & Furth (2023), providing a head start in space at signalized intersections through geometric improvements like CEs can encourage shorter LPI lengths, which could lead to less pedestrian and vehicle delay, as well as better pedestrian compliance by increasing capacity and reducing the necessary cycle length. Saneinejad & Lo (2019) also mention the potential of curb extensions in reducing the crossing time, which can reduce the number of seconds allocated to an LPI. They recommend conducting a feasibility analysis that looks into items such as the presence of on-street parking, bike lanes, and the predominant size of turning vehicles.

2.7.3 Slower Turning Speeds

A study by Ghomi & Hussein (2023) integrated a dynamic copula R-vine model and a binary logistic regression model to analyze the safety impacts of multiple Vision Zero treatments, including LPIs, that were implemented in the City of Toronto. The results from the model showed that the combination of speed limit reduction, LPIs, and community safety zones was the most frequent combination in terms of efficiency towards reducing pedestrian collisions. CEs encourage slower vehicle turning speeds by decreasing the turning radii and visually narrowing the road (Ewing, 1999). According to the 2020 NACTO City Limits Guide, the likelihood of fatality increases as vehicle speed increases. Although no previous studies have directly measured the effects in speed reduction when CEs are combined with LPIs, one aspect to consider is the potential effects in turning speed reduction experienced when these two treatments are used in conjunction.

2.8 SUMMARY

The literature review conducted in this research explored 1) the relationship between LPIs and CEs on signalized intersection safety, 2) agency practices related to LPIs and CEs, 3) factors that impact LPI duration and effectiveness, and 4) recommended LPI supplements. The literature review revealed that both LPIs and CEs are known for giving pedestrians a head start at intersections. While LPIs are known for providing pedestrians with a head start “in time”, curb

extensions are known for providing pedestrians with a head start “in space” (Saeidi-Razavi & Furth, 2023). They both share similar safety benefits and demonstrate great potential for improving pedestrian safety at signalized intersections.

To gain a better understanding on existing guidance related to LPIs and CEs across the United States, policy and guidelines from 10+ cities and state DOTs were reviewed. Additionally, factors such as corner radius, street furniture in sight triangle, lane configuration, crosswalk setback, approach and turning speeds, as well as signal operation scheme, were identified as factors that may impact the duration and effectiveness of an LPI. Finally, research and guidance on recommended LPI supplements such as APS and NTOR were also reviewed. Listed below are some of the research gaps identified during the literature review.

- No previous studies have evaluated the combined effects of CEs & LPIs through field empirical or laboratory experimentation.
- Few studies (Lin et al., 2017) have evaluated the effects of NTOR Signs in conjunction with LPIs.
- Notable accessibility concerns have been raised about the use of LPIs without Accessible Pedestrian Signals (APS). Policy changes are needed for LPIs to be classified as an alteration that would trigger the installation of an APS.
- The use of LPIs reduces the available green time for other modes and users, which may have operational and safety issues that need to be evaluated and quantified.

The objective of this research is to provide ODOT with refined tools to improve pedestrian safety at signalized intersections by developing enhanced guidance on when and where to implement Leading Pedestrian Intervals (LPI) either solely or in conjunction with complementary treatments such as Curb Extensions (CE), Accessible Pedestrian Signals (APS), and No Turn on Red (NTOR) signs. Additionally, ODOT needs a tool to quantitatively assess signal inventory to produce a priority list of signals suitable for LPI in order of greatest expected benefit. The research gaps identified above, and the insights gained from the literature review helped inform the methodology of the field and simulator studies, as well as the development of the LPI suitability assessment tool. The guidance provided in this research was developed in a way that can be easily integrated into agency design and practice documents, and an effort was made for the LPI suitability assessment tool to be as comprehensive as possible based on the literature and the findings obtained from this research. Overall, this research supports the ODOT Strategic Action Plan’s priority of a modern transportation system and the Strategic Action Plan’s goal of safety.

3.0 CONFLICT-BASED FIELD STUDY

This chapter presents details on the collection, reduction, and analysis of field data from eleven intersections in the Portland, Oregon area, which include four control, four experimental, and three before/after sites with curb extensions and/or LPIs alone. The primary objective of collecting the field data was to assess the frequency of pedestrian-vehicle conflicts (measured by Post Encroachment Time, or PET) and to explore how these conflicts differ between intersections with and without Leading Pedestrian Intervals (LPIs) and curb extensions.

3.1 VIDEO DATA COLLECTION

To assist with selecting sites for field data collection, the project team requested input from various contacts across ODOT and local agencies such as Washington County, Clackamas County, and the City of Portland. A total of 300 potential sites were received. Varying amounts of information were included in each file, but at a minimum, each file had the list of locations with LPIs. Some files obtained from the agencies had the phases that the LPIs were on and the duration of the LPI. To aid in selecting appropriate field data collection sites, the project team gathered additional information for each location, including speed limits, ADT, curb extension data, LPI duration, transit stop placement, and unique site characteristics.

From this initial list of sites, the project team prioritized sites that were at 4-legged intersections (to be able to compare to the site built in the driving simulator experiment), and that were not close to a school (as the data collection would occur in the summer when the school is closed and therefore crossing volumes would be low). The research team aimed to collect data at 10-12 sites: a third were control sites (no LPI or curb extensions), a third had only LPIs, and a third had LPIs and curb extensions.

Ultimately, the study selected eleven intersections in Portland and Lake Oswego. Two days of video data was collected at each intersection by Quality Counts and analyzed using VLC Media Player. Each intersection included two cameras (at two different corners) to provide multiple viewpoints of the intersection.

Table 3.1 provides a summary of the eleven intersections. The sites were divided into three different groups:

- Control Sites: No LPI or curb extensions.
- Experimental Sites: Both LPIs and curb extensions.
- Before/After Sites: No LPI or curb extension in ‘before’ period; LPI only in ‘after’ period.

For most intersections, two crosswalks were analyzed crossing a main street. At locations with LPIs, these were the crosswalks with LPIs. The individual diagrams for each site showing the

crosswalks of interest and conflicting turning movements (left- and right-turns) are shown in the Appendix.

Table 3.2 shows key characteristics for each crosswalk of each intersection, including the number of curb extensions (maximum 2 per crosswalk), the presence of an LPI, and the crossing distance. These variables are used to sort the intersections into treatments and will also be used for the modelling.

Note that the Holgate and 104th intersection has different treatments for the east and west crosswalk. The west crosswalk has no curb extensions, but has an LPI, so it is categorized as an LPI Only treatment. The east crosswalk has both an LPI and curb extensions, so it is categorized as an LPI + Curb Extension treatment. However, when looking at the conflicts, the east crosswalk only has three conflicts, a very low sample size. Therefore, this crosswalk will be excluded from the dataset and only the west crosswalk (LPI Only) will be included in the statistical analysis and modelling.

Table 3.1. Selected Sites

Site ID	Site	Treatment	City	Main Street	CWs Examined	ADT¹	Speed (mph)¹	Direction¹	Total # Travel Lanes¹	Data Collection Dates (2024)
1	NE Broadway & 21 st Ave	Control	Portland	NE Broadway	East, West	15,000	30	One-Way	3	8/20, 8/21
2	SE Holgate Blvd & SE 92 nd Ave	Control	Portland	SE Holgate Blvd	East, West	13,000	35	Two-Way	5	8/20, 8/21
3	A Ave & 8 th St	Control	Portland	A Ave	East, West	19,000	30	Two-Way	5	9/11, 9/12
4	SE Hawthorne Blvd & 30 th St	Control	Portland	Hawthorne Blvd	East, West	16,000	25	Two-Way	3	9/11, 9/12
5	NE Broadway & 14 th Ave	Experimental	Portland	NE Broadway	East, West	15,000	30	One-Way	3	8/20, 8/21
6	A Ave & 2 nd St	Experimental	Lake Oswego	A Ave	East, West	13,000	30	Two-Way	5	8/20, 8/21
7	SE Hawthorne Blvd & 49 th St	Experimental	Portland	Hawthorne Blvd	East, West	16,000	25	Two-Way ²	3	9/11, 9/12
8	SE Holgate Blvd & 104 th St	Experimental	Portland	SE Holgate Blvd	East, West	13,000	35	Two-Way	4	9/11, 9/12
9A	SE 52 nd & Duke	Before	Portland	SE 52nd	North, South	N/A	25	Two-Way	3	8/20, 8/21
9B	SE 52 nd & Duke	After	Portland	SE 52nd	North, South	N/A	25	Two-Way	3	10/15, 10/16
10A	NE Glisan St & 47 th Ave	Before	Portland	NE Glisan St	East, West	11,000	25	Two-Way	3	8/20, 8/21

Site ID	Site	Treatment	City	Main Street	CWs Examined	ADT¹	Speed (mph)¹	Direction¹	Total # Travel Lanes¹	Data Collection Dates (2024)
10B	NE Glisan St & 47 th Ave	After	Portland	NE Glisan St	East, West	11,000	25	Two-Way	3	10/2, 10/3
11A	W Burnside St & SW 10 th Ave	Before	Portland	W Burnside St	East, West	19,000	20	Two-Way ³	4	8/20, 8/21
11B	W Burnside St & SW 10 th Ave	After	Portland	W Burnside St	East, West	19,000	20	Two-Way ³	4	11/06, 11/07

¹Values are for the main street. ADT values sourced from ODOT TransGIS and rounded to the nearest 1,000. Total number of travel lanes represents the maximum number of travel lanes from both the east and west approaches.²49th Street is one-way.³SW 10th Ave is one-way.

Table 3.2. Intersection Characteristics by Approach

Site	Treatment	Intersection	Crosswalk	C E	LPI	Crossing Distance (ft)	Curb Radii ¹
Single Site	Control	21st & Broadway	East	0	No	56	15', 20'
Single Site	Control	21st & Broadway	West	0	No	56	20', 15'
Single Site	Control	A & 8th	East	0	No	80	14', 12'
Single Site	Control	A & 8th	West	0	No	80	12', 17'
Single Site	Control	Holgate & 92nd	East	0	No	74	12', 16'
Single Site	CE Only	30th & Hawthorne	East	2	No	42	10', 16'
Single Site	CE Only	30th & Hawthorne	West	2	No	41	10', 10'
Single Site	LPI Only	Holgate & 104th	West	0	Yes	66	12', 12'
Single Site	CE + LPI	14th & Broadway	East	2	Yes	42	12', 15'
Single Site	CE + LPI	14th & Broadway	West	2	Yes	46	15', 12'
Single Site	CE + LPI	A & 2nd	East	2	Yes	63	25', 18'
Single Site	CE + LPI	A & 2nd	West	2	Yes	65	20', *
Single Site	CE + LPI	Holgate & 104th	East	1	Yes	57	15', 15'
Single Site	CE + LPI	49th & Hawthorne	East	1	Yes	47	14', 12'
Single Site	CE + LPI	49th & Hawthorne	West	1	Yes	49	12', 9'
Before	Control	47th & Glisan	East	0	No	67	12', *
Before	Control	47th & Glisan	West	0	No	63	12', 12'
Before	Control	52nd & Duke	North	0	No	44	10', 10'
Before	Control	52nd & Duke	South	0	No	48	*, 10'
Before	Control	10th & Burnside	East	0	No	48	10', 12'
Before	Control	10th & Burnside	West	0	No	44	6', 4'
After	LPI Only	47th & Glisan	East	0	Yes	67	12', *
After	LPI Only	47th & Glisan	West	0	Yes	63	12', 12'
After	LPI Only	52nd & Duke	North	0	Yes	44	10', 10'
After	LPI Only	52nd & Duke	South	0	Yes	48	*, 10'
After	LPI Only	10th & Burnside	East	0	Yes	48	10', 12'
After	LPI Only	10th & Burnside	West	0	Yes	44	6', 4'

¹Values are shown for north and south curb radii, respectively. At Duke, values are shown for west and east curb radii, respectively.

*Could not be computed due to poor aerial quality.

3.2 VIDEO DATA REDUCTION

After videos were collected at each of the study sites, volumes and conflicts were extracted for the crosswalks of interest at each intersection.

3.2.1 Volumes

For each crosswalk of interest, researchers collected (1) the volume of pedestrians and the travel direction and (2) the volume of vehicular turning movements across the crosswalk in 5-minute intervals. A volume excel file was created for each day of video collection (two days, collected from 7 AM to 7 PM) and each crosswalk of interest.

In addition to this volume data collection, researchers screened potential vehicle-pedestrian conflicts by conducting a preliminary post-encroachment time (PET) analysis for conflicts that appeared to have a PET of less than 10 seconds. Conflicts with PETs of 6 seconds or less were flagged for the second stage of data reduction.

The research team employed one graduate student and four undergraduate students to perform this analysis. To assist research team members in reducing volume data uniformly, a volume data collection template spreadsheet and a set of instructions were created. Further, undergraduate students were trained on sample data and were provided with feedback prior to commencing data collection. The four undergraduate students completed pedestrian and vehicular volume data collection for one to two intersections each. The graduate student completed the rest of the volume analysis, as well as the conflict data reduction (See Section 3.3).

The data collected for each file is presented in Table 3.3. The video data was manually reviewed and recorded into an excel spreadsheet.

Table 3.3. Volume Data

Field	Description
Date	The date of data collection.
Intersection	The intersection being collected.
Crosswalk Position	East/North or West/South.
Vehicle Type	For each five-minute increment, there is a row for passenger vehicle counts, heavy vehicle counts, and a total.
Passenger Vehicles	Passenger vehicles include light vehicles and passenger vehicles, including cars, trucks, SUVs, ambulances, vans, small delivery vans, and cars with small trailers.
Heavy Vehicles	Heavy vehicles include semi-trucks, buses, large delivery vans, or large trucks with multiple axles.
Total Volume	A total volume is calculated as the sum of these two.
Time Bin	Shows the five-minute time bin.
Conflicting Vehicle Count	The number of left turn, adjacent right turn, and crossing right turn vehicles.
Pedestrian Volume	The number of pedestrians observed going north-south (east-west) and south-north (west-east). This includes the number of people walking, walking their bikes or other mobility devices, or riding their bike in the crosswalk. It does not include people riding their bike adjacent to the sidewalk or in the roadway.
Notes	Analyst notes on any unusual vehicle, pedestrian, weather, or site occurrences.

For each site, there were generally two crosswalks of interest with three vehicular movements of interest. These vehicular movements represent turning vehicles that must yield to pedestrians:

- A left turn from the perpendicular lane,
- An adjacent right turn, from the approach of the study crosswalk to the perpendicular lane, and
- A crossing right turn, from the perpendicular lane to the approach of the study crosswalk.

A diagram of the collected vehicular turning movements is shown in Figure 3.1. Turning movements are the only vehicular movements analyzed in this study, as they represent potential yielding conflicts at the study crosswalks. The figures for each individual intersection are shown in Appendix A (Figures 8.1 to 8.11).

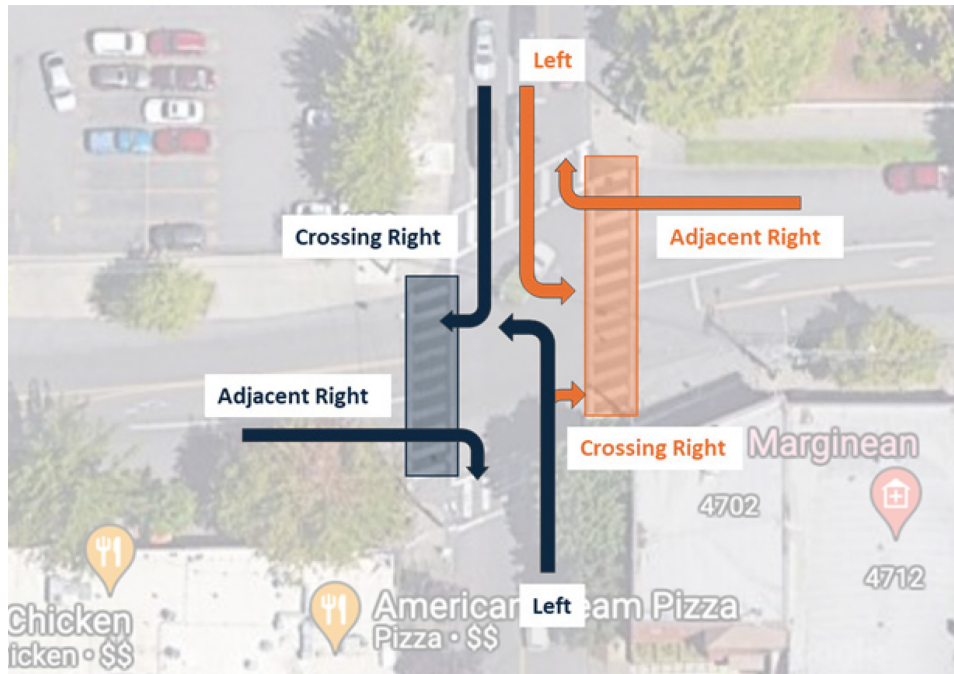


Figure 3.1. Collected Turning Movements

3.2.2 Conflicts

After volume data reduction, pedestrian-vehicle conflicts at the crosswalks of interest for each site were manually reduced from the field-collected videos. This second phase of data reduction produced a conflict file with detailed information on conflicts with PETs < 5. Each conflict with a PET of 6 seconds or less from the conflict screening in Phase 1 was verified using a millisecond measurement. If that PET was 5 seconds or less, detailed data was collected. To assist research team members in reducing conflict data uniformly, a conflict data collection template spreadsheet and a set of instructions were created. The measurements were recorded in quarter of second intervals, the granularity capable by VLC media player. The data elements collected as part of the conflict data extraction is summarized in Table 3.4.

Table 3.4. Conflict Data Reduction

Category	Field	Description
General Information	Date	The date of data collection.
General Information	Intersection	The intersection being collected.
General Information	Crosswalk Position	East/North or West/South.
General Information	Crosswalk Length	The length of the crosswalk (crossing distance).
General Information	Number of Lanes	Number of lanes being crossed.
General Information	Camera Placement	Which corner the camera was placed at for the video being analyzed.
General Information	Time of Day	Morning (7 AM – 12 PM), Afternoon (12 PM – 5 PM), and Evening (5 PM – 7 PM)
IDs	Pedestrian ID	The chronological ID for a pedestrian experiencing a conflict.
IDs	Conflict ID	The chronological ID for a conflict.
IDs	Pedestrian Group Size	How many individuals in a group for each conflict.
Crossing Information	Arrival Time (h.mm.ss.000)	When a user or group arrived at the intersection. Measured as the time when a user stopped or pushed the button. If a user proceeded directly through the intersection without waiting, this time should be the same as the start time.
Crossing Information	Start Time (h.mm.ss.00)	When a user or group began to cross the intersection.
Crossing Information	End Time (h.mm.ss.00)	When a user or group ended crossing the intersection.
Crossing Information	Dwell Time (h.mm.ss.00)	How long a user waited before crossing (Start Time – Arrival Time)
Crossing Information	Crossing Time (h.mm.ss.000)	The time it took a user to cross the intersection (End Time – Start Time)
Crossing Information	Walking Speed (ft/s)	The walking speed of the pedestrian (Length of Crosswalk / Crossing Time)
Signal Timing	Walk Indication Time Stamp (h.mm.ss.000)	Time stamp at which the WALK indication began.
Signal Timing	FDW Indication Time Stamp (h.mm.ss.000)	Time stamp at which the FLASH DON'T WALK indication began.
Signal Timing	DW Indication Time Stamp	Time stamp at which the DON'T WALK indication began.

Category	Field	Description
Conflict Information	Unit 1	Which unit arrived at the conflict point first. 1 if a pedestrian, 2 if a vehicle, 3 if a user riding a bike, 4 if a user walking a bike, and 5 if a scooter
Conflict Information	Unit 1 Departure	Time stamp at which the first user departed the conflict point.
Conflict Information	Unit 2	Which unit arrived at the conflict point second. 1 if a pedestrian, 2 if a vehicle, 3 if a user riding a bike, 4 if a user walking a bike, and 5 if a scooter
Conflict Information	Unit 2 Arrival	Time stamp at which the second user arrived at the conflict point.
Conflict Information	PET Value	Time (in seconds) between the Unit 2 arrival and Unit 1 departure. The approach is detailed in the following section.
Conflict Information	Conflict Time After Walk Signal	Time (in seconds) between the conflict time and the time the WALK indication began
Speed	Speed	Speed of the turning vehicle. The approach is detailed in the following section.
Additional Characteristics	Vehicle Type	0 if passenger vehicle, 1 if pickup truck, 2 if bus, 3 if ambulance, 4 if heavy vehicle (semi-truck, etc.), 5 if van, 6 if motorcycle, 7 if other
Additional Characteristics	Driver Evasive Action	0 if none, 1 if hard braking, 2 if hard swerving, 3 if other
Additional Characteristics	Pedestrian Evasive Action	0 if none, 1 if hard stopping, 2 if hard swerving, 3 if running, 4 if other
Additional Characteristics	Driver Stop Zone	What part of the intersection a driver stopped in (0 if no stopping, one if before first crosswalk, 2 if in first crosswalk, 3 if in intersection, 4 if in second crosswalk)
Additional Characteristics	Driver Stop Type	0 if full stop, 1 if rolling, 2 if partial stop, 3 if a vehicle started from a stop
Additional Characteristics	Pedestrian Distraction	0 if no distraction, 1 if talking on cell, 2 if texting on cell, 3 if headphones, 4 if other
Additional Characteristics	Pedestrian Age	1 if child, 2 if adult, 3 if older adult, 4 if unknown, 5 if group, 6 if teen
Additional Characteristics	Child Present?	0 if no, 1 if yes
Additional Characteristics	Pedestrian Gender	1 if male, 2 if female, 3 if unknown, 4 if group
Additional Characteristics	Pedestrian with Additional Mobility Device	0 if no, 1 if wheelchair/walking aid, 3 if other
Additional Characteristics	Driver Following Other Vehicle	0 if no (driver is first in a vehicular queue/platoon), 1 if yes (driver is behind another vehicle in a queue/platoon)

Category	Field	Description
Additional Characteristics	Pedestrian Crosswalk Violation	0 if no, 1 if yes (pedestrian walks outside of the crosswalk for a portion of the crossing event)
Note	Note	Notes on the conflict

3.2.2.1 Post Encroachment Time

The conflicts were measured using post-encroachment time (PET), and only conflicts with a PET of 5 seconds or less were included in this data. Post encroachment time was originally introduced by Allen et al. (Allen et al., 1978), and is defined as “the time between the moment when the first road user leaves the path of the second and the moment when the second reaches the path of the first (i.e., the PET indicates the extent to which they miss each other)” (Johnsson et al., 2018).

PET is calculated as the difference between the vehicle entering the conflict area and the pedestrian leaving the conflict area i.e., $T_2 - T_1$. The speed of the turning vehicle was measured at both crosswalks near the conflict area using measured distances between landmarks and time differences (T_3 , T_4 , T_5 , and T_6). A schematic of the concept of PET is presented in Figure 3.2.

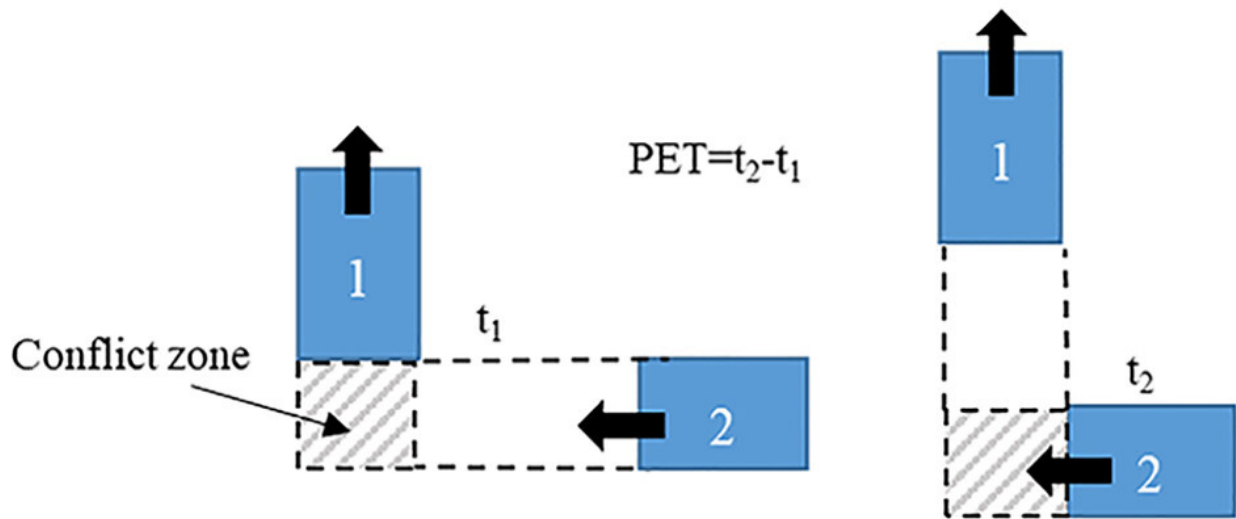


Figure 3.2. Concept of PET (Russo et al., 2020)

3.2.2.2 Speed

For each conflict, an estimated vehicular speed was measured using a two-stage approach. First, for each site, the width of the crosswalks was measured. Then, for each conflict, four timestamps were measured:

- Timestamp when the leading edge of the vehicle crossed the first edge of the first crosswalk (T_3)
- Timestamp when the leading edge of the vehicle crossed the second edge of the first crosswalk (T_4)
- Timestamp when the leading edge of the vehicle crossed the first edge of the second crosswalk (T_5)

- Timestamp when the leading edge of the vehicle crossed the second edge of the second crosswalk (T6)

A diagram of this approach is shown for the crossing right turn of the west crosswalk at Glisan Street and 47th Avenue in Figure 3.3. D1 represents the width of the first crosswalk and D2 represents the width of the second crosswalk.

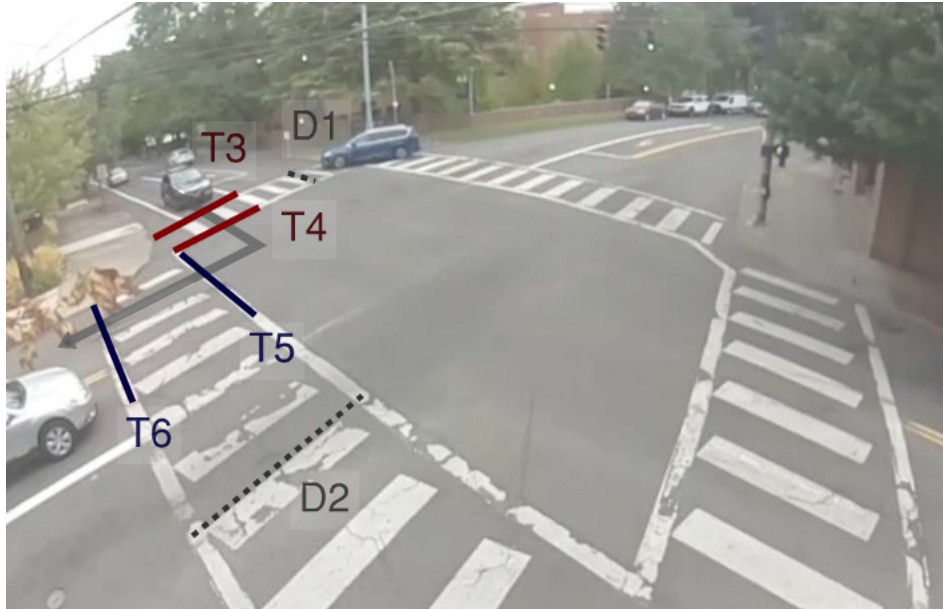


Figure 3.3. Example Speed Methodology

A speed measurement for each crosswalk was then calculated as the time (seconds) between the two timestamps divided by the distance travelled. The final speed was the average of the two stages, converted to miles per hour:

$$Speed (mph) = avg \left(\frac{T4 - T3}{D1}, \frac{T6 - T5}{D2} \right) * \frac{3600}{5280} \quad (3-1)$$

3.3 ANALYSIS

The analysis of the field data was carried out in two major phases: descriptive analysis and modeling. The first phase focused on understanding the descriptive characteristics of the observed data. Rates, trends, and descriptive statistics related to pedestrian and vehicular volume and conflict frequency and severity were evaluated. This included a comparative examination of crosswalks with and without LPs and curb extensions, using both control and treatment sites, as well as sites with before-and-after treatments. Summary statistics were computed across different sites and configurations to identify patterns and variations in pedestrian exposure and vehicular behavior and statistical tests to compare conflict rates among treatment types and sites.

In the second phase, statistical modeling techniques were applied to better understand the factors associated with the frequency and severity of pedestrian-vehicle conflicts. The frequency models explored the likelihood of a conflict occurring, based on exposure variables and treatment conditions. The severity analysis centered on PET as a proxy for conflict risk. Models were constructed to investigate how conflict frequency and severity vary across different intersection designs, traffic volumes, and treatment types.

3.4 DESCRIPTIVE ANALYSIS

3.4.1 Volumes

Figure 3.4 and Figure 3.5 present the conflicting vehicle volumes and pedestrian volumes by intersection, respectively. The presented volumes are summed over the two days of data collection and two crosswalks for each intersection.

Sites generally fall into three volume categories for vehicular volumes: 7,000 – 10,000 (49th and Hawthorne, 47th and Glisan, Holgate and 92nd), 4,000 – 6,000 (21st and Broadway, 52nd and Duke, 30th and Hawthorne) and 2,000 – 3,000 (10th and Burnside, A and 8th, Holgate and 104th, 14th and Broadway, A and 2nd). Holgate and 92nd had the highest volume, followed by 47th and Glisan. A and 8th had the lowest volume but were closely followed by several other intersections.

For pedestrian volume, 10th and Burnside had by far the highest volume, especially in the before period (almost 5,000 pedestrians). This is especially notable given that only one day of data was collected for 10th and Burnside, in comparison to two days for the other sites. This is because 10th and Burnside is the only true ‘downtown’ location in the study, and the intersection includes the popular Powell’s bookstore, leading to high pedestrian volumes. Other pedestrian volumes ranged from 159 (52nd and Duke – Before) to 955 (47th and Glisan – After).

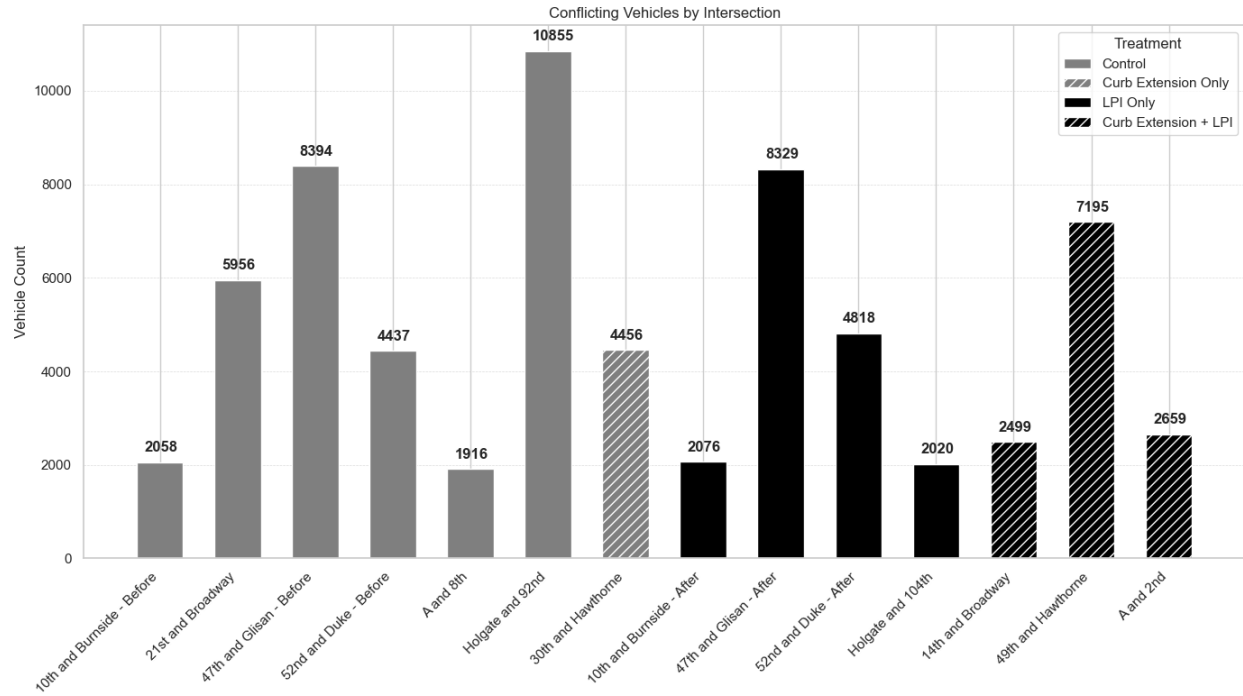


Figure 3.4. Conflicting Vehicle Volumes by Intersection

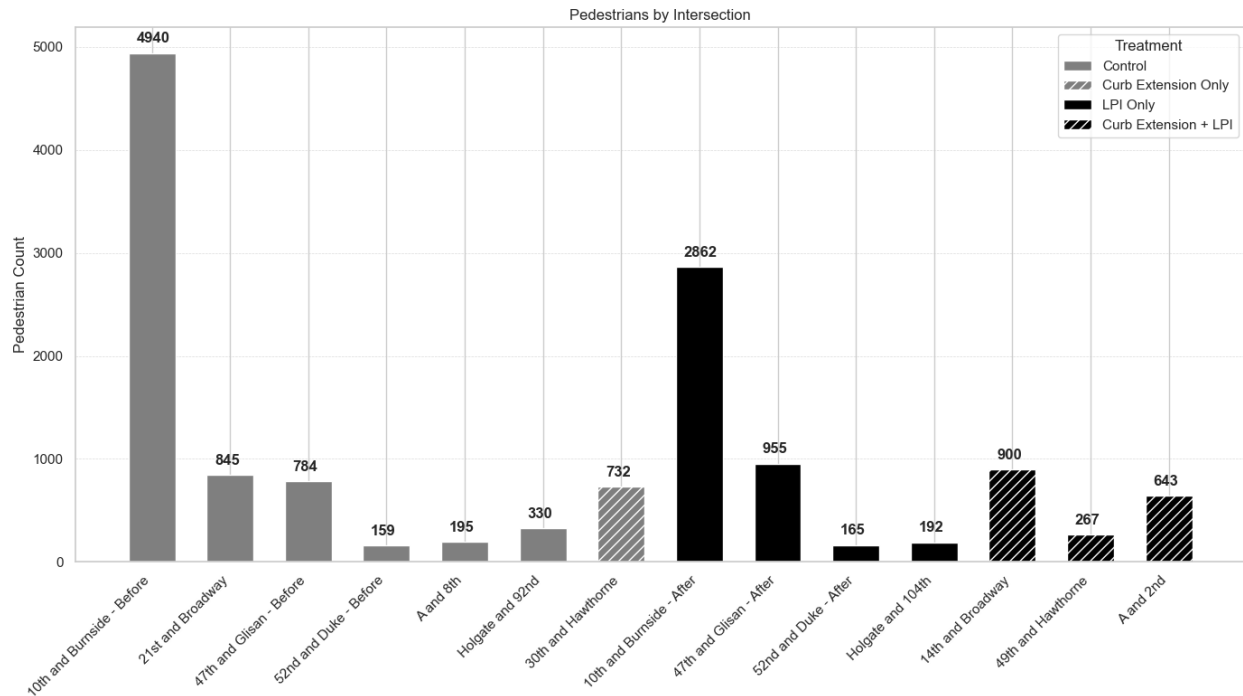


Figure 3.5. Pedestrian Volumes by Intersection

Table 3.5 shows the proportion of left, adjacent right, and crossing right turning movements for each intersection and crosswalk, as well as the total number of vehicles (for all data collected). Values vary based on individual site characteristics.

Table 3.5. Vehicle Volumes for Sites with All Movements

Site	Treatment	Intersection	Cross-walk	Left Turn	Adjacent Right Turn	Crossing Right Turn	Total
Single	Control	21st & Broadway	East	0 (0%)	793 (100%)	0 (0%)	793
Single	Control	21st & Broadway	West	3658 (70.9%)	0 (0%)	1505 (29.1%)	5163
Single	Control	A & 8th	East	148 (19.4%)	108 (14.1%)	508 (66.5%)	764
Single	Control	A & 8th	West	496 (43.1%)	504 (43.8%)	152 (13.2%)	1152
Single	Control	Holgate & 92nd	East	2213 (35.8%)	2045 (33.1%)	1924 (31.1%)	6182
Single	Control	Holgate & 92nd	West	1696 (36.3%)	1526 (32.7%)	1451 (31.1%)	4673
Single	CE Only ¹	30th & Hawthorne	East	1240 (45.2%)	867 (31.6%)	638 (23.2%)	2745
Single	CE Only ¹	30th & Hawthorne	West	467 (27.3%)	420 (24.5%)	824 (48.2%)	1711
Single	LPI Only	Holgate & 104th	West	596 (29.5%)	673 (33.3%)	751 (37.2%)	2020
Single	LPI + CE	14th & Broadway	East	0 (0%)	511 (100%)	0 (0%)	511
Single	LPI + CE	14th & Broadway	West	1546 (77.8%)	0 (0.0%)	442 (22.2%)	1988
Single	LPI + CE	A & 2nd	East	322 (24.9%)	467 (36.1%)	504 (39.0%)	1293
Single	LPI + CE	A & 2nd	West	386 (28.3%)	525 (38.4%)	455 (33.3%)	1366
Single	LPI + CE	49th & Hawthorne	East	2246 (40.3%)	3329 (59.7%)	0 (0%)	5575
Single	LPI + CE	49th & Hawthorne	West	0 (0.0%)	149 (9.2%)	1471 (90.8%)	1620
Before	Control	47th & Glisan	East	2242 (43.8%)	1970 (38.5%)	902 (17.6%)	5114
Before	Control	47th & Glisan	West	443 (13.5%)	619 (18.9%)	2218 (67.6%)	3280
Before	Control	52nd & Duke	North	148 (5.6%)	220 (8.4%)	2263 (86.0%)	2631
Before	Control	52nd & Duke	South	797 (44.1%)	947 (52.4%)	62 (3.4%)	1806

Site	Treatment	Intersection	Cross-walk	Left Turn	Adjacent Right Turn	Crossing Right Turn	Total
Before	Control	10 th & Burnside	East	0 (0%)	660 (50.6%)	644 (49.4%)	1304
Before	Control	10 th & Burnside	West	754 (100%)	0 (0%)	0 (0%)	754
After	LPI Only	47th & Glisan	East	2164 (41.7%)	2066 (39.8%)	958 (18.5%)	5188
After	LPI Only	47th & Glisan	West	477 (15.2%)	703 (22.4%)	1961 (62.4%)	3141
After	LPI Only	52nd & Duke	North	135 (4.6%)	220 (7.5%)	2596 (88.0%)	2951
After	LPI Only	52nd & Duke	South	824 (44.1%)	991 (53.1%)	52 (2.8%)	1867
After	LPI Only	10 th & Burnside	East	0 (0%)	529 (44.0%)	673 (56.0%)	1202
After	LPI Only	10 th & Burnside	West	874 (100%)	0 (0%)	0 (0%)	874

Table 3.6 shows the proportion of pedestrians walking north to south and south to north for each intersection and crosswalk, as well as the total number of pedestrians (for all data collected). The volumes presented in Table 3.6 are the total of observed volumes across all the hours of video that was reviewed. Values vary based on individual site characteristics but typically are close to an even split.

Table 3.6. Pedestrian Volumes by Crosswalk

Site	Treatment	Intersection	Crosswalk	N-S or W-E	S-N or E-W	Total
Single	Control	21st & Broadway	East	120 (46.7%)	137 (53.3%)	257
Single	Control	21st & Broadway	West	294 (50.0%)	294 (50.0%)	588
Single	Control	A & 8th	East	69 (43.4%)	90 (56.6%)	159
Single	Control	A & 8th	West	23 (63.9%)	13 (36.1%)	36
Single	Control	Holgate & 92nd	East	73 (50.0%)	71 (48.6%)	146
Single	Control	Holgate & 92nd	West	77 (41.8%)	107 (58.2%)	184
Single	CE Only ¹	30th & Hawthorne	East	201 (53.0%)	178 (47.0%)	379
Single	CE Only ¹	30th & Hawthorne	West	204 (57.8%)	149 (42.2%)	353
Single	LPI Only	Holgate & 104th	West	83 (43.2%)	109 (56.8%)	192
Single	LPI + CE	14th & Broadway	East	211 (43.2%)	277 (56.8%)	488
Single	LPI + CE	14th & Broadway	West	190 (46.1%)	222 (53.9%)	412
Single	LPI + CE	A & 2nd	East	210 (50.0%)	210 (50.0%)	420
Single	LPI + CE	A & 2nd	West	142 (63.7%)	81 (36.3%)	223
Single	LPI + CE	49th & Hawthorne	East	45 (49.5%)	46 (50.5%)	91
Single	LPI + CE	49th & Hawthorne	West	80 (45.5%)	96 (54.5%)	176
Before	Control	47th & Glisan	East	187 (48.8%)	196 (51.2%)	383
Before	Control	47th & Glisan	West	218 (54.4%)	183 (45.6%)	401
Before	Control	52nd & Duke	North	20 (35.1%)	37 (64.9%)	57

Site	Treatment	Intersection	Crosswalk	N-S or W-E	S-N or E- W	Total
Before	Control	52nd & Duke	South	58 (56.9%)	44 (43.1%)	102
Before	Control	10 th & Burnside	East	881 (48.7%)	929 (51.3%)	1810
Before	Control	10 th & Burnside	West	1424 (45.5%)	1706 (54.5%)	3130
After	LPI Only	47th & Glisan	East	185 (38.9%)	291 (61.1%)	476
After	LPI Only	47th & Glisan	West	271 (56.6%)	208 (43.4%)	479
After	LPI Only	52nd & Duke	North	39 (58.2%)	28 (41.8%)	67
After	LPI Only	52nd & Duke	South	57 (58.2%)	41 (41.8%)	98
After	LPI Only	10 th and Burnside	East	540 (45.2%)	654 (54.8%)	1194
After	LPI Only	10 th and Burnside	West	721 (43.2%)	947 (56.8%)	1668

3.4.2 Speed

Vehicle turning speed was manually measured as the average of vehicle speed across the two crosswalks the vehicle was turning across. This average speed was used to classify conflicts by high and low speed. However, crosswalk-specific speed is also analyzed by turning movement to better understand how speeds vary by type of turn.

For the conflict analysis, a speed threshold was set at 9 mph, as supported in the literature (Fink et al., 2024b; Russo et al., 2023; Shangguan et al., 2024). While there is no one, universal threshold used across studies, typically a value of 8 to 10 mph has been used. 9 mph falls within the middle of that range. This threshold will determine whether a conflict is classified as high speed or low speed.

To confirm this value, the distribution of the data is examined. Table 3.7 provides the median, average, and 85th percentile speeds by intersection, and overall. The histogram of average speed for all intersections is shown in Figure 3.6. The median speed for all sites is 6.93 mph, the 75th percentile speed is 9.08 mph, and the 85th percentile speed is 10.20. Note that, like with volumes, the Burnside site has different speed characteristics, with much lower speed than the other intersections: 6.00 mph for Burnside alone and 7.97 mph for all other intersections. Overall, these statistics indicate that the 9 mph threshold is an approximate 75th percentile value.

Finally, to verify that the data is relatively evenly distributed around the threshold, two other plots are examined: a histogram centered around 9 mph (Figure 3.7) and an Empirical Cumulative Distribution Function (ECDF) plot (Figure 3.8) which shows the percent of observations that have a speed lower than a given value. The histogram shows a comparable distribution of speeds just below and above the threshold (five values between 8.9 and 9 mph, and 6 between 9 and 9.1 mph). The ECDF plot further indicates that approximately 74.6 % of observations fall at or below 9 mph, suggesting that this value represents a reasonable demarcation between lower and higher turning speeds. Together, these plots support the use of 9 mph as a practical threshold for classifying high speed conflicts.

Table 3.7. Speed by Intersection

Site	Treatment	Intersection	n	Min (mph)	Mean (mph)	Median (mph)	85th (mph)	Max (mph)
Single	Control	21st & Broadway	316	3.91	9.2	8.85	11.93	27.27
Single	Control	A & 8th	23	3.34	8	6.88	13.51	17.45
Single	Control	Holgate & 92nd	159	2.24	8.42	7.91	11.75	23.37
Single	CE Only	30th & Hawthorne	145	2.35	8.17	7.81	10.9	23.13
Single	LPI Only	Holgate & 104th	40	3.85	7.89	7.62	10.22	14.69
Single	Curb Extension + LPI	14th & Broadway	106	2.85	6.84	6.62	9.12	13.65
Single	Curb Extension + LPI	A & 2nd	88	3.77	7.26	7.27	9.03	15.91
Single	Curb Extension + LPI	49th & Hawthorne	68	4.65	9.79	8.79	14.15	20.45
Before -After	Control	47th & Glisan - Before	285	3.2	8.43	7.78	10.9	24.61
Before -After	Control	52nd & Duke - Before	50	3.93	9.85	9.12	13.64	24.42
Before -After	Control	10th & Burnside - Before	792	1.22	6.21	5.81	8.18	17.26
Before -After	LPI Only	47th & Glisan - After	260	3.07	8.33	7.79	10.92	21.65
Before -After	LPI Only	52nd & Duke - After	60	4.07	9.65	9.09	13.59	24.37
Before -After	LPI Only	10th & Burnside - After	527	2.83	6.77	6.42	8.73	17.74

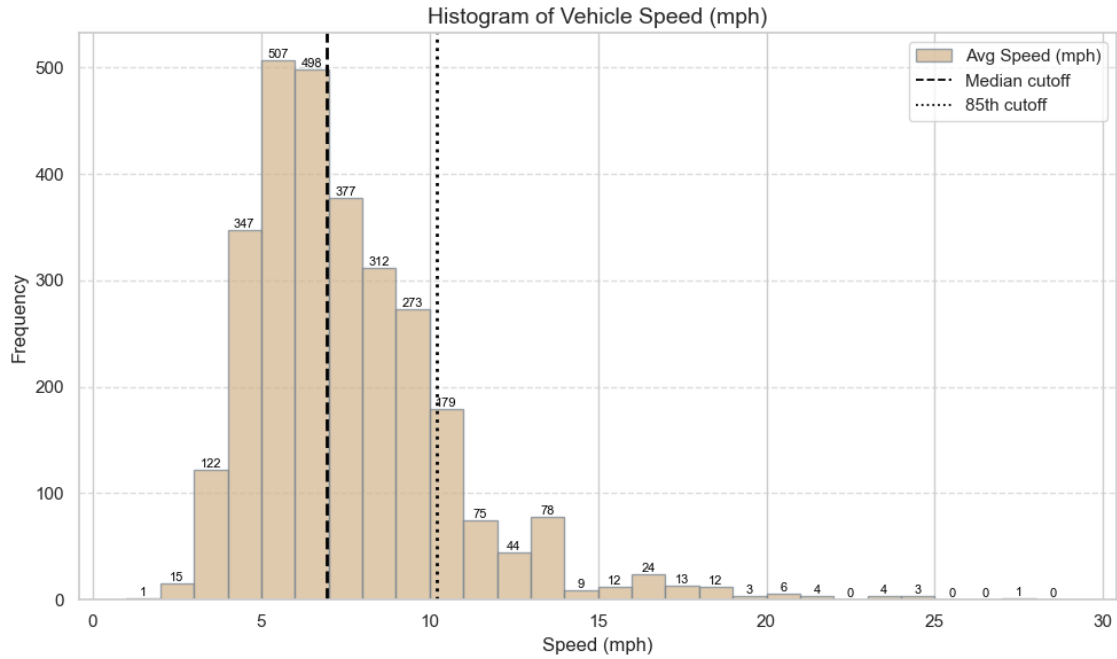


Figure 3.6. Vehicle Turning Speed Histogram (All Intersections)

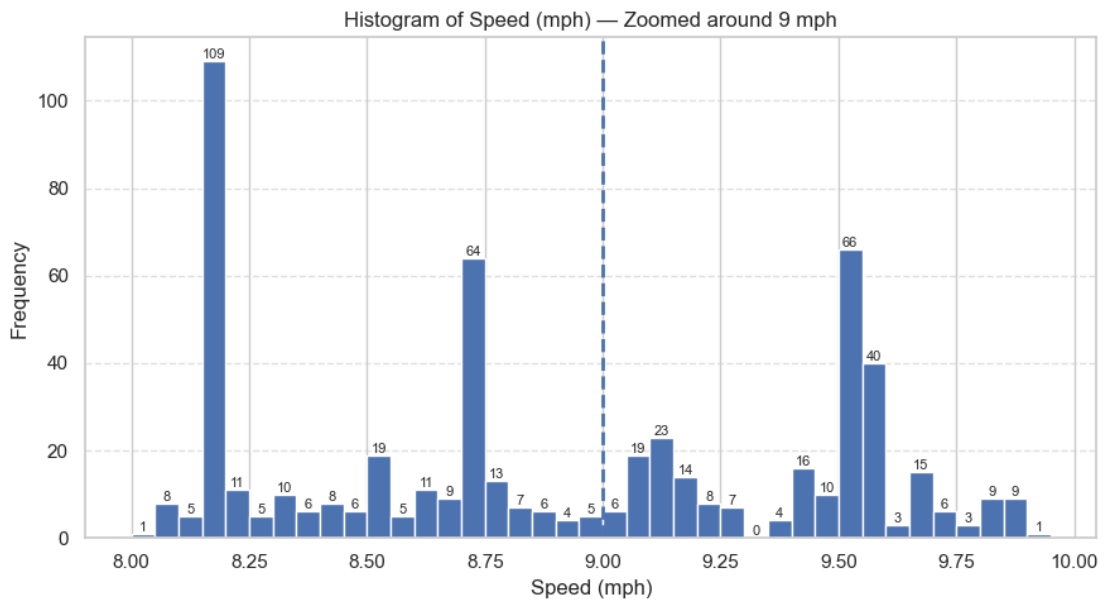


Figure 3.7. Histogram of Speeds around 9 mph

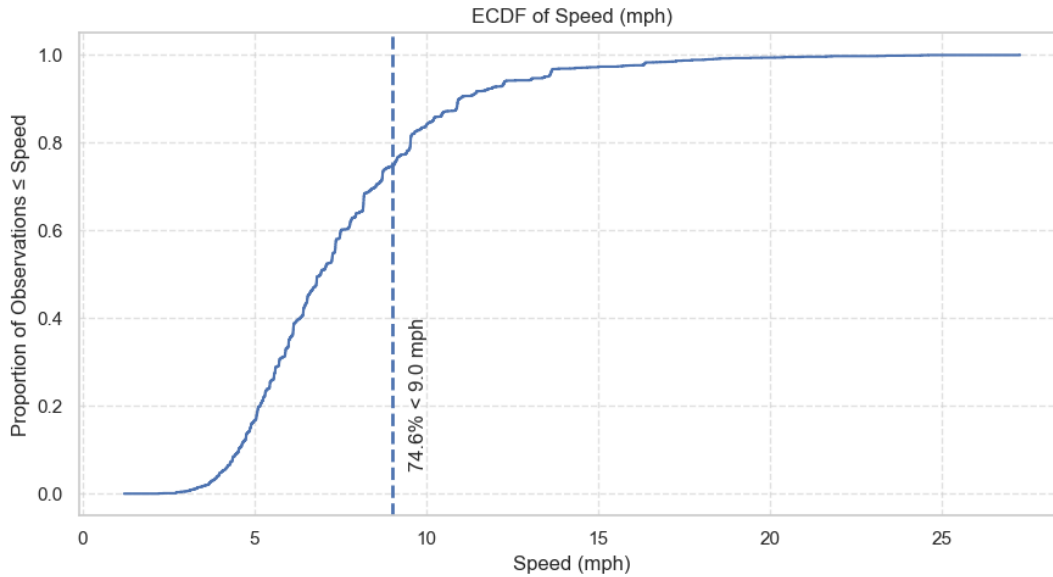


Figure 3.8. ECDF Plot

3.4.3 Conflicts

3.4.3.1 *By Intersection*

Figure 3.9 shows the distribution of PET values, aggregated for all intersections. Conflicts by severity and by intersection are presented in Table 3.8. Conflict Frequency and Severity by Intersection. Overall, 2,916 conflicts were observed across all the sites. 1.8% are high severity (53), 24.5% are medium severity (715), and 73.7% (2148) are low severity.

The highest frequency of conflicts was observed at the 10th and Burnside location (1,319 total for before and after). A high frequency of conflicts was also observed at 21st and Broadway (316 conflicts, control site) and 47th and Glisan (545 total for before and after).

Based on the literature review (Zangenehpour *et al.*, 2016; Kothuri *et al.*, 2018; Russo *et al.*, 2023; Fink *et al.*, 2024a; Shangguan *et al.*, 2024), the conflicts were categorized by PET and speed. The PET thresholds were determined to be:

- High severity: $PET \leq 1.5$ seconds
- Medium severity: $1.5 < PET \leq 3.0$ seconds
- Low severity: $3.0 < PET \leq 5.0$ seconds

Lower PET indicates the potential for more severe conflict. These PET thresholds were drawn from the previous research and the histogram of PET values, which show a distinct jump at 3 seconds. As additional context, Oregon law requires drivers not to start their turn until the pedestrian has cleared the receiving turning lane and is 6 ft into the next

lane or space. At 3.5 ft/s walk speed this would be a PET of approximately 1.7 seconds. While this is a legal standard, it does highlight that the selection of less than 1.5 seconds for high severity is a reasonably objective selection.

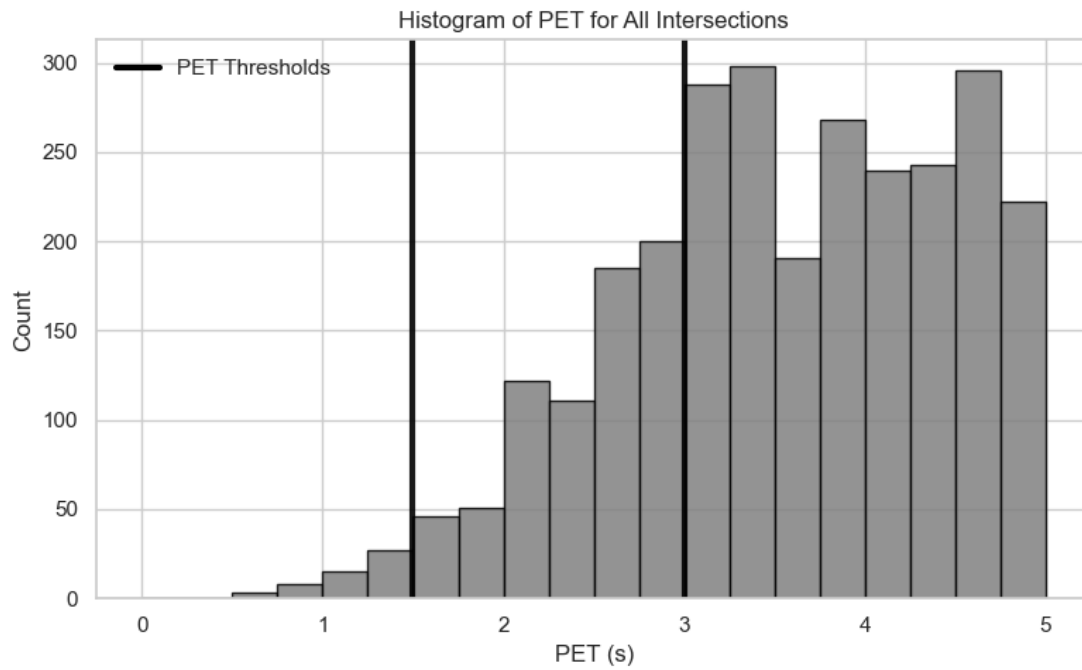


Figure 3.9. Histogram of PET Values

Table 3.8. Conflict Frequency and Severity by Intersection

Site	Treatment	Intersection	Volumes (Vehs)	Volumes (Peds)	High Severity	Medium Severity	Low Severity	All Conflicts
Single	Control	21st and Broadway	5956	845	12 (3.8%)	100 (31.6%)	204 (64.6%)	316
Single	Control	A and 8th	1916	195	0 (0%)	4 (17.4%)	19 (82.6%)	23
Single	Control	Holgate and 92nd	10855	330	4 (2.5%)	37 (23.3%)	118 (74.2%)	159
Single	CE Only	30th and Hawthorne	4456	732	0 (0%)	24 (16.6%)	121 *83.4%)	145
Single	LPI Only	Holgate and 104th	2020	192	0 (0%)	2 (5.4%)	35 (94.6%)	37
Single	LPI + Curb Extension	14th and Broadway	2499	900	1 (0.9%)	27 (25.5%)	78 (73.6%)	106
Single	LPI + Curb Extension	A and 2nd	2659	643	2 (2.3%)	9 (10.2%)	77 (87.5%)	88
Single	LPI + Curb Extension	49th and Hawthorne	7195	267	0 (0%)	12 (17.6%)	56 (82.4%)	68
Before-After	Control	47th and Glisan	8394	784	2 (0.7%)	59 (20.7%)	224 (78.6%)	285
Before-After	Control	52nd and Duke	4437	159	1 (2.0%)	12 (24.0%)	37 (74.0%)	50
Before-After	Control	10 th and Burnside	2058	4940	14 (1.8%)	217 (27.4%)	561 (70.8%)	792
Before-After	LPI Only	47th and Glisan	8329	955	8 (3.1%)	63 (24.2%)	189 (72.7%)	260
Before-After	LPI Only	52nd and Duke	4818	165	2 (3.3%)	16 (26.7%)	42 (70.0%)	60
Before-After	LPI Only	10 th and Burnside	2076	2862	7 (1.3%)	133 (25.2%)	387 (73.4%)	527
Total	All	All	67,668	13,969	53 (1.8%)	715 (24.5%)	2148 (73.7%)	2916

Additionally, conflicts are categorized by a high-speed cutoff (9 mph) as described previously. The primary six categories are presented in **Error! Reference source not found.**, and are as follows:

- High Speed, High Severity
- High Speed, Medium Severity
- High Speed, Low Severity
- Low Speed, High Severity
- Low Speed, Medium Severity
- Low Speed, Low Severity

For statistical tests, due to the low number of high severity conflicts (53 conflicts, 1.8% of the total sample), high and medium severity conflicts are combined as 'high or medium severity' (768 conflicts, 26.3% of the total sample).

Table 3.9. Conflict Severity and Speed by Intersection

Site	Treatment	Intersection	High Severity High Speed	High Severity Low Speed	Medium Severity High Speed	Medium Severity Low Speed	Low Severity High Speed	Low Severity Low Speed	All Conflicts
Single	Control	21st and Broadway	5 (1.6%)	7 (2.2%)	45 (14.2%)	55 (17.4%)	99 (31.3%)	105 (33.2%)	316
Single	Control	A and 8th	0 (0.0%)	0 (0.0%)	0 (0.0%)	4 (17.4%)	5 (21.7%)	14 (60.9%)	23
Single	Control	Holgate and 92nd	1 (0.6%)	3 (1.9%)	17 (10.7%)	20 (12.6%)	54 (34.0%)	64 (40.3%)	159
Single	CE Only	30th and Hawthorne	0 (0.0%)	0 (0.0%)	5 (3.4%)	19 (13.1%)	37 (25.5%)	84 (57.9%)	145
Single	LPI Only	Holgate and 104th	0 (0.0%)	0 (0.0%)	0 (0.0%)	2 (5.4%)	14 (37.8%)	21 (56.8%)	37
Single	LPI + Curb Extension	14th and Broadway	0 (0.0%)	1 (0.9%)	3 (2.8%)	24 (22.6%)	16 (15.1%)	62 (58.5%)	106
Single	LPI + Curb Extension	A and 2nd	0 (0.0%)	2 (2.3%)	3 (3.4%)	6 (6.8%)	11 (12.5%)	66 (75.0%)	88
Single	LPI + Curb Extension	49th and Hawthorne	0 (0.0%)	0 (0.0%)	5 (7.4%)	7 (10.3%)	28 (41.2%)	28 (41.2%)	68
Before- After	Control	47th and Glisan	1 (0.4%)	1 (0.4%)	22 (7.7%)	37 (13.0%)	72 (25.3%)	152 (53.3%)	285
Before- After	Control	52nd and Duke	0 (0.0%)	1 (2.0%)	7 (14.0%)	5 (10.0%)	18 (36.0%)	19 (38.0%)	50
Before- After	Control	10 th and Burnside	1 (0.1%)	13 (1.6%)	25 (3.2%)	192 (24.2%)	56 (7.1%)	505 (63.8%)	792
Before- After	LPI Only	47th and Glisan	1 (0.4%)	7 (2.7%)	21 (8.1%)	42 (16.2%)	67 (25.8%)	122 (46.9%)	260
Before- After	LPI Only	52nd and Duke	1 (1.7%)	1 (1.7%)	8 (13.3%)	8 (13.3%)	21 (35.0%)	21 (35.0%)	60
Before- After	LPI Only	10 th and Burnside	2 (0.4%)	5 (0.9%)	18 (3.4%)	115 (21.8%)	49 (9.3%)	338 (64.1%)	527
Total	All	All	12 (0.4%)	41 (1.4%)	179 (6.1%)	536 (18.4%)	547 (18.8%)	1601 (54.9%)	2916

Figure 3.10 visualizes the total conflicts by pairs of intersections (treatment-control). As with pedestrian volume, the Burnside intersection has the most conflicts of all the intersection pairs, with 792 in the before period and 527 in the after. Note the low sample size for both A and 8th (23 conflicts) and Holgate and 104th (37 conflicts) sites. In general, conflicts at the treated sites or in the after condition reduced compared to the control or before condition except at a couple of site pairs. Recall that the Burnside, Glisan, and Duke pairs are the three true before-after pairs and thus are the most comparable.

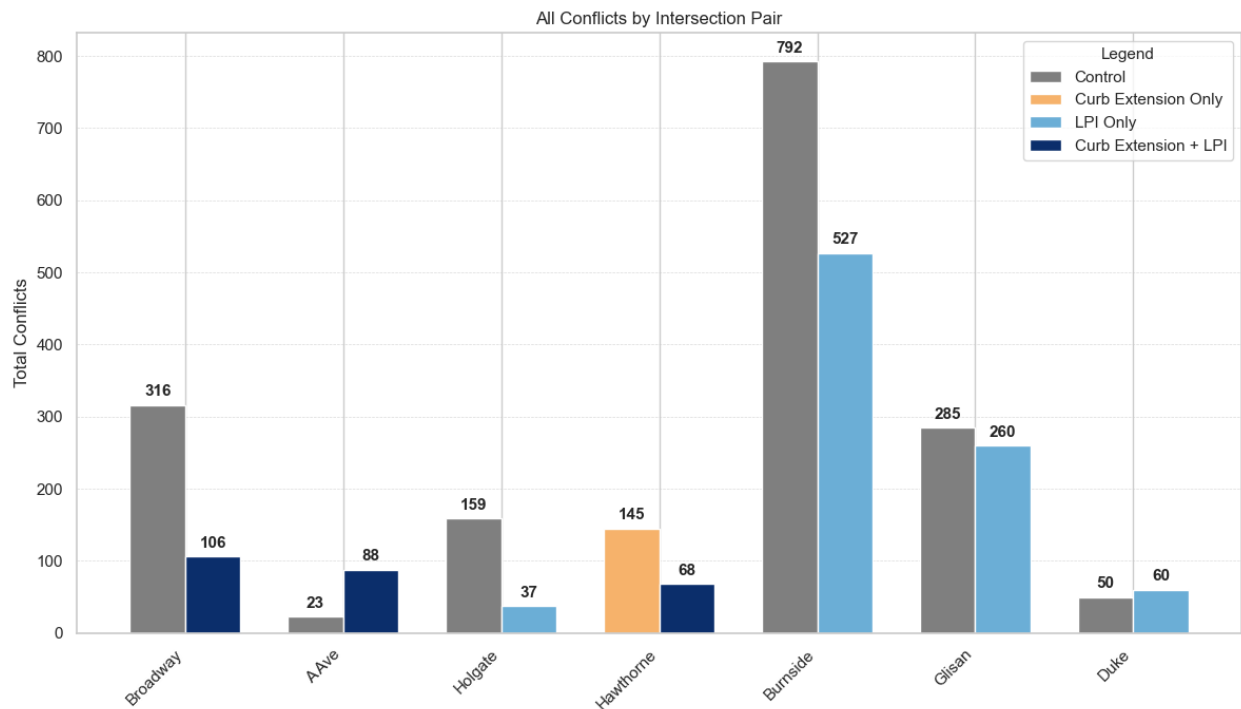


Figure 3.10. Total Conflicts by Pair

To assess whether conflict characteristics varied meaningfully between intersections, a series of Chi-Square tests of independence are conducted on matched and before/after intersection pairs. This test assesses whether the observed frequencies in categorical data differ significantly from expected frequencies under the assumption of independence. This test is supplemented by a conflict severity model.

The first test compares the proportion of high or medium severity conflicts versus low severity conflicts, regardless of vehicle speed. This test evaluates whether intersections with treatments exhibited a higher or lower share of high/medium severity (as defined by $PET < 3$) conflicts relative to all observed events.

The second test compares the proportion of high-speed versus low-speed conflicts, combining all severity levels. This test assesses whether treatments influenced the general speed environment during pedestrian-vehicle interactions.

Overall, most intersection pairs showed no statistically significant differences in the distribution of conflict severity and speed. Broadway (control vs. LPI + curb extension) exhibited significant shifts in high-speed conflicts, with higher proportions of high-speed conflicts observed at the control site. Holgate (control vs LPI only) also exhibited a significant shift, with higher proportions of high/medium severity conflicts observed at the control site. Conversely, the Hawthorne pair showed more high-speed conflicts in the treated site (specifically, more low severity, high speed conflicts). This could be caused by different intersection geometries or other roadway or vehicle characteristics leading to slightly higher turning speeds at 49th & Hawthorne.

These mixed patterns, summarized in Table 3.10, do not provide strong evidence that the treatment (LPI or LPI + curb extension) can shift conflict severity when looking at pairwise comparisons. However, conflict severity will still be explored via a discrete choice model to investigate whether a stronger trend may emerge when controlling for other factors.

Table 3.10. Conflict Severity Significance

Intersection Pair	High/Medium Severity vs Low Severity	High Speed vs Low Speed
Broadway (Control vs LPI+CE)	NS	Control ↑ ($p < 0.001$)
A Ave (Control vs LPI+CE)	NS	NS
Holgate (Control vs LPI)	Control ↑ ($p < 0.05$)	NS
Hawthorne (CE Only vs LPI+CE)	NS	CE + LPI ↑ ($p < 0.05$)
47th & Glisan (Control vs LPI)	NS	NS
52nd & Duke (Control vs LPI)	NS	NS
10th & Burnside (Control vs LPI)	NS	NS

NS=Not Significant. Directional arrows (↑) indicate which site in the pair exhibited a higher proportion of more severe or higher-speed conflicts, and p-values denote statistical significance.

3.4.3.2 By Treatment

Figure 3.11 demonstrates the number of conflicts over the full 24 hours (two days of 7 AM to 7 PM) of video collected, categorized by treatment type. As evidenced, the control treatment has the highest sample size (1625 conflicts), as there are six sites. The LPI treatment has 884 conflicts (4 sites) and the LPI + curb extension site has 262 conflicts (3 sites). The curb extension only site had just 145 conflicts and one site, 30th and Hawthorne.

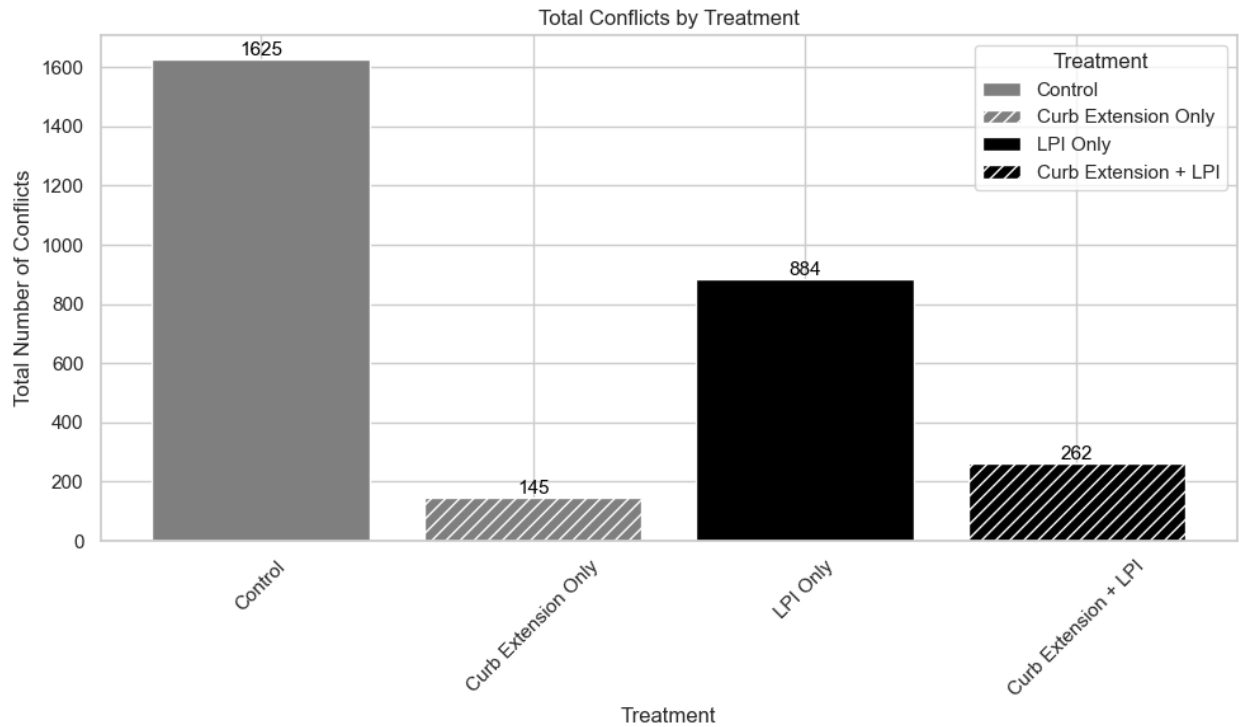


Figure 3.11. Total Conflicts per Treatment

Table 3.11 provides a summary of the observed conflicts categorized by conflict severity. Figure 3.12 presents the proportions of the six primary conflict categories by treatment, categorized by both severity and speed. Figure 3.12 presents proportions by severity only. Note that, for sites with curb extensions, there are no high speed, high severity conflicts.

Note that the curb extension treatment is presented in the table for reference, but excluded from the graphs, as this treatment will not be further analyzed (only one site).

Table 3.11. Conflict Frequency by Treatment (Excluding Burnside Sites)

	Control	CE Only	LPI Only	LPI + CE
Number of Sites	6	1	4	3
Total Pedestrian Volume	7253	732	4174	1810
Total Conflicting Vehicle Volume	33616	4456	17243	12353
All Conflicts	1625	145	884	262
High-Speed Conflicts	428	42	202	66
High Severity Conflicts	33	0	17	3
All-Speed High/Medium Severity Conflicts	462	24	231	51
<i>Proportion of All-Speed High/Medium Severity Conflicts</i>	28.40%	16.60%	26.10%	19.50%
High-Speed, High/Medium Severity Conflicts	124	5	51	11
High Severity Conflicts: High Speed	8 (0.5%)	0 (0.0%)	4 (0.5%)	0 (0.0%)
High Severity Conflicts: Low Speed	25 (1.5%)	0 (0.0%)	13 (1.5%)	3 (1.1%)
Medium Severity Conflicts: High Speed	116 (7.1%)	5 (3.4%)	47 (5.3%)	11 (4.2%)
Medium Severity Conflicts: Low Speed	313 (19.3%)	19 (13.1%)	167 (18.9%)	37 (14.1%)
Low Severity Conflicts: High Speed	304 (18.7%)	37 (25.5%)	151 (17.1%)	55 (21.0%)
Low Severity Conflicts: Low Speed	859 (52.9%)	84 (57.9%)	502 (56.8%)	156 (59.5%)

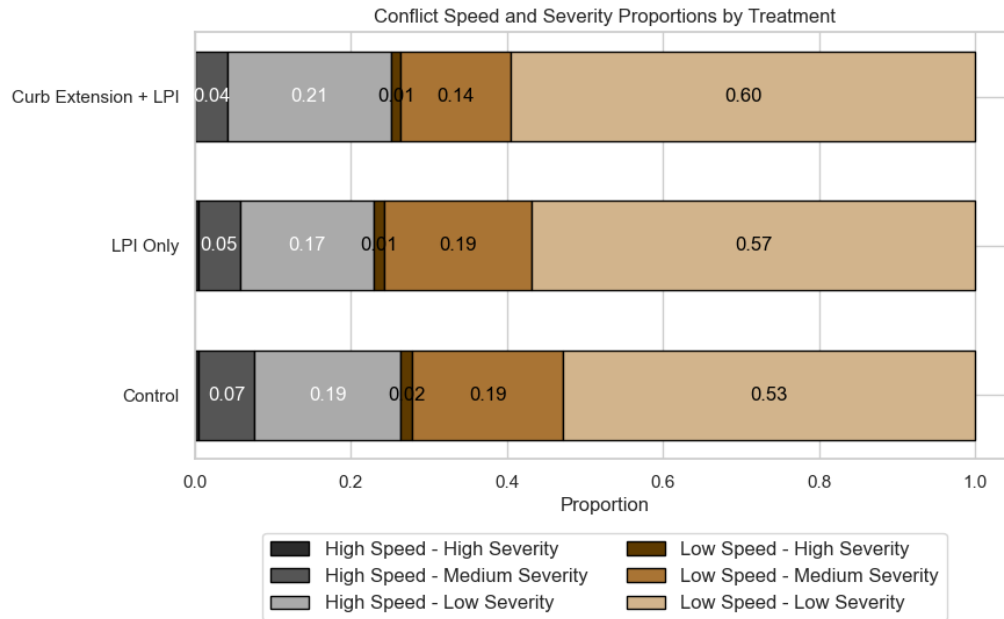


Figure 3.12. Conflict Proportions by Treatment

To evaluate whether the distribution of conflict severity and speed types differed across intersection treatments, a Chi-Square Test of Independence was conducted, similar to the by-intersection comparison. These tests looked at conflict proportions by speed and severity for three treatment groups: control, LPI only, and LPI + curb extension. Curb extension only was excluded due to its low sample size. Results are provided in Figure 3.12.

As evinced, conflict severity varies between the groups ($p < 0.01$), with the control having a higher proportion of all speed high/medium severity conflicts than the treatments. The LPI treatment has the second highest proportion of severe conflicts, and the LPI + curb extension treatment has the lowest proportion of severe conflicts. This provides an indication that curb extensions may be most effective at reducing severe conflicts, though LPIs are also effective. Note that when just looking at speed, there were no significant differences between the treatments. Further investigation and modelling are required to better understand this trend.

Table 3.12. Summary of Conflict Frequency by Treatment (Excluding Burnside Sites)

	High/Medium Severity vs Low Severity	High Speed vs Low Speed
Control	28.4% high/medium severity	26.3% high speed
LPI Only	26.1% high/medium severity	22.9% high speed
LPI + CE	19.5% high/medium severity	25.2% high speed
Result	Control ↑ ($p < 0.01$)	NS

3.4.4 Conflict Rates

To better understand how pedestrian-vehicle conflicts vary by intersection design and treatment type, the research team developed a set of conflict rate metrics normalized by different exposure factors. These metrics help compare safety performance across locations with different volumes of pedestrian and vehicle activity.

First, conflict rates normalized by vehicle volume measure how frequently conflicts occur relative to the number of conflicting turning vehicles at an intersection:

- **Total Conflicts per Vehicle Volume:** The overall number of conflicts divided by the turning vehicle volume.
- **High-Speed Conflicts per Vehicle Volume:** The number of conflicts involving vehicles at high speeds divided by the turning vehicle volume.
- **High/Medium Severity Conflicts per Vehicle Volume:** The number of high/medium severity conflicts per turning vehicle volume.

Conflict rates normalized by pedestrian volume assess how often pedestrians are exposed to conflicts based on their volume:

- **Total Conflicts per Pedestrian Volume:** The overall number of conflicts divided by the pedestrian volume.
- **High-Speed Conflicts per Pedestrian Volume:** The number of conflicts involving vehicles at high speeds divided by the pedestrian volume.
- **High/Medium Severity Conflicts per Pedestrian Volume:** The number of high/medium severity conflicts per pedestrian volume.

Conflict rates normalized by combined exposure account for interactions between pedestrians and vehicles more holistically by using the product of pedestrian and vehicle volumes:

- **Total Conflicts per Combined Volume:** The overall number of conflicts divided by the combined volume.
- **High-Speed Conflicts per Combined Volume:** The number of conflicts involving vehicles at high speeds divided by the combined volume.
- **High/Medium Severity Conflicts per Vehicle Volume:** The number of high/medium severity conflicts per combined volume.

3.4.4.1 By Intersection

To understand how conflict rates differed between treatments, conflict rates for the paired sites and the before-after sites were compared. Figure 3.13 through Figure 3.15 plot the all-conflict rates by vehicle, pedestrian, and combined exposure.

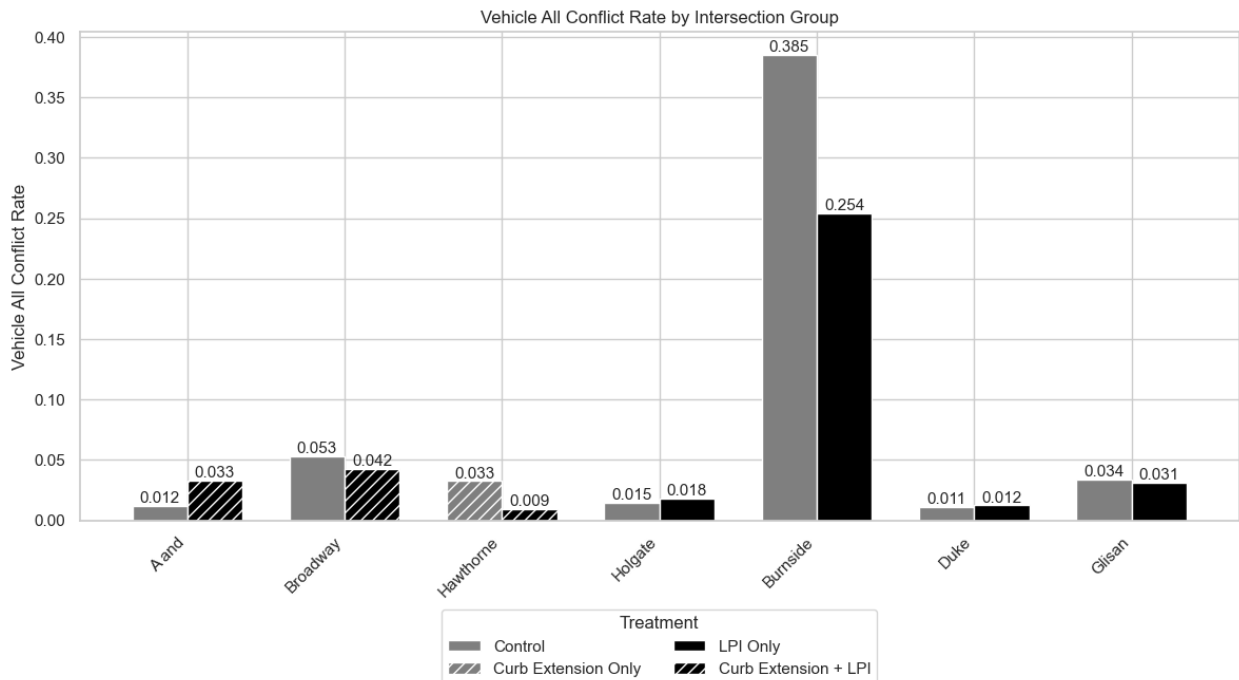


Figure 3.13. Vehicle All Conflict Rate by Intersection

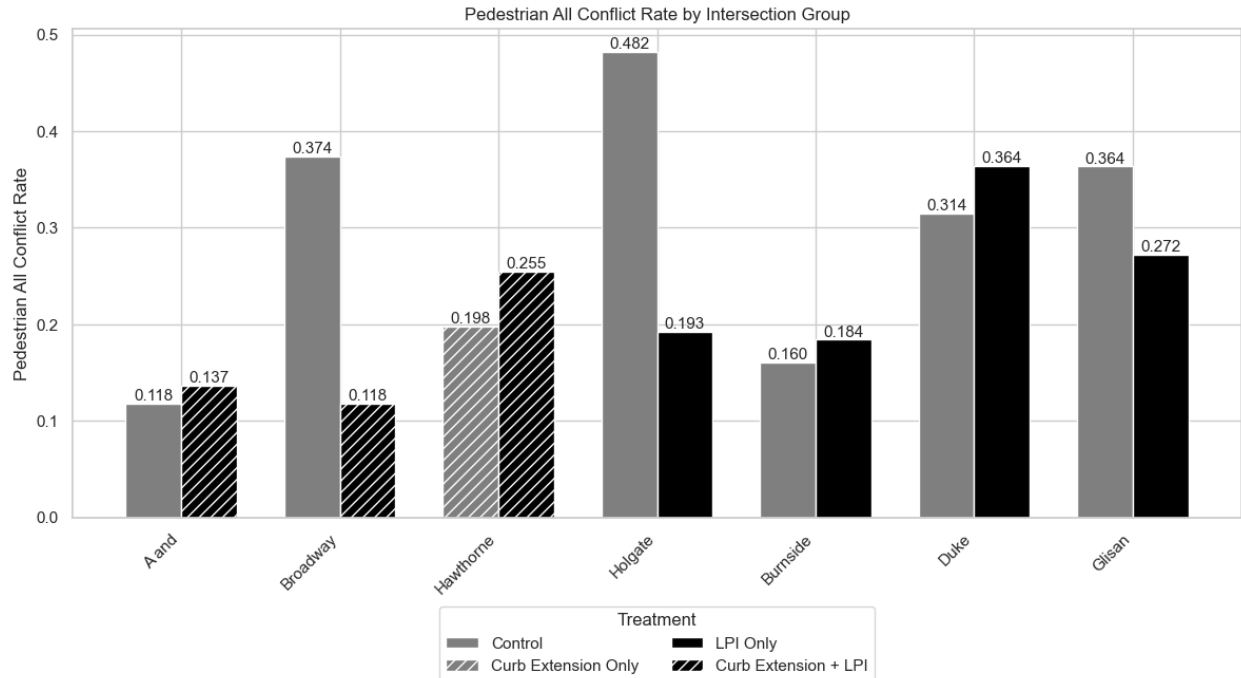


Figure 3.14. Pedestrian All-Conflict Rate by Intersection

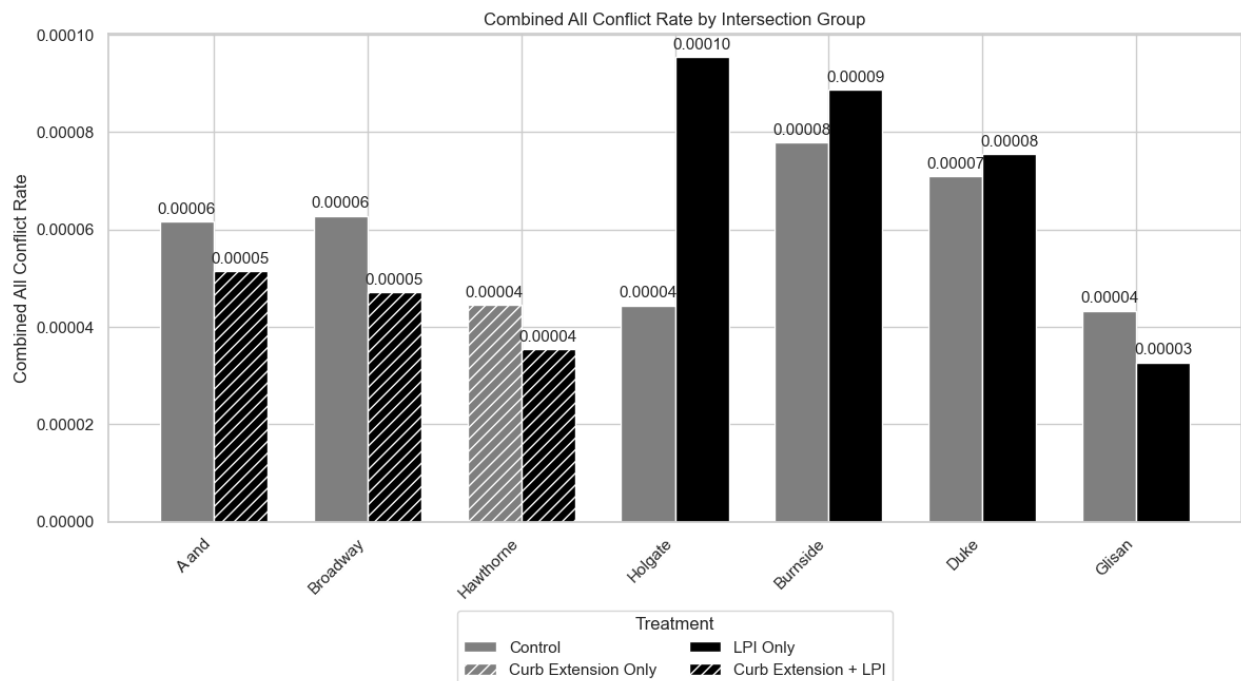


Figure 3.15. Combined All-Conflict Rate by Intersection

To assess whether differences in conflict rates are statistically meaningful, Kruskal-Wallis H tests were conducted on hourly conflict rate distributions for each metric. This non-parametric method tests whether the distribution of hourly conflict rates differs

significantly across treatments, without assuming normality or equal variances. Table 3.13 shows the marginally significant ($p < 0.1$) significant ($p < 0.05$) results of the comparison for all conflicts, high speed conflicts, and high/medium severity conflicts by vehicle, pedestrian, and combined exposure.

3.4.4.2 LPI Only

Across the intersections where pairwise differences reached statistical significance, LPI only treatments produced consistent and often substantial safety improvements. Vehicle conflict rates declined at Burnside and Holgate, with reductions in overall vehicle conflicts (-34%) and high/medium-severity conflicts (-40 to -74%). Glisan and Duke had no significant vehicle-level changes. Pedestrian conflict rates were also reduced at Holgate (-60 to -67%) and Glisan (-25%). Burnside and Duke were not significant on these pedestrian measures. When normalized by combined pedestrian-vehicle exposure, only Glisan showed significance, with a 25% reduction in all conflicts.

Overall, three of the four LPI only pairs (Holgate, Burnside, and Glisan) showed reductions in at least three measures of conflict rates. The all-conflicts rate has the highest sample size and also shows the most consistent results. Duke showed no significant differences, likely reflecting its low sample size (approximately 100 conflicts between the before and after periods).

3.4.4.3 LPI + Curb Extension

With LPIs paired with curb extensions, results were more mixed. At Broadway and Hawthorne, the treatment was associated with a reduction in overall vehicle conflicts (-71%), and high-speed vehicle conflicts (-70%), but an increase for A Ave (+176%). Note that A Ave showed an increase in the vehicle all conflict rate, though the control treatment had few conflicts (23).

Pedestrian conflict rates followed a similar pattern. At Broadway, overall pedestrian conflicts declined by 69% and high-speed pedestrian conflicts declined by 88%. However, there were increases for both A Ave and Hawthorne. When normalized by combined pedestrian-vehicle exposure, only Broadway showed a significant effect, with high-speed conflicts decreasing 72%.

Taken together, LPI + curb-extension results are inconclusive. Some intersections exhibited meaningful reductions, while others showed increases possibly due to small sample sizes and within-pair differences. Additional modeling that incorporates roadway geometry, volume exposure, and contextual variables is needed to more precisely estimate treatment effects on conflict frequency.

Table 3.13. Intersection Pair Summary

Intersection Pair		Control vs LPI Only				Control vs LPI + CE		
		Holgate	Burnside	Glisan	Duke	Broadway	A Ave	Hawthorne ¹
Veh Vol	All Conflicts	NS	LPI ↓ (-34%)*	NS	NS	NS	LPI + CE ↑ (+176%)*	LPI + CE ↓ (-71%)*
Veh Vol	High Speed Conflicts	NS	NS	NS	NS	LPI + CE ↓ (-70%)*	NS	NS
Veh Vol	High/Med Severity	LPI ↓ (-74%)*	LPI ↓ (-40%)*	NS	NS	NS	NS	NS
Ped Vol	All Conflicts	LPI ↓ (-60%)*	NS	LPI ↓ (-25%)*	NS	LPI + CE ↓ (-69%)*	LPI + CE ↑ (+16%)*	NS
Ped Vol	High Speed Conflicts	LPI ↓ (-67%)*	NS	NS	NS	LPI + CE ↓ (-88%)*	NS	LPI + CE ↑ (+115%)*
Ped Vol	High/Med Severity	NS	NS	NS	NS	NS	NS	NS
Tot Vol	All Conflicts	NS	NS	LPI ↓ (-25%)*	NS	NS	NS	NS
Tot Vol	High Speed Conflicts	NS	NS	NS	NS	LPI + CE ↓ (-72%)*	NS	NS
Tot Vol	High/Med Severity	NS	NS	NS	NS	NS	NS	NS

¹Hawthorne LPI + CE site is compared to a control site with curb extensions.

• Significant at p < 0.1 * Significant at p < 0.05 ** Significant at p < 0.01 *** Significant at p < 0.001, NS Not significant

3.4.4.4 By Treatment

In addition to the intersection-level analysis, treatment-level conflict rates are compared with the Kruskal-Wallis H test and are shown in Table 3.14. Figure 3.16 through Figure 3.18 plot overall conflict rates by treatment.

Table 3.14. Conflict Rates by Treatment – Excluding Burnside¹

Exposure	Measure	Control	LPI Only	Curb Extension + LPI
Vehicle Volume	All Conflicts*	0.0483	0.0513	0.0212
Vehicle Volume	High Speed Conflicts***	0.0127	0.0117	0.0053
Vehicle Volume	High/Medium Severity Conflicts***	0.0137	0.0134	0.0041
Pedestrian Volume	All Conflicts***	0.2240	0.2118	0.1448
Pedestrian Volume	High Speed Conflicts***	0.0590	0.0484	0.0365
Pedestrian Volume	High/Medium Severity Conflicts***	0.0637	0.0553	0.0282
Combined Volume	All Conflicts	0.0020	0.0019	0.0021
Combined Volume	High Speed Conflicts***	0.0005	0.0004	0.0005
Combined Volume	High/Medium Severity Conflicts**	0.0006	0.0005	0.0004

* Significant at $p < 0.05$, ** Significant at $p < 0.01$, *** Significant at $p < 0.001$

Bold values indicate a decrease in conflict rate compared to the control.

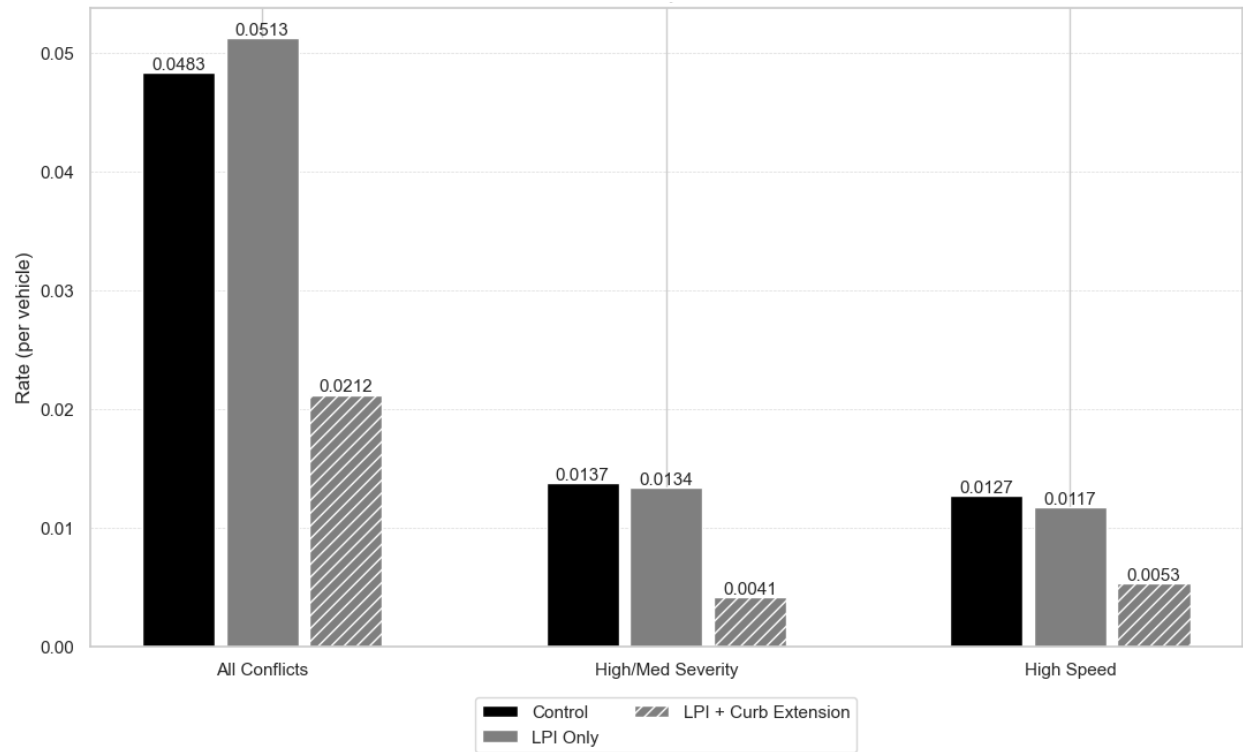


Figure 3.16. Vehicle Conflict Rates by Treatment

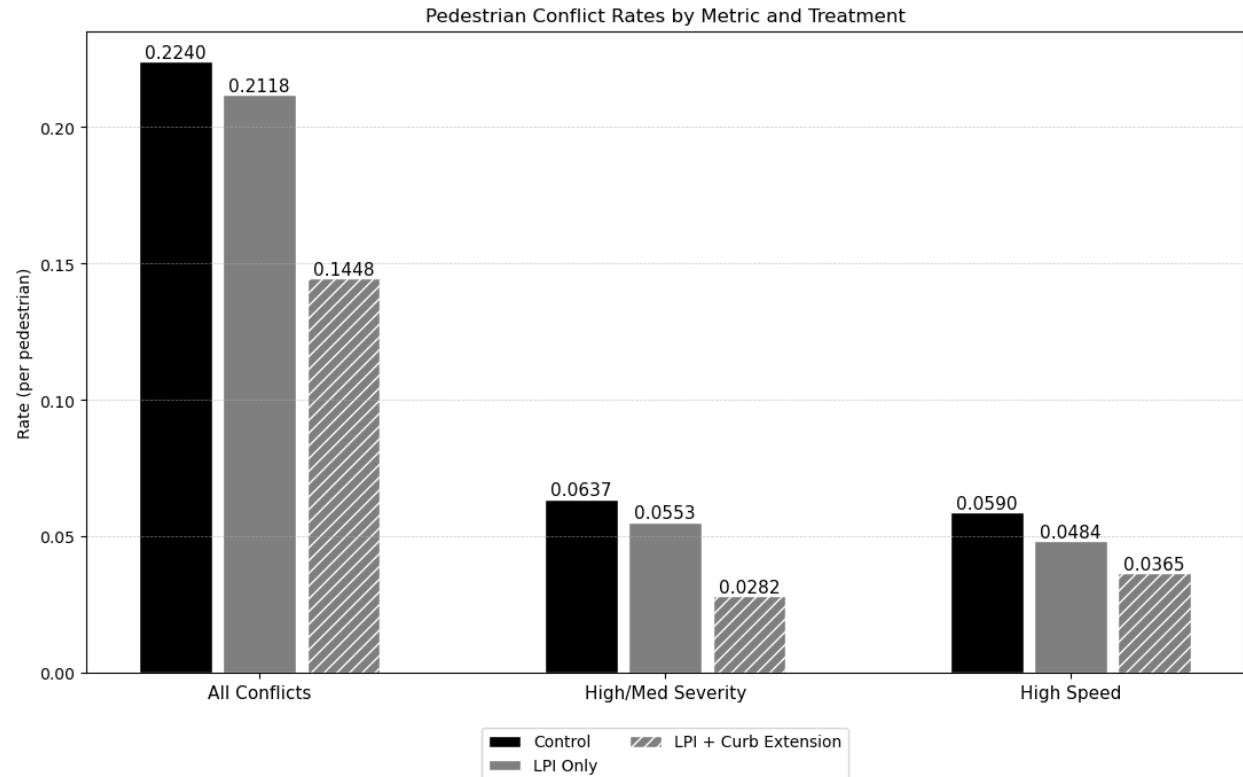


Figure 3.17. Pedestrian Conflict Rates by Treatment

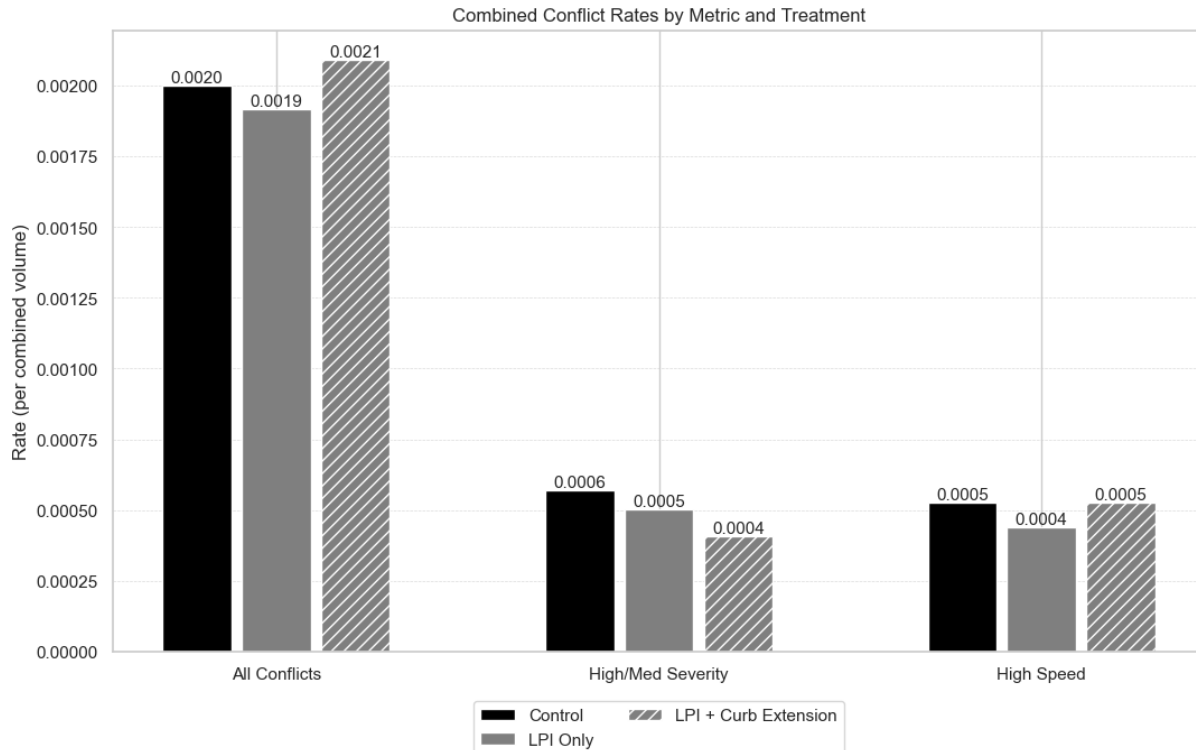


Figure 3.18. Combined Conflict Rates by Treatment

Generally, the three treatments exhibit significantly different distributions of hourly conflict rates. The histograms and pooled conflict rates indicate that sites with the LPI + curb extension treatment have the lowest conflict rates, while control treatment sites have the highest. One exception to this trend is observed for the vehicle-based “all conflicts” metric, where the LPI-only sites show a slightly higher average rate than both the control and LPI + curb-extension treatments.

Overall, the treatment level and intersection level results underscore a need for more detailed analysis. While these comparisons reveal the potential for treatments to reduce conflicts, they do not account for other influencing factors such as traffic volumes, geometry, or temporal variation. To isolate the independent effect of each treatment and control for these covariates, Chapter 6 develops formal conflict frequency models using count data methods to identify whether treatment variables are significant in altering the number of conflicts. This modelling framework provides a more rigorous test of whether the observed reductions remain significant after adjusting for site characteristics and exposure levels.

3.4.5 Conflict Characteristics

The research team conducted a descriptive analysis on a number of key conflict characteristics collected in the conflict severity data reduction. The following sections provide a summary of all the conflict characteristics, categorized by topic.

3.4.5.1 *Demographics & Pedestrian Crossing Characteristics*

Adults comprise the majority of pedestrian crossings, accounting for over 90% at most intersections (peaking at 100% at Holgate and 104th) and never dropping below 73.9% (A and 8th). Non-adult groups remain minimal, with child/teen under 3.4% everywhere, older adults generally below 10% (except 13.0% at 47th and Glisan Before), and unknown/group under 5% at nearly all sites. Child presence at crossings is consistently low. At most intersections, under 6% of child crossings were observed, the exceptions being A and 8th at 21.7% and A and 2nd at 9.1%.

Male pedestrians predominate at most intersections, comprising over 50% of crossings at seven of the fourteen site-treatment combinations. Notable exceptions include A and 2nd, where females account for 56.8% of crossings, and both A and 8th and 10th and Burnside Before, who exhibit unusually large “Unknown/Group” observations.

For all intersections, most pedestrians (over 87%) do not use any type of mobility aid. The site with the highest proportions of wheelchair or walking aid users was 14th and Broadway (8.5%). The site with the highest proportion of stroller use was A and 8th (13%).

For all intersections, the majority of pedestrians (over 87%) do not use any type of mobility aid. The site with the highest proportions of wheelchair or walking aid users was 14th and Broadway (8.5%). The site with the highest proportion of stroller uses was A and 8th (13%).

3.4.5.2 *Pedestrian Operations*

Pedestrian distraction remained rare across all locations. Over 90% of crossings were undistracted at every site, with most intersections showing 2.5 to 8.1% distraction. The highest distraction rate was 11.4% at A and 2nd, while A and 8th saw zero distracted crossings.

The average pedestrian group size is 1.32, showing that while most crossings are by individuals, a meaningful share involves groups. Group sizes vary by location, peaking at a mean of 1.51 on 10th and Burnside before treatment, and dipping to 1.03 at Holgate and 104th. This indicates that some sites may exhibit more group crossing behaviors than others.

Pedestrian dwell time refers to the amount of time a pedestrian waited between arriving at the intersection and beginning crossing. There is a wide variation in average dwell times. A and 8th shows the longest mean dwell at 49.5 s, almost three times the overall average, while 14th and Broadway has the shortest mean of 11.5 s.

Typical pedestrian crossings take about 11 seconds, with an overall mean of 10.9 s (median 10.8 s) and most intersections clustering within ± 3 s of that average. Lowest crossing times were observed at 52nd and Duke After LPI (mean 8.6 s) and 30th and Hawthorne (mean 9.1 s), while highest crossing times are at A & 8th Control (mean 15.6 s) and A and 2nd (mean 13.8 s).

Crosswalk violation (defined as whether the pedestrian stayed fully within the marked crosswalk (no violation) or stepped outside the markings at any point (violation) rates vary substantially by location, peaking at around 40% at A and 8th and Holgate and 104th. Most sites remain below 15%, with the lowest rates of under 6% observed at 14th and Broadway, A and 2nd, and 10th and Burnside After. Cyclists who briefly used the crosswalk are recorded as “no violation.”

Most pedestrians complied with the signal indication. The LPI was activated 100% of the time for the after period for the 10th and Burnside and 47th and Glisan intersections. Additionally, activation rates were high for 14th and Broadway (99.1%) and A and 2nd (96.6%), and 49th and Hawthorne (92.6%). Conversely, several LPI sites had lower compliance rates, including 52nd and Duke (58.3%) and Holgate and 104th (81.1%). This indicates that many pedestrians crossed without a WALK interval and therefore without the aid of the LPI.

3.4.5.3 Conflicts

In almost all intersections, over 80% of conflicts involved a pedestrian arriving first to the conflict zone, with the exception of Holgate and 92nd (65%).

For all intersections, over 80% of conflicts involve a person walking. Cyclists have the highest representation at Holgate and 92nd (13.8%) and 47th and Glisan after (9.6%).

On average, conflicts occur about 15 seconds after the WALK signal begins (mean 14.96 s, median 14.5 s), indicating that most pedestrian-vehicle encounters happen well into the crossing phase. Some intersections deviate from this trend: 52nd and Duke consistently sees quicker conflicts (mean of approximately 10 s), whereas 10th and Burnside experiences later conflicts (mean of approximately 16 s). A handful of negative values (e.g. at 47th and Glisan After) suggest occasional pre-WALK conflicts, indicating that pedestrians crossed during the SDW phase.

Rates of pedestrians in multiple conflicts are generally low (under 5% at most crossings) but several have rates close to 10%, including Holgate and 92nd east crosswalk and 52nd and Duke After south crosswalk.

At some crossings, the conflict-involved pedestrian direction is heavily skewed toward the less-frequent movement in overall volume. For example, for 21st and Broadway east crosswalk, north to south crossings make up 46.7% of the volume but 80% of the conflict involvements, and at Holgate and 104th west crosswalk, south to north crossings account for 56.8% of volume yet 75.7% of conflicts. Other sites maintain similar direction shares between all pedestrians and conflict cases.

Passenger vehicles account for most conflict-involved vehicles, typically 85 - 95% at every intersection, underscoring that most pedestrian-vehicle interactions involve everyday cars rather than heavy vehicles. Pickup trucks are the second most common, making up about 5-10% of conflict vehicles at most sites, while buses, ambulances,

heavy vehicles, vans, motorcycles, and others collectively contribute only 0 to 4% of conflicts.

Most data were collected in the summer, and thus those conflicts occurred in the light. However, both 52nd and Duke After and 10th and Burnside After had data collected in October/November and thus had a couple hours of darkness in the 7 AM – 7 PM period.

3.4.5.4 Driver Behavior

In the vast majority of conflicts (95% or more at most intersections), the driver performed no evasive action. A and 8th had the highest rate of driver evasive action, with 2 drivers (8.7%) hard braking. 47th and Glisan Before had the highest rate of pedestrian evasive action, with about 7% running or hard stopping.

Across intersections, drivers most commonly stop before the first crosswalk, with rates ranging from about 30% (A and 2nd Control) up to 70.6% (10th and Burnside After LPI). “No-stop” behavior is prominent in some locations, including Holgate and 92nd (68.6%), 30th and Hawthorne (60%), 52nd and Duke After (58.3%), and A and 8th (56.5%).

Three sites exhibit majority start-from-stop behavior: 10th & Burnside after at 69.6%, A and 2nd at 58.0 %, and 14th and Broadway at 56.6%. The remaining sites fall below the 50% threshold, indicating more mixed yielding. At two control locations (Holgate and 92nd, 68.6% and A and 8th, 56.5%) rolling is the primary behavior. After LPI installation, rolling still leads at 47th and Glisan (51.9%) and 52nd and Duke (56.7%), showing that many drivers turn without fully stopping. Holgate and 104th presents a nearly even split among rolling (40.5%), start-from-stop (29.7%), and full stops (27%), making it the site with the most varied driver responses. Similarly, 52nd and Duke Before splits rolling and start-from-stop equally at 38% each. While full stops never dominate, they peak at 27% (Holgate and 104th) and 24% (10th and Burnside Before), demonstrating pockets where drivers come to a complete standstill.

At several locations, nearly half of the drivers involved in conflicts were following another vehicle closely (defined as a time gap of five seconds or less), including Holgate and 92nd, 30th & Hawthorne, and 47th & Glisan after. Other intersections saw much lower close-following rates (4 to 10%), notably A and 8th, Holgate and 104th, and 10th and Burnside both before and after treatment.

3.4.5.5 Vehicle Direction

To understand which turning vehicles are most involved with conflicts, the research team conducted an analysis comparing the proportion of turning movements for all conflicting vehicles and the proportion of turning movements for conflicting vehicles involved in conflicts.

The analysis found that adjacent-right turns are under-represented in conflicts relative to their share of total turning volume. This suggests that, per turn, these maneuvers pose lower pedestrian risk than other movements. However, note that adjacent right turns may take place at all phases in a cycle, including when the pedestrian has a SDW indication

and therefore is not typically crossing. Crossing-right turns are over-represented in conflicts, indicating a disproportionately high risk for pedestrians when vehicles make right turns into the crosswalk. These movements may also take place at all phases of the cycle.

Across the 27 intersection-crosswalk pairs, most (19) retained the same dominant turning movement when comparing total volume to conflict volume. However, 8 pairs experienced a shift:

- 4 pairs shifted from adjacent right being the dominant movement in total volume to left turns being dominant in conflicts.
- 2 pairs shifted from adjacent right to crossing right.
- 2 pairs shifted from left turns to crossing right.

Several intersection-specific hotspots emerge from the analysis. At 10th and Burnside east crosswalk (Before and After), crossing right turns account for over 90% of conflicts, despite making up less than 60% of overall turns. Left turns are twice as common in conflicts than in overall turning movements for A and 2nd (both crosswalks) and 52nd and Duke Before and After (south crosswalk).

Table 3.15 presents a table of the difference in vehicle turning proportions for all turns and for turns involved in conflicts. Figure 3.19 plots these differences for adjacent right turn.

Table 3.15. Vehicle Direction: Difference in Percentages between All Conflicting Vehicles and Conflicting Vehicles in Conflicts

Site	Treatment	Intersection	Crosswalk	Left ¹	Adjacent Right ¹	Crossing Right ¹
Single	Control	21st & Broadway	East	0%	0%	0%
Single	Control	21st & Broadway	West	13.7%	-0.3%	-13.3%
Single	Control	A & 8th	East	-1.7%	14.1%	-12.4%
Single	Control	A & 8th	West	-56.9%	43.8%	13.2%
Single	Control	Holgate & 92nd	East	20.3%	14.1%	-34.4%
Single	Control	Holgate & 92nd	West	16.3%	18.0%	-34.2%
Single	CE Only ¹	30th & Hawthorne	East	-4.8%	30.5%	-25.7%
Single	CE Only ¹	30th & Hawthorne	West	3.7%	20.9%	-24.5%
Single	LPI Only	Holgate & 104th	West	2.5%	11.7%	-14.2%
Single	LPI + Curb Extension	14th & Broadway	East	0%	0%	0%
Single	LPI + Curb Extension	14th & Broadway	West	11.1%	0%	-11.1%
Single	LPI + Curb Extension	A & 2nd	East	-24.2%	36.1%	-11.9%
Single	LPI + Curb Extension	A & 2nd	West	-14.1%	35.4%	-21.2%
Single	LPI + Curb Extension	49th & Hawthorne	East	-43.5%	43.5%	0.0%
Single	LPI + Curb Extension	49th & Hawthorne	West	0%	6.0%	-6.0%
Before-After	Control	47th & Glisan - Before	East	-7.6%	29.8%	-22.3%
Before-After	Control	47th & Glisan - Before	West	4.7%	17.5%	-22.2%
Before-After	Control	52nd & Duke - Before	North	-3.50%	8.40%	-4.90%

¹ Difference (All – Conflict)

Site	Treatment	Intersection	Crosswalk	Left ¹	Adjacent Right ¹	Crossing Right ¹
Before-After	Control	52nd & Duke - Before	South	-38.00%	38.10%	-0.20%
Before-After	Control	10 th & Burnside - Before	East	0%	46.60%	-46.60%
Before-After	Control	10 th & Burnside - Before	West	0%	0%	0%
Before-After	LPI Only	47th & Glisan - After	East	-7.70%	22.30%	-14.60%
Before-After	LPI Only	47th & Glisan - After	West	4.20%	19.40%	-23.60%
Before-After	LPI Only	52nd & Duke - After	North	4.60%	7.50%	-12.00%
Before-After	LPI Only	52nd & Duke - After	South	-38.00%	38.80%	-0.80%
Before-After	LPI Only	10 th & Burnside - After	East	0%	40.90%	-40.90%
Before-After	LPI Only	10 th & Burnside - After	West	0%	0%	0%

Note: A positive value indicates a higher percentage of that movement in all turning movements, and thus an underrepresentation in the conflict data (lower risk). A negative value indicates that the movement was overrepresented in conflict data (higher risk).

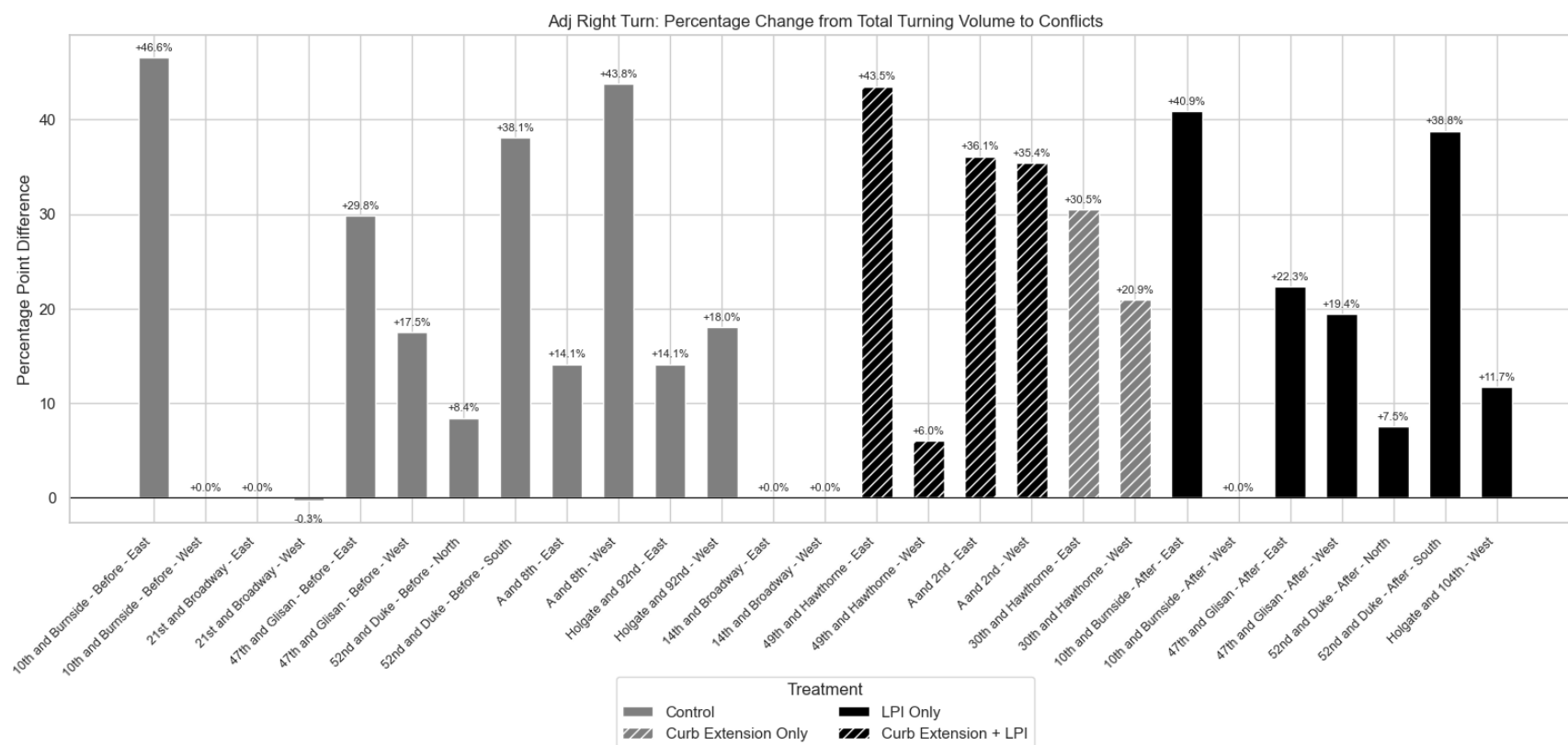


Figure 3.19. Adjacent Right Turn: Percentage Change from Total Turning Volume to Conflicts

3.5 FIELD DATA MODELING

This section describes the conflict frequency and severity model development and analysis.

3.5.1 Conflict Frequency Model Development

Conflict frequency is modeled at the hourly level (per intersection and crosswalk) using a count-data model. The final sample contains $N = 600$ hour-crosswalk-intersection records. The potential explanatory variables for this analysis reflect a combination of treatment conditions, roadway characteristics, temporal factors, and traffic volumes that may influence conflict frequency. The dependent variable is the number of conflicts per hour for each intersection, date, and crosswalk.

Note that all intersections were included in this model. Intersection indicators were used to account for site-level differences. However, note that because of the large sample size at Burnside (1,319 conflicts, $\approx 45\%$ of all conflicts in the sample), results may be influenced by this site's dominance.

Three dependent variables will be examined, as shown in Table 3.16: all conflicts, high speed conflicts (> 9 mph), and high/medium severity conflicts. There are a total of 2,916 conflicts, with 738 high speed conflicts and 768 high/medium severity conflicts.

Table 3.16. Conflicts by Intersection

Site	Treatment	Intersection	All Conflicts	High Speed Conflicts	High or Medium Severity Conflicts
Single	Control	21st and Broadway	316	149 (47.2%)	112 (35.4%)
Single	Control	A and 8th	23	5 (21.7%)	4 (17.4%)
Single	Control	Holgate and 92nd	159	72 (45.3%)	41 (25.8%)
Single	Curb Extension Only	30th and Hawthorne	145	42 (29.0%)	24 (16.6%)
Single	LPI Only	Holgate and 104th	37	14 (37.8%)	2 (5.4%)
Single	LPI + Curb Extension	14th and Broadway	106	19 (17.9%)	28 (26.4%)
Single	LPI + Curb Extension	A and 2nd	88	14 (15.9%)	11 (12.5%)
Single	LPI + Curb Extension	49th and Hawthorne	68	33 (48.5%)	12 (17.6%)
Before-After	Control	47th and Glisan	285	95 (33.3%)	61 (21.4%)
Before-After	Control	52nd and Duke	50	25 (50.0%)	13 (26.0%)
Before-After	Control	10 th and Burnside	792	82 (10.4%)	231 (29.2%)
Before-After	LPI Only	47th and Glisan	260	89 (34.2%)	71 (27.3%)
Before-After	LPI Only	52nd and Duke	60	30 (50.0%)	18 (30.0%)
Before-After	LPI Only	10 th and Burnside	527	69 (13.1%)	140 (26.6%)
Total	All	All	2916	738 (25.3%)	768 (26.3%)

3.5.1.1 Descriptive Statistics

There were an average of 4.86 conflicts per hour, 2.43 high speed conflicts per hour, and 1.28 high/medium severity conflicts per hour. The three outcome measures are all positively skewed with a substantial proportion of zeros, with means exceeding medians and a long upper tail. These plots support the descriptive statistics, showing no major outliers or unexpected trends. Finally, histograms of the three dependent variables show many hours with 0-5 conflicts, but also a long upper tail with up to 80 conflicts per hour.

Plots of conflicts against pedestrian and vehicle volume are also examined. These variables are key to estimating hourly conflicts, as a conflict cannot occur without a vehicle and a pedestrian. There is a clear relationship between conflicts and pedestrian volumes for all three-conflict metrics. Note that 10th & Burnside appears to have a different pattern than the other sites, possibly in part due to its high pedestrian volumes and in part due to specific site characteristics. The trend is similar for vehicle volumes, with a visible positive relationship between vehicles and conflicts for all metrics, though again with Burnside exhibiting a different trend than the other sites. This underscores the importance of including intersection indicators that help account for underlying differences at Burnside.

Further, two variables are added to the potential explanatory variable pool: an interaction term for the 10th & Burnside intersection and vehicle volume and an interaction term for the 10th & Burnside intersection and pedestrian volume. These terms allow different effective coefficients for Burnside and all other intersections. To prevent overfitting and collinearity, the model does not allow both a spline-transformed pedestrian (or vehicle) volume term and a Burnside-specific interaction term to appear simultaneously, ensuring that nonlinear and site-specific effects are not redundantly modeled.

The relationship between the treatment variables (LPI presence and curb extension presence) on conflicts is also examined. For both LPIs and curb extensions, there generally seem to be less conflicts at treated sites, though trends vary based on the conflict metric. To isolate the treatment effects by intersection, intersection/treatment interaction variables are also included in the explanatory variable pool.

Overall, one could expect that, if these exposure and treatment variables are significant, a generally positive trend between exposure and conflicts might emerge, while the relationship between the treatment and conflicts may be inverse.

3.5.1.2 Model Form

The fit of both a Poisson model and a negative binomial model is evaluated. The preferred specification is a pooled model without fixed effects or mixed effects, allowing full variation across intersections while retaining interpretable exposure and treatment terms.

Alternative model structures were also explored. Fixed effects and mixed effects count data models were considered to account for unobserved heterogeneity at the intersection level. However, these approaches substantially restricted the usable variation in the data.

Intersection fixed effects absorbed nearly all between-site variation, which restricted the ability to identify effects of roadway, volume, and treatment characteristics. Similar, mixed-effects models produced unstable estimates because the crosswalk-hour data contained limited within-intersection variation in key predictors.

Because these structures would have forced the analysis to rely only on within-intersection variation, severely limiting the ability to estimate the effects of interest, a pooled modeling framework was adopted. The pooled specification allows the models to leverage the full cross-sectional and temporal variation in the dataset and to incorporate intersection and roadway characteristics directly, rather than attempting to partial them out through fixed or mixed effects.

Model predictors were drawn from an a priori set of exposure variables (e.g., pedestrian and vehicular volumes, turning-movement percentages). To prepare the data for modelling, all categorical predictors were converted to binary dummy variables, while continuous predictors were left on their original scales, except for average daily traffic (ADT), which was divided by 1,000 so that its coefficient reflects thousands of vehicles per day.

Three dependent variables (DVs) are examined:

- **DV 1:** All Conflicts
- **DV 2:** High-Speed Conflicts (> 9 mph)
- **DV 3:** High/Medium Severity Conflicts

To capture potential non-linear relationships, spline terms were included, which allow the slope of a variable to change across different ranges of its values.

To evaluate the robustness of the fitted models, each specification is first estimated on the full training dataset (80% of all observations), setting aside a 20% test set. Five-fold cross validation was conducted on the training set and holdout validation was conducted on the testing set. Two models were fit as negative binomial (all conflicts and high-speed conflicts), while the high/ medium severity conflicts model was retained as Poisson.

3.5.2 Selected Models

Table 3.17 presents the three models' selected variables and performance measures. All models will be evaluated to understand how the treatment variables (e.g., LPI and curb extension) perform under different conflict definitions.

Overall, the all-conflict and high/medium severity conflict models performed well. These two models had high McFadden R^2 values (0.292 and 0.556, respectively), indicating significantly better performance over the intercept-only specification. Further, these models had strong cross-

validation and holdout performance, with cross-validation R^2 scores of 0.714 (all conflicts) and 0.744 (high/medium severity conflicts) and holdout validation R^2 scores of 0.815 (all conflicts) and 0.812 (high/medium severity conflicts). The high-speed model had the weakest model fit, with lower validation R^2 scores (0.425 for cross-validation and 0.642 for hold-out validation).

All three models include a treatment variable as significant, though for model 3, it is modelled as an LPI x Burnside interaction term. For an additional layer of analysis, the all-conflicts model will be further analyzed given the robust model fit, inclusion of the treatment variable, and stronger evidence in the sensitivity analysis.

The final specification for the all-conflicts model includes linear terms for LPI, vehicle volume, left turn percent, and speed limit = 30; intersection indicators for 47th & Glisan and A & 8th; and spline terms for pedestrian volume and adjacent right turn percent. Note that this model exhibited evidence of overdispersion and thus the negative binomial form was appropriate and used.

Note that in subsequent sections the specifications include the estimate (or coefficient), standard error of the estimate, p -value and the incidence rate ratio, or IRR. An IRR represents the expected change in conflict frequency as a multiplicative factor and is determined by exponentiating the parameter estimate; that is, e^β . Alternately, IRRs can be interpreted as a percent increase in the expected number of conflicts as $e^\beta - 1$. IRRs will be used throughout the analysis to describe reductions in conflicts.

² The coefficient of determination (R^2) is computed as $1 - \frac{SS_{res}}{SS_{tot}}$, where SS_{res} is the sum of squared residuals between observed and predicted conflict counts in the test set, and SS_{tot} is the total variance in the observed test outcomes. This measure captures the proportion of variation explained out-of-sample.

Table 3.17. Conflict Frequency Model Options

Mod	DV	Selected Variables	BIC	Null³	Conv.³	R2 (MF¹)	R2²⁴	R2 S.D.⁴	CV RMSE⁴	RMSE S.D.⁴	R2⁵	RMS E⁵
1	All Conflicts	LPI Presence, Pedestrian Volume (spline = 2), Vehicle Volume, Adjacent Right Turn Percent (spline = 2), Left Turn Percent, Intersection = 47 th & Glisan, Intersection = A & 8 th , Speed = 30	1812	-1227	-869	0.292	0.714	0.128	3.952	0.838	0.815	4.714
2	High Speed Conflicts	Curb Extension + LPI, Vehicle Volume (spline = 2), Main Street Direction, Hour, Intersection = 10th & Burnside	1231	-710	-591	0.167	0.425	0.16	1.346	0.324	0.642	1.28
3	High/ Medium Severity Conflicts	Burnside x LPI Only, Pedestrian Volume, Vehicle Volume (spline = 2), Adjacent Right Turn Percent, Day = Thursday, Intersection = 10th & Burnside, Burnside x Pedestrians	967	-1026	-456	0.556	0.744	0.12	1.172	0.188	0.812	1.298

³ Log Likelihood

⁴ Cross Validation

⁵ Holdout

3.5.2.1 *Sign Verification*

For verification, a series of reduced models were estimated, each including only the intercept and one explanatory variable, to confirm the consistency of coefficient direction. Coefficient signs were largely consistent between univariate and multivariable models, with two exceptions. In Model 1, speed limit = 30 mph switched from negative to positive after adjustment, consistent with confounding by exposure and site. In Model 3, the Burnside x pedestrians and Burnside x LPI-only variables reversed sign, reflecting the influence of volumes and site indicators on the adjusted (within-specification) effects. Importantly, the LPI-only flip, from a positive crude association to a negative adjusted association ($IRR \approx 0.63$), is consistent with the potential issue of targeted placement of LPIs at higher-risk sites; once exposure and site context are controlled, LPI-only is associated with fewer conflicts.

3.5.2.2 *Linear Comparison*

Table 3.18 presents the three models' spline and linear model fit specifications. The spline-based selection procedure consistently outperformed the linear algorithm across all three conflict outcomes. Allowing nonlinear functional forms for pedestrian and vehicle volumes yielded substantially lower BIC values and higher McFadden R^2 , indicating improved model fit even after accounting for increased flexibility. These gains suggest that exposure-conflict relationships are not well described by linear trends for this data and that spline transformations more accurately capture more complex relationships between volume and conflicts.

Importantly, treatment indicators such as LPI and curb extension + LPI were only retained in the spline models, while the linear algorithm excluded them entirely. This difference reinforces the importance of flexible modeling: when exposure effects are constrained to be linear, the model may misattribute variation that is partly due to treatments to correlated continuous predictors, suppressing treatment coefficients. Once the nonlinear effects of pedestrian and vehicle volume are modeled correctly, the distinct influence of treatments reemerges. Therefore, the spline models are preferred for inference, as they better represent real-world exposure-risk dynamics while maintaining interpretable treatment effects.

Table 3.18. Conflict Frequency Model Options Including Spline and Linear Fit

Mod	Dep. Variable	Specification⁶	BIC⁶	R2 (M¹)⁶	Specification⁷	BIC⁷	R2 (M¹)⁷
1	All Conflicts	LPI Presence, Pedestrian Volume (spline = 2), Vehicle Volume, Adjacent Right Turn Percent (spline = 2), Left Turn Percent, Intersection = 47 th & Glisan, Intersection = A & 8 th , Speed = 30	1812	0.292	Pedestrian Volume, Vehicle Volume, Adjacent Right Turn Percent, Parking Lane, Hour, Intersection = A & 2 nd , Intersection = 10 th & Burnside, Intersection = 47 th & Glisan, Intersection = 49 th & Hawthorne, Intersection = Holgate & 104 th	1889	0.261
2	High-Speed Conflicts	Curb Extension + LPI, Vehicle Volume (spline = 2), Main Street Direction, Hour, Intersection = 10 th & Burnside	1231	0.167	Vehicle Volume, Adjacent Right Turn Percent, Bike Lane, Hour, Intersection = 10 th & Burnside, Intersection = 30 th & Hawthorne	1254	0.151
4	High/Medium Severity Conflicts	Burnside x LPI Only, Pedestrian Volume, Vehicle Volume (spline = 2), Adjacent Right Turn Percent, Day = Thursday, Intersection = 10 th & Burnside, Burnside x Pedestrians	967	0.556	Pedestrian Volume, Vehicle Volume, Adjacent Right Turn Percent, Main Street Direction, Day = Thursday, Intersection = 10 th & Burnside, Intersection = 47 th & Glisan, Burnside x Pedestrian Volume	980	0.549

⁶ Spline

⁷ Linear

3.5.2.3 Treatment Comparison

To understand how the target treatments performed across conflict definitions and model specifications, the estimated coefficients and IRRs for the three models are compared. The results (Table 3.19) show that all three models include a treatment-related variable. The all-conflict model identifies LPI presence (binary, 1 = LPI present) as a significant contributing factor, encompassing intersections with either an LPI alone or an LPI combined with a curb extension. The negative coefficient of -0.285 and the corresponding IRR (0.752) suggest a reduction of approximately 25% in conflicts at intersections with an LPI.

The high-speed conflict model identifies the curb extension + LPI variable (binary, 1 = both treatments present) as a significant contributing factor. The negative coefficient of -0.546 and the corresponding IRR (0.579) suggest a reduction of approximately 42% in high-speed conflicts where both treatments were implemented. However, note that the sensitivity analysis does not confirm these results, so results should be interpreted with caution.

The high/medium severity conflict model identifies the interaction of Burnside and LPI only (binary, 1 = only LPI present) as a significant contributing factor, implying an approximately 37% reduction (estimate = -0.458, $p = 0.003$, IRR = 0.632) in conflicts at Burnside when only an LPI is present. However, again note that the sensitivity analysis does not confirm these results, so results should be interpreted with caution.

Overall, the results indicate that LPIs are consistently associated with lower conflict frequency in the pooled models. Evidence for reductions in high-speed and high/medium-severity conflicts is suggestive but not confirmed by the sensitivity analyses and thus should be interpreted cautiously. Taken together, LPIs, and, to a lesser extent, curb extensions, appear negatively associated with conflicts, but additional sites and larger samples are needed to establish the magnitude and generalizability of these effects across conflict definitions.

Table 3.19. Conflict Frequency: Treatment Variables

Mod.	Dependent Variable	Treatment Variable	Estimate	p-value	IRR
1	All Conflicts	LPI Presence	-0.285	< 0.001	0.752
2	High Speed Conflicts	Curb Extension + LPI	-0.546	0.002	0.579
3	High/Medium Severity Conflicts	Burnside x LPI Only	-0.458	0.003	0.632

3.5.2.4 *All Conflicts*

In this section, model 1 (all conflicts) is examined in greater detail as the primary specification.

Table 3.20 shows the final model specifications for modelling hourly conflicts using the negative binomial framework.

Table 3.20. All Conflicts: Final Model Coefficients

Category	Variable	Estimate	Std. Error	z-value	p-value	IRR
	Intercept	-0.072	0.123	-0.584	0.559	0.931
Volume	Pedestrian Volume (Spline 1)	6.726	0.201	33.472	< 0.001	NA
Volume	Pedestrian Volume (Spline 2)	1.204	0.223	5.402	< 0.001	NA
Volume	Vehicle Volume	0.005	0.000	10.399	< 0.001	1.005
Volume	Left Turn %	0.004	0.001	3.483	< 0.001	1.004
Volume	Adjacent Right Turn % (Spline 1)	-1.213	0.196	-6.172	< 0.001	NA
Volume	Adjacent Right Turn % (Spline 2)	-1.778	0.255	-6.980	< 0.001	NA
Treatment	LPI	-0.285	0.065	-4.405	< 0.001	0.752
Roadway	Speed = 30	0.332	0.094	3.541	< 0.001	1.394
Intersection Indicators	<i>Intersection = 21st & Broadway</i>	<i>Reference</i>	-	-	-	-
Intersection Indicators	Intersection = 47 th & Glisan	0.466	0.076	6.123	< 0.001	1.594
Intersection Indicators	Intersection = A & 8th	-1.289	0.276	-4.670	< 0.001	0.276

Table 3.21 shows the model fit statistics. These statistics are discussed in detail in the sections below.

Table 3.21. All Conflicts: Final Model Fit

Metric		Value
Number of Observations (Training Set)		480
Number of Observations (Testing Set)		120
Model Fit	BIC	1812
Model Fit	Log Likelihood (Null)	-1227
Model Fit	Log Likelihood (Convergence)	-869
Model Fit	χ^2 (Log-Likelihood Ratio Test)	717
Model Fit	χ^2 p -value	< 0.001
Model Fit	McFadden R^2	0.292
Five-Fold Cross Validation	Cross-Validation R^2	0.714
Five-Fold Cross Validation	Cross-Validation R^2 S.D.	0.128
Five-Fold Cross Validation	Cross-Validation RMSE	3.952
Five-Fold Cross Validation	Cross-Validation RMSE S.D.	0.838
Holdout Validation	Holdout R^2	0.815
Holdout Validation	Holdout RMSE	4.714

There were 480 observations used in the training set, which represent each hour of data collected for each crosswalk at each intersection. The BIC is 1812. The model substantially improves over an intercept only baseline ($\chi^2 = 717$, $p < 0.001$). The McFadden R^2 is 0.292, which indicates meaningful improvement in fit relative to the null (Heshner and Stopher, 1979). Overall, the fit statistics show good fit with substantial improvement over an intercept-only model.

The five-fold cross-validation yielded an average R^2 of 0.714 with a standard deviation of 0.128, while the corresponding RMSE averaged 3.952 conflicts (S.D. = 0.838). On average, the model's predictions differ from the observed hourly conflict counts by about four conflicts per hour. This corresponds to roughly 80% of the average hourly conflict count (4.86), indicating that individual hourly predictions are relatively noisy. However, the model still distinguishes between low and high conflict hours reasonably well, as reflected by the relatively high R^2 .

The holdout validation produced an R^2 of 0.815 and an RMSE of 4.714, indicating stable out-of-sample performance but higher RMSE than from cross-validation. This may reflect more random variation in the holdout sample. Again, while RMSE is high compared to the mean, the high R^2 still indicates that the model can capture more general variation in the data.

Two of the predictors included in the final model are spline terms. Because a spline rewrites the variable x into several cubic basis functions that all move together when x changes, an IRR cannot be read directly from any single spline coefficient. Instead, IRRs are computed for changes in x while holding all other parameters fixed. Practically, this is done by first creating a reference case in which all other variables are held constant at their baseline or median values. The model (which predicts the log of the expected conflict rate through η) is then used to generate two predictions: one at a starting value of the variable (x_0) and another at a higher value (x_1). The IRR is obtained by taking the difference between these two predicted η values and exponentiating it: $\text{IRR}(x_0 \rightarrow x_1) = \exp\{\eta(x_1) - \eta(x_0)\}$. The IRRs presented below therefore represent the change in the expected conflict rate associated with a specific, fixed increase in the variable (such as a 50-pedestrian increase in hourly pedestrian volume or a 20-percentage-point increase in the adjacent right-turn percentage) while all other covariates are held constant at their reference values.

Pedestrian volume is modeled with a two-degree spline (basis 1: estimate = 6.73, $p < 0.001$; basis 2: estimate = 1.20, $p < 0.001$) with a knot (e.g., median value) at approximately 10 pedestrians/hour.

For most pedestrian volumes, as pedestrian volume increases, the number of predicted conflicts also rises, a natural result of having more vehicles interacting with pedestrians. Table 3.21 displays the results, where the y-axis represents the number of predicted conflicts per hour. As evinced, predicted conflicts increase sharply up to about 225 pedestrians/hour, then plateau and slightly decline. However, this apparent ‘safety-in-numbers’ effect likely reflects Burnside’s high pedestrian volumes rather than a true systemic decrease.

The IRRs support this analysis, showing an $\text{IRR} < 1$ at higher pedestrian volumes.

- 0 $\rightarrow$ 50 pedestrians/hour: 4.87
- 50 $\rightarrow$ 100 pedestrians /hour: 2.98
- 100 $\rightarrow$ 150 pedestrians /hour: 1.95
- 150 $\rightarrow$ 200 pedestrians /hour: 1.36
- 200 $\rightarrow$ 250 pedestrians /hour: 1.02
- 250 $\rightarrow$ 300 pedestrians /hour: 0.825
- 300 $\rightarrow$ 350 pedestrians /hour: 0.712

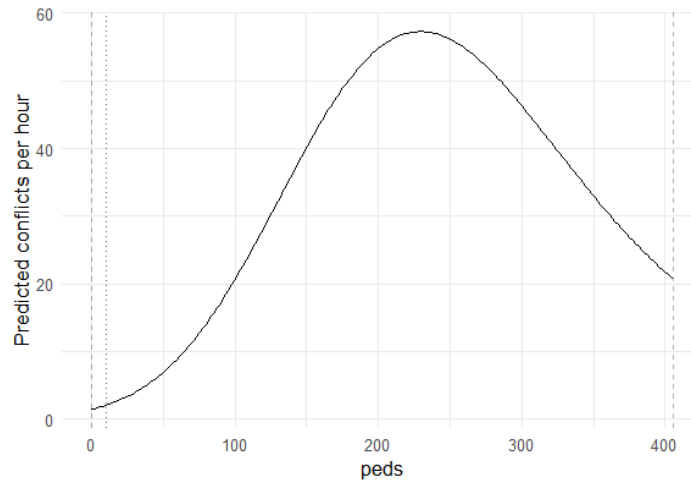


Figure 3.20. Pedestrians vs. Conflicts

Vehicle adjacent right turn share is modeled with a two-degree spline (basis 1: estimate = -1.21, $p < 0.001$; basis 2: estimate = -1.78, $p < 0.001$) with a knot at approximately 32.7%. Table 3.21 displays the results. In general, the number of conflicts decreases as the share of adjacent rights increases. This can be interpreted in relation to the other two turning movements, crossing right and left turns, which, when more prevalent, correspond to higher conflict counts. In other words, higher shares of adjacent right turns imply fewer crossing and left turns, and therefore fewer opportunities for conflicts. This pattern aligns with the descriptive statistics, which showed that left turns and crossing right turns were overrepresented in the conflict dataset relative to the full dataset. The relationship is steepest at moderate shares (approximately 25-75%), suggesting that conflict frequency is most sensitive to the composition of turning movements within this middle range.

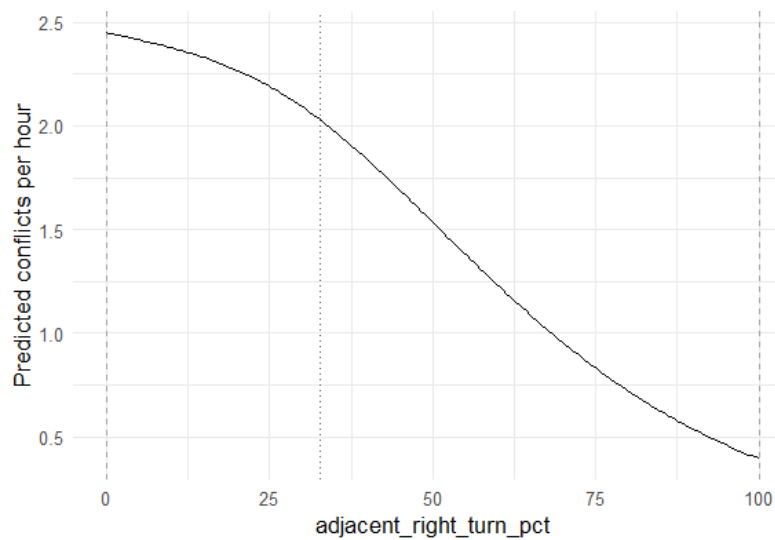


Figure 3.21. Adjacent Right Turn vs. Conflicts

The IRRs are calculated for 20 percentage point buckets and support this analysis:

- 0 → 20 %: 0.926
- 20 → 40 %: 0.810
- 40 → 60 %: 0.669
- 60 → 80 %: 0.586
- 80 → 100 %: 0.549

The presence of an LPI (Estimate = -0.285, $p < 0.001$) is associated with a 24.8% reduction in the expected hourly conflict rate. This indicates a significant safety benefit for intersections with LPIs as compared to intersections without.

Additionally, three linear variables and two intersection indicators were found to be significant contributing factors.

Each additional hourly vehicle (Estimate = 0.005, IRR = 1.005, $p < 0.001$) is associated with a 0.5% increase in the expected hourly conflict rate, holding other factors constant. This aligns with expectations and the physical reality of conflicts, which cannot occur without a vehicle.

Each additional vehicle left turn percentage (Estimate = 0.004, IRR = 1.004, $p < 0.001$) is associated with an 0.4% increase in the expected hourly conflict rate, holding other factors constant. This aligns with the finding from the descriptive analysis, which showed that left turn and crossing right turns were more associated with conflicts than adjacent rights. A speed limit of 30 mph (Estimate = 0.332, $p < 0.001$, IRR = 1.394) is associated with a 39.4% increase in the number of hourly conflicts. As this is the highest speed limit bucket included in the model, this suggests a positive relationship between conflicts and speed limit.

Finally, the intersection indicators for 47th & Glisan and A & 8th are both significant contributing factors, with an expected increase in conflicts at 47th & Glisan compared to the control (21st & Broadway), and an expected decrease at A & 8th.

The CURE plots demonstrate the fitted values on the x-axis and the cumulative residuals (observed – fitted) on the y-axis. Positive values for the residual mean the prediction was too low, and negative values mean the prediction was too high; zero means the guess was exactly correct.

The plot in Figure 3.22 demonstrates the CURE plot for the all-conflicts model. The red lines represent the 95% simulation envelope expected under the fitted negative binomial model. Ideally, the residual path should fluctuate randomly around zero and remain within these bounds, indicating an adequate fit. In this case, the curve dips below zero at fitted values below about ten conflicts (suggesting slight over-prediction), dips below zero between roughly ten and fifty (over-prediction), and returns below zero. However, the majority of the path remains within the 95% envelope, providing no strong evidence of systematic lack of fit. Notably however, the residual path exits the envelope between 60 and 80 conflicts, indicating severe overprediction at very high numbers of conflicts.

This makes sense, as there was only one site (Burnside) that exhibited these extremes. Thus, the negative binomial specification generally appears appropriate for the all-conflicts model, though performance deteriorates at more large numbers of hourly conflicts.

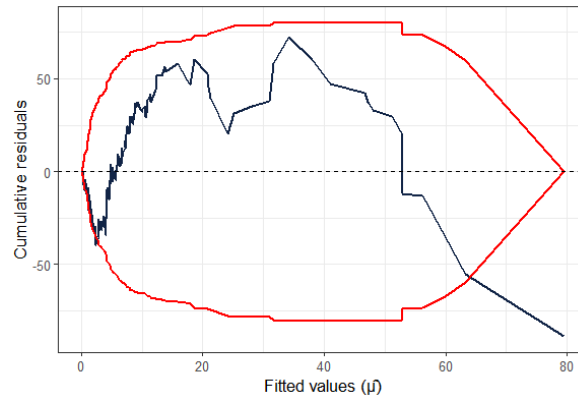


Figure 3.22. All Conflicts Cumulative Residual Plot

Figure 3.23 presents an aggregate histogram of observed vs predicted conflicts. In alignment with the CURE plot, there is some over-representation for the predicted values in the 1-2 conflict bin, and more underrepresentation at moderate conflict values.

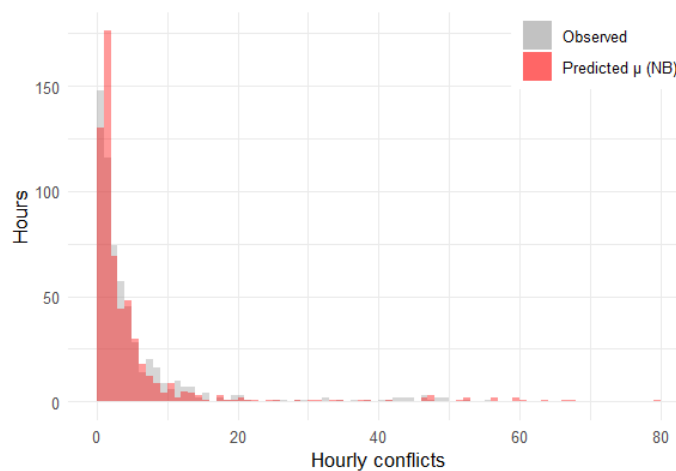


Figure 3.23. Histogram of Observed vs Predicted Conflicts

This model achieved good explanatory power (McFadden $R^2 = 0.29$) and stable cross-validation ($R^2 \approx 0.71$). LPI presence corresponds to an estimated 25% reduction in hourly conflicts, while exposure variables (pedestrian and vehicle volume, left turn share, adjacent right share) show expected effects. A posted speed limit of 30 mph corresponds to more conflicts relative to 20–25 mph sites. Intersection indicators confirm spatial heterogeneity, with 47th & Glisan exhibiting elevated baseline risk and A & 8th lower risk.

Overall, this model suggests that the presence of LPIs is effective in reducing conflict frequency for all conflicts, though exposure and site-specific variables are still crucially important.

3.5.2.5 LPI Only Intersection Analysis

Because the conflict frequency model indicated that the presence of an LPI was associated with reductions in conflict frequency, an additional analysis was conducted restricting the sample to the three true before–after intersections (10th & Burnside, 47th & Glisan, and 52nd & Duke) that implemented an LPI during the study period. Limiting the analysis to these sites provides a more rigorous test of the treatment effect, as each intersection serves as its own control and reduces confounding from geometric and contextual differences across the broader intersection set. Full model development and results are provided in Appendix C.

Results from this restricted analysis indicate that the LPI effect persists for all conflicts model. Specifically, LPI implementation is associated with an estimated 14% reduction in hourly conflict frequency ($\beta = -0.150, p = 0.035, IRR = 0.861$). While this effect size is smaller in magnitude than the LPI effect observed in the all-intersections model (approximately 25%), it confirms that the reduction in conflict frequency is present within the smaller, true before/after subset of intersections. However, note that this effect did not carry through to high-speed or high/medium severity conflict subsets.

3.5.3 Conflict Severity Model Development

Conflict severity is modeled at the conflict level using a binary dependent variable with two PET-based categories: low severity and high/medium severity. Both all conflicts ($N = 2847$) and high-speed conflicts ($N = 703$) are examined. This sample set is lower than the one used for conflict frequency because missing explanatory variable values were excluded to ensure comparable samples. These rows were specifically missing data from conflict-specific attributes (especially related to the conflict time after the WALK), so were included in the frequency model.

The all-conflicts dataset contains 1,534 (53.9%) low-severity conflicts, 1,263 medium severity conflicts (44.4%), and 50 (1.8%) high severity conflicts. The high-speed (> 9 mph) conflicts dataset contains 384 (54.6%) low severity conflicts, 309 medium severity conflicts (44%) and 10 high severity conflicts (1.4%). Due to the small percentage of high severity conflicts, they are combined with medium severity conflicts and thus generate a binary model: high/medium severity vs low severity.

Severity is modeled using a binary discrete-choice model that compares high/medium severity conflicts to low severity conflicts. Both binary logit (logistic error) and binary probit (normal error) are considered. To select the best model structure, the same specification is fit under both links on the same rows and Bayesian Information Criterion (BIC) is compared to balance fit and parsimony.

The same automated routine used for the frequency models is followed, adapted to binary outcomes. However, note that splines were not used for this model due to the large proportion of binary variables, which are not suited for splines. The same validation procedure was used as for the conflict frequency model, except accuracy is reported in lieu of R^2 . For every predictor, marginal effects are also reported.

3.5.3.1 All Conflicts Severity Model

BIC is essentially identical for the probit (3084.93) and logit (3084.88) models ($\Delta\text{BIC} = 0.05$). Given this indistinguishable fit, the logit model was chosen due to its more common application in relevant studies (Stipancic *et al.*, 2016; Zangenehpour *et al.*, 2016; B. Russo *et al.*, 2020; Ghadirzadeh, Mirbaha and Rassafi, 2022; Raha *et al.*, 2024).

Multicollinearity is assessed among predictors in each model using variance inflation factors. Across both models, VIF values were low - ranging roughly from 1.02 to 1.28 - and none exceeded the conventional threshold of 5. This indicates limited redundancy among covariates and suggests the coefficient estimates are not unduly inflated by collinearity.

To incorporate flexibility in model selection, the stepwise algorithm was modified to allow a BIC tolerance of 2, following Raftery (Raftery, 1995), who notes that BIC differences less than two indicate only “weak” evidence favoring one model, and differences up to about six constitute merely “weak to positive” evidence. This adjustment prevents the exclusion of potentially meaningful predictors when the improvement in model fit is marginal.

For the all-conflicts model, the BIC increased modestly from 3084.9 under strict selection to 3089.3 ($\Delta\text{BIC} = 4.4$) when a 2-unit tolerance was applied within the algorithm, which allowed significant variables to be retained if the BIC did not worsen by more than 2 points.

According to Raftery’s scale, this difference represents only weak-to-positive evidence favoring the simpler model and is therefore not substantively meaningful. The more flexible specification (BIC = 3089.3) achieved similar performance (accuracy = 0.591, log loss = 0.666) compared to the stricter model (accuracy = 0.605, log loss = 0.665) while including several additional predictors (47th and Glisan, curb extension presence, and crosswalk position west) that provide richer spatial and contextual interpretation. This trade-off is accepted because the focus of this thesis is inference, and the expanded specification allows deeper exploration of treatment effects and site-specific behavioral differences without meaningfully sacrificing model fit or parsimony.

Table 3.22 shows the final model coefficients for modelling all-speed conflict severity using the binary logit model. Again, note that the specification used here is for the relaxed BIC threshold requirements. For verification, a series of reduced models were estimated, each including only the intercept and one explanatory variable, to confirm the consistency of coefficient direction. Across all fourteen predictors, the coefficient signs were identical in the reduced and full models, indicating stable directional effects.

Table 3.22. Conflict Severity All Conflicts Model Specifications

Category	Predictor	Estimate	Std. Error	z value	p-value	Margin al Effect
Pedestrian	Pedestrian Starts Crossing at WALK	<i>Reference</i>	-	-	-	-
Pedestrian	Pedestrian Starts Crossing at FDW	0.489	0.143	3.424	0.001	0.115
Pedestrian	Pedestrian Crossing Time	-0.076	0.017	-4.434	< 0.001	-0.018
Pedestrian	Pedestrian Dwell Time	-0.005	0.002	-2.467	0.014	-0.001
Pedestrian	Child Present	-0.493	0.228	-2.162	0.031	-0.110
Vehicle	Vehicle Volume	0.221	0.056	3.958	< 0.001	0.051
Vehicle	Driver Stops Before First Crosswalk	<i>Reference</i>	-	-	-	-
Vehicle	Driver Stops in Intersection	0.582	0.190	3.062	0.002	0.135
Vehicle	Adjacent Right Turn	<i>Reference</i>	-	-	-	-
Vehicle	Left Turn	-0.528	0.101	-5.251	< 0.001	-0.122
Vehicle	Vehicle Arrives First	0.405	0.137	2.955	0.003	0.095
<i>Treatment</i>	Curb Extension Presence	-0.347	0.131	-2.652	0.008	-0.079
Roadway	Crosswalk Position = East	<i>Reference</i>	-	-	-	-
Roadway	Crosswalk Position = West	0.235	0.102	2.313	0.021	0.054
Time of Day	Darkness	-0.650	0.216	-3.004	0.003	-0.143
Intersection	Intersection = 21 st & Broadway	<i>Reference</i>	-	-	-	-
Intersection	Intersection = Holgate & 92 nd	-1.241	0.252	-4.917	< 0.001	-0.251
Intersection	Intersection = Holgate & 104 th	-1.456	0.563	-2.588	0.010	-0.280
Intersection	Intersection = 47 th & Glisan	-0.388	0.131	-2.958	0.003	-0.088

Table 3.23 shows the model fit statistics.

Table 3.23. Conflict Severity All Conflicts Model Fit

Metric		Value
Number	Number of Observations (Training Set)	2277
Number	Number of Observations (Testing Set)	570
Model Fit	BIC	3089
Model Fit	Log Likelihood (Null)	-1487
Model Fit	Log Likelihood (Convergence)	-1568
Model Fit	χ^2 (Log-Likelihood Ratio Test)	162
Model Fit	χ^2 p -value	$p < 0.001$
Model Fit	McFadden R^2	0.0517
Five-Fold Cross Validation	Accuracy	0.614
Five-Fold Cross Validation	Accuracy Standard Deviation	0.027
Five-Fold Cross Validation	Log Loss Mean	0.658
Five-Fold Cross Validation	Log Loss Standard Deviation	0.011
Holdout Validation	Accuracy	0.5912
Holdout Validation	Log Loss Mean	0.6657

The model was trained on 2,277 observed pedestrian–vehicle conflicts and validated on a 570-observation holdout set. Overall fit is modest. The fitted model performs significantly better than an intercept-only baseline (χ^2 $p < 0.001$), but the McFadden R^2 of 0.0517 indicates only moderate improvement relative to an intercept-only specification. Validation results confirm that predictive performance is limited, which is expected given the behavioral complexity and noise in conflict-level data. During five-fold cross-validation, the model achieved a mean accuracy of 0.614 (SD = 0.027), meaning it correctly classified about 61% of conflicts - moderately better than simply predicting the majority severity class for all observations (46.2%). The mean log loss of 0.658 indicates that, on average, the model assigns moderate probabilities to the correct outcome: slightly better than random guessing (which would yield ≈ 0.693) but far from perfectly confident predictions.

On the independent test set, accuracy was 0.591 and log loss was 0.666, both consistent with the cross-validation results. These results indicate limited predictive strength but consistent calibration, implying that while the model cannot predict severity outcomes precisely, it captures meaningful directional patterns. This justifies its use for inference and effect estimation, particularly when interpreting marginal effects and treatment variables rather than for precise classification.

Marginal effects (MEs) tell us how the probability of each severity category changes when a predictor switches from 0 to 1, averaged over all conflicts.

Installing curb extensions is associated with a 7.9% decrease in the probability of a conflict being classified as high/medium severity. Therefore, curb extensions shift the distribution toward less serious outcomes (PET of 3-5 seconds).

Additionally, several pedestrian-related variables were significant:

- A pedestrian that starts crossing at FDW (as opposed to WALK) is associated with an 11.5% increase in the probability of a conflict being classified as high/medium severity. This is intuitive: pedestrians crossing later in the cycle have less time to cross and may be more exposed to more vehicles, leading to closer conflicts.
- Pedestrian crossing time and dwell time both decrease the probability of a conflict being classified as high/medium severity conflicts by 1.8% and 0.1%, respectively. This could be due to more cautious pedestrian behavior with longer crossing times and dwell times: pedestrians may walk slower and be more cautious, or wait until it is safe to cross, both decreasing conflict severity.
- The presence of a child reduces the probability of a conflict being high/medium severity by 11%. People with children may be more cautious, or drivers may be more cautious, leading to higher PET times.

Vehicle characteristics also were significant.

- Each additional hourly vehicle is associated with a 5.1% increase in the probability of a conflict being high/medium severity. More vehicles are associated with more conflicts (per the conflict frequency model) and more severe conflicts.
- A left turn vehicle is associated with a 12.5% decrease in the probability of a conflict being high/medium severity, as opposed to an adjacent right turn. This is an interesting complement to the conflict frequency analysis, which showed that adjacent right turns decrease the frequency of conflicts. However, a more severe outcome makes sense geometrically, as typically adjacent rights are stopped directly behind the crosswalk a pedestrian is walking on, so the time needed to reach the crosswalk is short.
- A driver stopping in the intersection, as opposed to before the first crosswalk, is associated with a 13.5% increase in the probability of a conflict being high/medium severity. Drivers stopped closer to the pedestrian have less distance to travel to get to the pedestrian, thus leading to shorter PET times.

Darkness is associated with a 14.3% decrease in the probability of conflict being high/medium severity, again perhaps due to pedestrians and drivers being more cautious. A west crosswalk (as opposed to an east crosswalk) is associated with a 5.4% increase in

the probability of a high/medium severity conflict. Finally, three intersection indicators (Holgate & 92nd, Holgate & 104th, and 47th & Glisan) indicated lower probabilities of high/medium severity conflicts as opposed to the reference, 21st & Broadway.

A high-speed conflict severity model was also estimated. Like the all-conflicts model, the high-speed severity model shows only weak explanatory power, with low pseudo-R² (0.0473) and only moderately better accuracy than a majority-class glass (cross-validation mean accuracy of 0.587, compared to a 46.2% share of high/medium severity conflicts). However, curb extension presence was retained as a significant, negative variable, with an estimated 14.7% reduction in the probability of a high-speed conflict being classified as high/medium severity (Estimate = -0.656, $p = 0.011$).

3.6 SUMMARY

This chapter aims to explore how Leading Pedestrian Intervals (LPIs), with and without curb extensions, impact pedestrian safety. Video data was collected for four matched-pair intersections and three before/after sites, all including a control and treatment site. This data was manually reduced to record volume and conflict data, totaling 600 hours of video and 2,916 conflicts. Conflicts were categorized as low, medium, or high severity based on Post Encroachment Time (PET) thresholds and as high-speed and low-speed through a distribution-based speed threshold. Data were analyzed through descriptive statistics, statistical tests (Kruskal Wallis for conflict rates and Chi-Square for conflict severity), conflict frequency modelling, and conflict severity modelling. Overall, the results of these analyses indicate strong evidence for LPI effectiveness, as well as evidence that curb extensions further reduce high-speed conflict frequency and conflict severity.

The descriptive analysis and statistical tests show that conflicts (all, high-speed, high/medium severity, and high-speed high/medium severity conflicts), controlling for vehicle and pedestrian exposure, are significantly lower at curb extension only, LPI only, and LPI + curb extension sites, as compared to control (no treatment) sites. Analysis of conflict rates by vehicle exposure and by pedestrian exposure found significant reductions for LPI sites from the control, and an additional reduction for LPI + curb extension sites. For example, the all-conflict, high-speed conflict, and high-speed high/medium severity conflict rates (by vehicle exposure) were reduced by 11 to 24% for LPI treatment and 20 to 61% for the LPI + curb extension treatment, relative to the control.

This trend was mirrored in the Chi-Square test for conflict severity. Specifically, the most severe conflicts (high-speed, high/medium severity) decreased from 50.1% of total conflicts under control conditions to 44.1% with LPIs alone (a 6.0 percentage-point drop) and to 35.0% when LPIs were combined with curb extensions (a 15.1 pp drop).

Additionally, the descriptive analysis raised some key considerations for intersections with LPIs and curb extensions. The data showed a disproportionately higher share of crossing right turns, and to a lesser extent left turns, in the conflict data (as compared to overall vehicle composition). This indicates that these movements pose a higher risk to people walking, even when provided with an LPI and a curb extension. It also highlights an opportunity for Right Turn on Red

restrictions in conjunction with LPIs, which would prevent crossing right turning vehicles from turning during the LPI phase.

Additionally, the analysis showed that crosswalks without automatic pedestrian recall (e.g., requiring a pedestrian to push the button to request a pedestrian phase) have a high proportion of non-compliance, with 52nd and Duke seeing only about 40% of crossings during the pedestrian WALK interval. This indicates reduced effectiveness of the LPI, as fewer pedestrians use it.

Conflict frequency modeling reinforced these findings. In pooled hourly count models, LPI presence was associated with an approximately 25% reduction in all conflicts. Curb extensions combined with LPIs were associated with substantial reductions in high-speed conflicts. A focused before–after analysis of the three intersections that implemented LPIs during the study period confirmed that the LPI effect persists when each intersection serves as its own control, with an estimated 14% reduction in hourly conflict frequency. While the magnitude of this effect is smaller than in the pooled analysis, it supports the conclusion that LPIs contribute to reduced conflict frequency under comparable before–after conditions.

The models also highlighted the importance of exposure and turning movements. Pedestrian and vehicle volumes were strongly associated with conflict frequency, as expected, while left turns and crossing right turns were consistently linked to higher conflict rates than adjacent right turns. These findings align with the descriptive analysis, which showed that crossing right turns and left turns are overrepresented in conflicts relative to their overall share of vehicle movements. Together, these results suggest that LPIs reduce conflicts while interacting meaningfully with traffic composition and operational characteristics.

Conflict severity modeling produced weaker overall fit, reflecting the inherent variability in conflict-level outcomes. Even so, curb extensions emerged as a meaningful predictor of reduced severity. In pooled severity models, curb extension presence was associated with an approximately 8% reduction in the probability that a conflict would be classified as high or medium severity, indicating a shift toward less severe interactions. LPIs were not significant in these models.

Taken together, the results indicate that LPIs are effective at reducing pedestrian–vehicle conflict frequency across a range of exposure conditions and intersection types. Curb extensions appear to provide additional benefits, particularly in lowering conflict severity. While exposure and site-specific characteristics remain critical drivers of conflict outcomes, the findings provide evidence that LPIs and curb extensions, contribute meaningfully to safer pedestrian–vehicle interactions.

3.7 LIMITATIONS

There were a number of limitations encountered in this analysis, which are detailed in this section. A low number of intersections (seven pairs) means that site-specific factors may have influenced results. While fixed-effects and mixed-effects count-data model for conflict frequency were considered to attempt to control for intersection and crosswalk specific factors, there were also limitations in these models' ability to capture both within and between site variation in the data. Therefore, intersection indicators were used instead. More intersections or more days of data collection, aided by computer-aided volume and conflict detection, would improve

modelling power and limit the inclusion of potential spurious variables (like AADT, the presence of a parking lane) that may be acting more as site indicators rather than true characteristics.

Secondly, there was only one intersection with curb extensions only. This severely limited any conclusions on the safety benefits of curb extensions alone. Therefore, this analysis mainly focused on LPIs alone versus LPIs with curb extensions.

Third, the number of conflicts between intersections varied significantly. 10th and Burnside had 800 conflicts in one day of collection, whereas other sites had as low as 23 over two days of data collection. This means that the Burnside pair had a stronger influence on the models than other, smaller sites. Additionally, this led to an imbalance in the number of conflicts per treatment. Although the LPI only had four pairs and LPI + curb extension had 3, the difference in conflicts was much starker, with almost 900 at the LPI only sites and less than 300 at the LPI + curb extension sites. To understand how this affected the models, a sensitivity analysis could have been run with and without Burnside to understand if and how results change.

Additionally, the data collection window was short. Only two days of conflict data were collected per site. A longer collection period would have reduced sensitivity to day-to-day variation in traffic and pedestrian patterns. Collecting more data would likely have been more feasible with automated or computer-aided PET and volume extraction, thereby reducing the burden of fully manual review. Note that some manual review would still be required if there was a desire to capture more difficult variables, like gender or evasive action. However, since most of these variables were not significant, future analyses could consider excluding these variables in favor of gathering more data.

Next, the modelling looked at all conflicts, in contrast to those conflicts occurring only in the WALK phase. The descriptive analysis showed that several intersections had a high number of pedestrian crossings outside of the WALK phase, meaning that the LPI did not activate. While 'LPI activation' was a variable in the conflict severity model, this was not considered in the conflict frequency model. If more data were available, future analysis could focus solely on conflicts occurring during the WALK interval to isolate the effects of the LPI.

Further, only three of the treated intersections were true before-after sites with pre and post treatment data. The remaining four sites were matched, leaving results more vulnerable to unobserved differences across locations. Additionally, across all sites, factors such as pedestrian behavior, driver yielding tendencies, or site-specific geometric features may not have been fully captured in the explanatory variable set.

Finally, the binary severity models generally showed weaker fit and less consistent parameter significance than the frequency models. This limits confidence in conclusions about the determinants of severity, especially beyond the pooled models. Future work could consider applying a fixed effects or mixed effects ordered or binary model to better capture intersection effects. Additionally, more conflict data would help with model fit.

4.0 DRIVING SIMULATOR STUDY

This chapter provides a detailed overview of the driving simulator study conducted at Oregon State University. The chapter begins with an overview of the study's methodology, which covers items such as experimental equipment, experimental design, experimental protocol, and the analysis techniques employed in the study. A result section then provides descriptive statistics, visualizations, and statistical analysis for the data collected in the driving simulator study (speed and visual attention). The chapter then concludes with a summary of the results obtained from the driving simulator study.

4.1 METHODOLOGY

Provided in this chapter is the methodology used to conduct the driving simulator study. The chapter begins by providing a description of the primary pieces of equipment used (e.g. driving simulator and eye tracking glasses). An overview of the experimental design employed in this study is then provided. Finally, the chapter concludes with a description of the analysis techniques used to transcribe the collected data.

4.1.1 Experimental Equipment

This section provides an overview of the primary pieces of equipment used for the driving simulator study. First, a description of the simulation equipment used to design, simulate, and collect research data is provided (desktop simulator, full cab driving simulator, and the SimObserver). Then a description of the wearable equipment used to collect visual attention data is provided (eye tracking glasses).

4.1.1.1 Simulation Equipment

This section provides a description of the three pieces of simulation equipment used to design and test the simulation environment, conduct the simulation experiment, and collect simulation data (e.g. vehicle speed). These pieces of equipment include a desktop simulator, a full cab driving simulator, and the SimObserver. All three pieces of equipment are located at the Oregon State University (OSU) Driving & Bicycling Simulator Laboratory in Corvallis, Oregon. In addition to a description of the general characteristics of each of these three pieces of simulation equipment, this section also provides a brief overview of the software used to develop the virtual environments, run the simulation experiments, and collect simulation data.

Desktop Simulator

OSU researchers built and tested the driving simulator experiment using a desktop simulator. The desktop simulator consists of a triple-monitor setup (left, center, right), a steering wheel, floor pedals, and a host computer to develop and test simulation

environments in the triple-monitor setup. Figure 4.1 shows an image of the desktop simulator and its respective components.

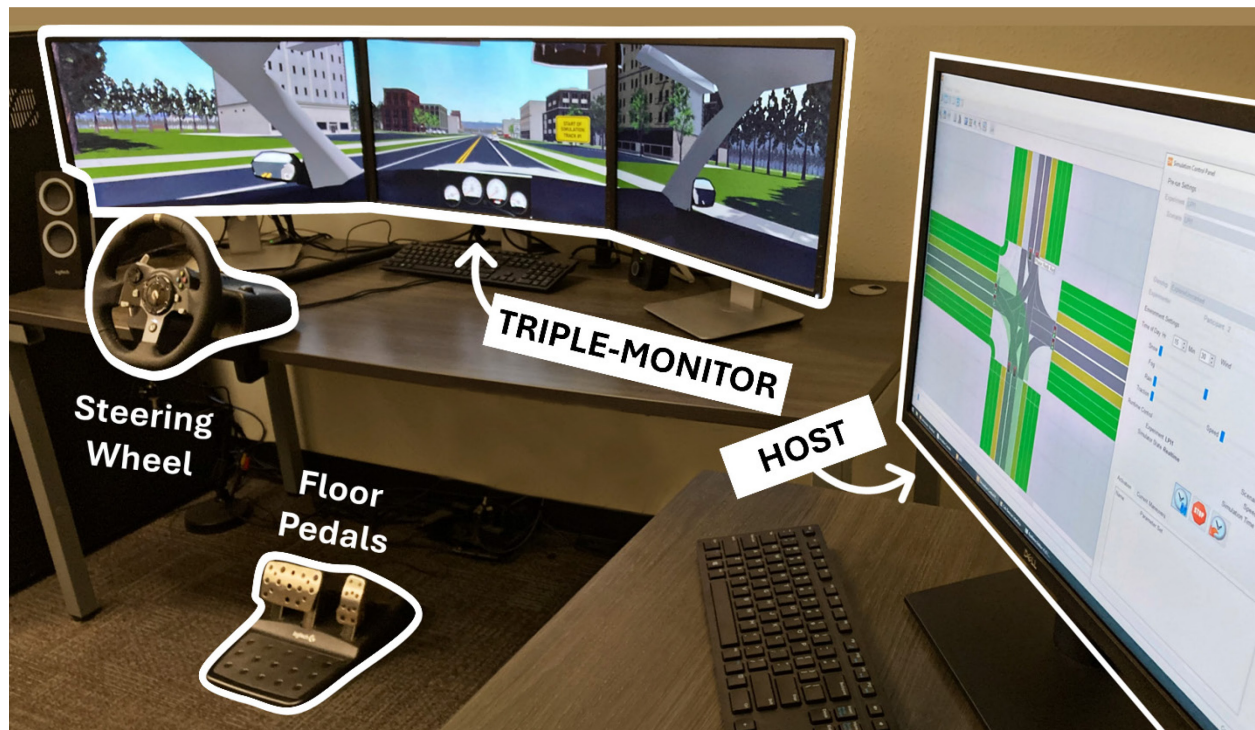


Figure 4.1. Desktop Simulator at Oregon State University

A summary of the workflow used to develop and test the simulation environments at the desktop simulator is shown in Figure 4.2. As shown in the figure, static 3D environments were first modeled using RoadRunner R2023b (Update 7) by MathWorks. Once the 3D environments consisting of roadways, sidewalks, static signalized intersections, buildings, landscaping, and signage were modeled, the RoadRunner file (rrscene) was then exported and converted to (dx) format so that the dynamic components (e.g., traffic signal) could be modeled using SimCreatorDX software by Realtime Technologies at the Desktop Simulator's host computer. Once all dynamic scenarios were created, the simulation environments were tested at the desktop simulator. During testing, the researchers made note of any required modifications in the 3D environment or the dynamic elements, updated the simulation files as needed, and re-tested. Once the researchers were satisfied with the simulation environments the completed files were then transferred to the full cab driving simulator.

DEVELOPMENT WORKFLOW AT DESKTOP SIMULATOR

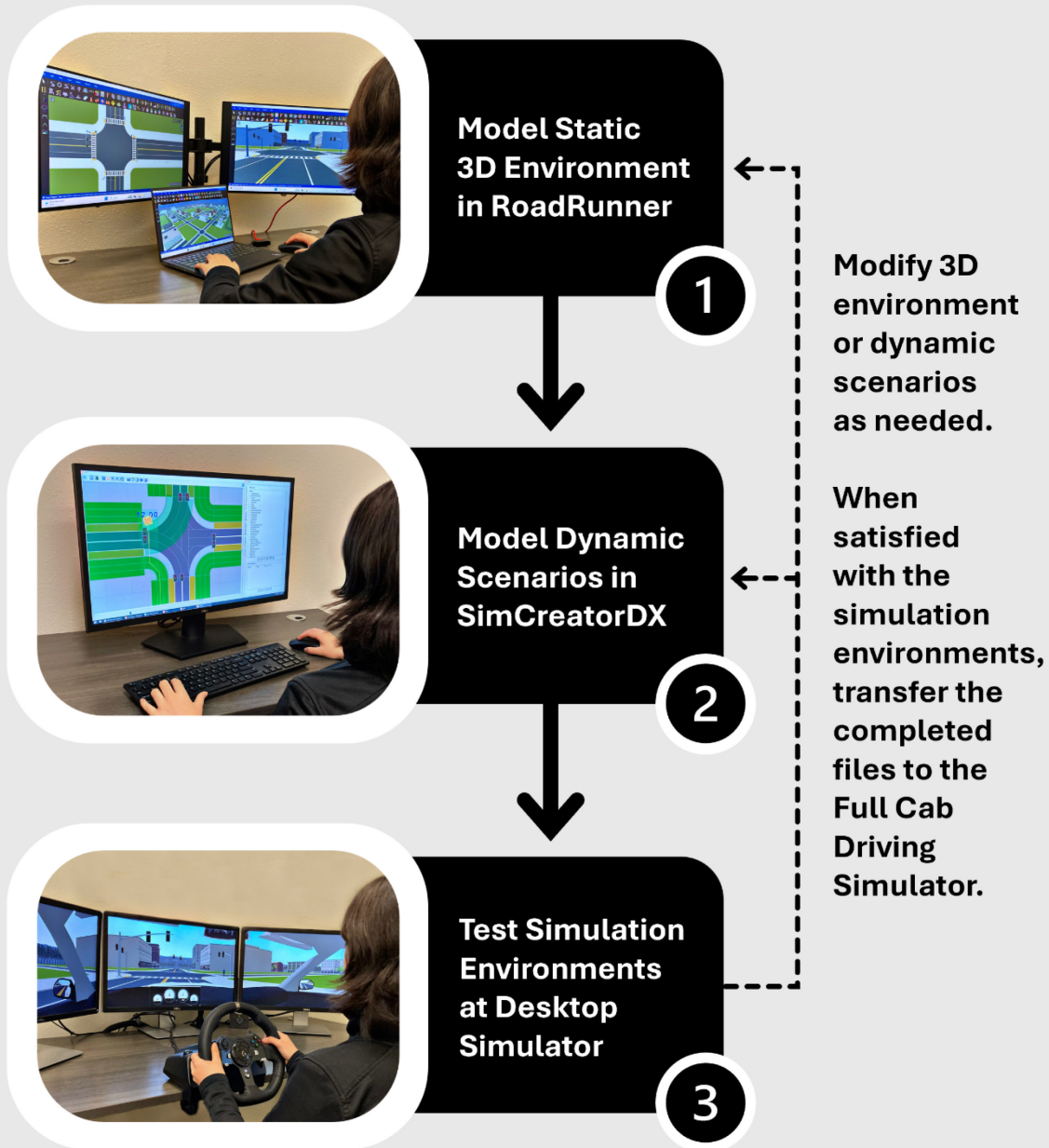


Figure 4.2. Development Workflow at Desktop Simulator

Full Cab Driving Simulator

After multiple design and testing iterations at the desktop simulator, the finalized simulation environments were then transferred to a full cab driving simulator for beta testing and for conducting the actual experiment. The driving simulator at Oregon State University consists of a Realtime Technologies full 2009 Ford Fusion cab mounted on top of a pitch motion system. Three projectors produce a 180-degree front view, and a fourth projector displays a rear image for the driver's rearview mirror. The two side mirrors of the vehicle have embedded LCD displays that are synchronized with the rest of the screens. Figure 4.3 shows an image of the full cab driving simulator at Oregon State University.



Figure 4.3. Full Cab Driving Simulator at Oregon State University

The simulation vehicle includes fully functional features commonly found in a real-life vehicle. A customizable virtual dashboard behind the steering wheel displays the speedometer (mph/kph) and other common dashboard features. Finally, an audio system provides ambient sound from the engine, transmission, wind, and tires to provide a more authentic driving experience.

Operator Workstation

An operator workstation (Figure 4.4) located outside of the full cab driving simulator room is operated by the researcher when conducting an experiment. The operator workstation provides the researcher with real-time monitoring of the subject's interaction with the scenarios. The workstation consists of three monitors displaying the subject view, the scenario view, and the map view. Additionally, an intercommunication device and an emergency stop button are within accessible reach of the researcher to provide a means to communicate with the subjects and to stop the experiment in case of any emergencies.

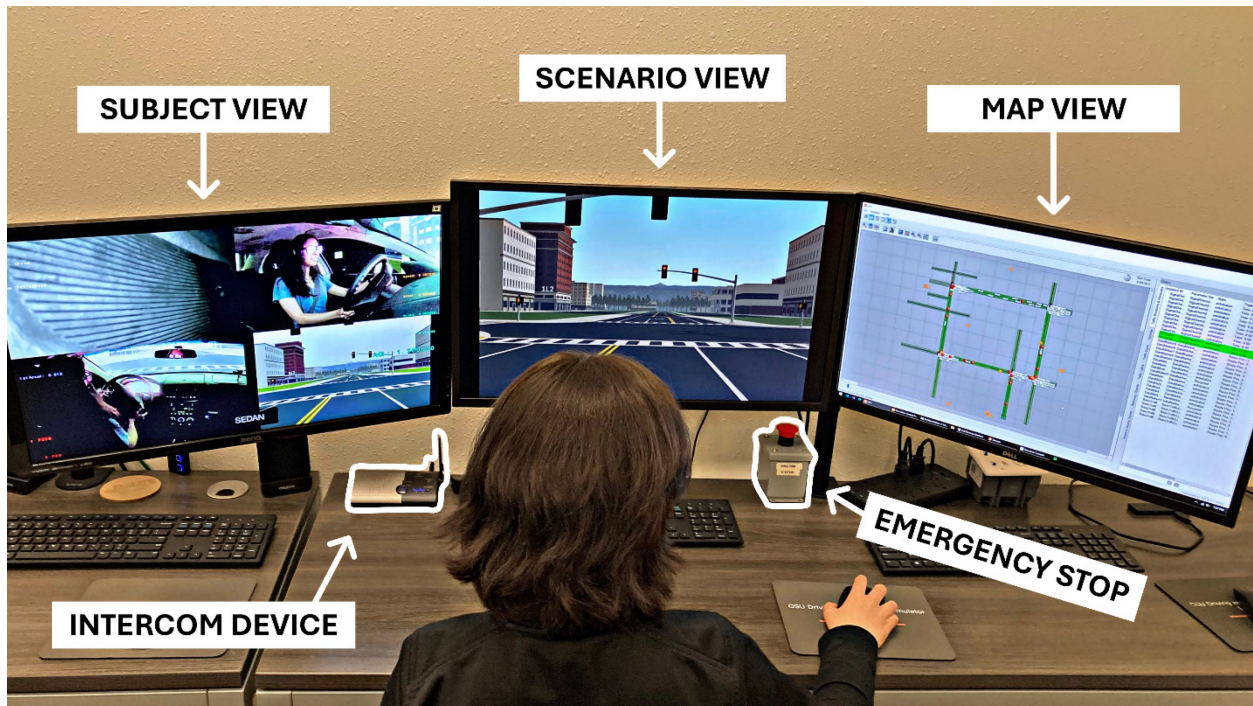


Figure 4.4. Operator Workstation at Oregon State University

Subject View - The subject view monitor runs a data acquisition system called SimObserver Pro by Realtime Technologies. This system allows the researcher to synchronously record video data from three 4K digital cameras with performance data such as the vehicle's speed and position. This system allows the researcher to monitor the subject for any signs of simulation sickness and ensure the subject is following all directions properly.

Scenario View – The scenario view monitor allows the researcher to see the exact same scenario that the subject is interacting with. This allows the researcher to take notes, which could help for later analysis, and gain the subject's perspective and observe how the subject is responding to the experimental scenarios.

Map View – The map view monitor is the driving simulator's host computer, and it runs SimCreatorDX and Fusion 2, which allows the researcher to edit and launch the simulation files onto the full cab driving simulator, and it also provides a map view

showing the real-time location of the subject vehicle as it navigates the virtual environment.

4.1.1.2 *Wearable Equipment*

This section provides a description of the wearable equipment that the research subjects were equipped with during the experiment. This included a pair of eye tracking glasses (Tobii Pro Glasses 3) to collect visual attention data. Included in this section is also a brief overview of the software and data collection laptop that was used to collect data from the eye tracking glasses.

Eye Tracking Glasses

Research subjects were equipped with a pair of eye-tracking glasses (Tobii Pro Glasses 3) to collect visual attention data as they navigated the virtual environment. These glasses feature 4 eye tracking cameras (2 per eye) and 16 infrared illuminators (8 per eye) integrated within the lenses to record eye orientation and movement. Additionally, a scene camera with a 106-degree field of view is located in the top center of the glasses to record video data (Tobii, 2025). This video data is collected wirelessly to a laptop and eye tracking data (e.g. gaze, saccades, fixation) is later transcribed by defining Areas of Interest (AOIs) through the eye tracking glasses module of a software called iMotions. Once the eye tracking data is transcribed, the results can be exported to (.csv) format for further analysis.

Figure 4.5 (A) shows an image of the eye tracking glasses used in the driving simulator study.

To calibrate the glasses, all research subjects were asked to stand 2 feet away from a calibration card and focus their gaze on the center of the calibration target as demonstrated in Figure 4.5 (B). The glasses could be customized for subjects with near- and farsightedness using attachable corrective lenses from a kit with 44 attachable lenses for both left and right eyes, ranging from -8.0 to +3 diopters in intervals of 0.5 diopters.



Figure 4.5. Eye Tracking Glasses (Tobii Pro Glasses 3)

The eye-tracking glasses were wirelessly paired with a data-collection laptop running iMotions 10.1 (Eye Tracking Glasses Module) and the Tobii Pro Glasses 3 Controller App. The iMotions 10.1 software and the Tobii Pro Glasses 3 Controller App enabled OSU researchers to monitor in real time the status of the eye-tracking glasses (Tobii Pro Glasses 3) during data collection. Figure 4.6 shows an image of the data collection laptop and example close-up views of the iMotions status dashboard and the Tobii Pro Glasses 3 Controller App used during data collection. In Figure 5.6, the black arrow shows a close-up view of the iMotions status dashboard for the eye tracking glasses. Researchers also monitored the live video feed of the glasses through Tobii Pro Glasses 3's controller app in a separate window (orange arrow).

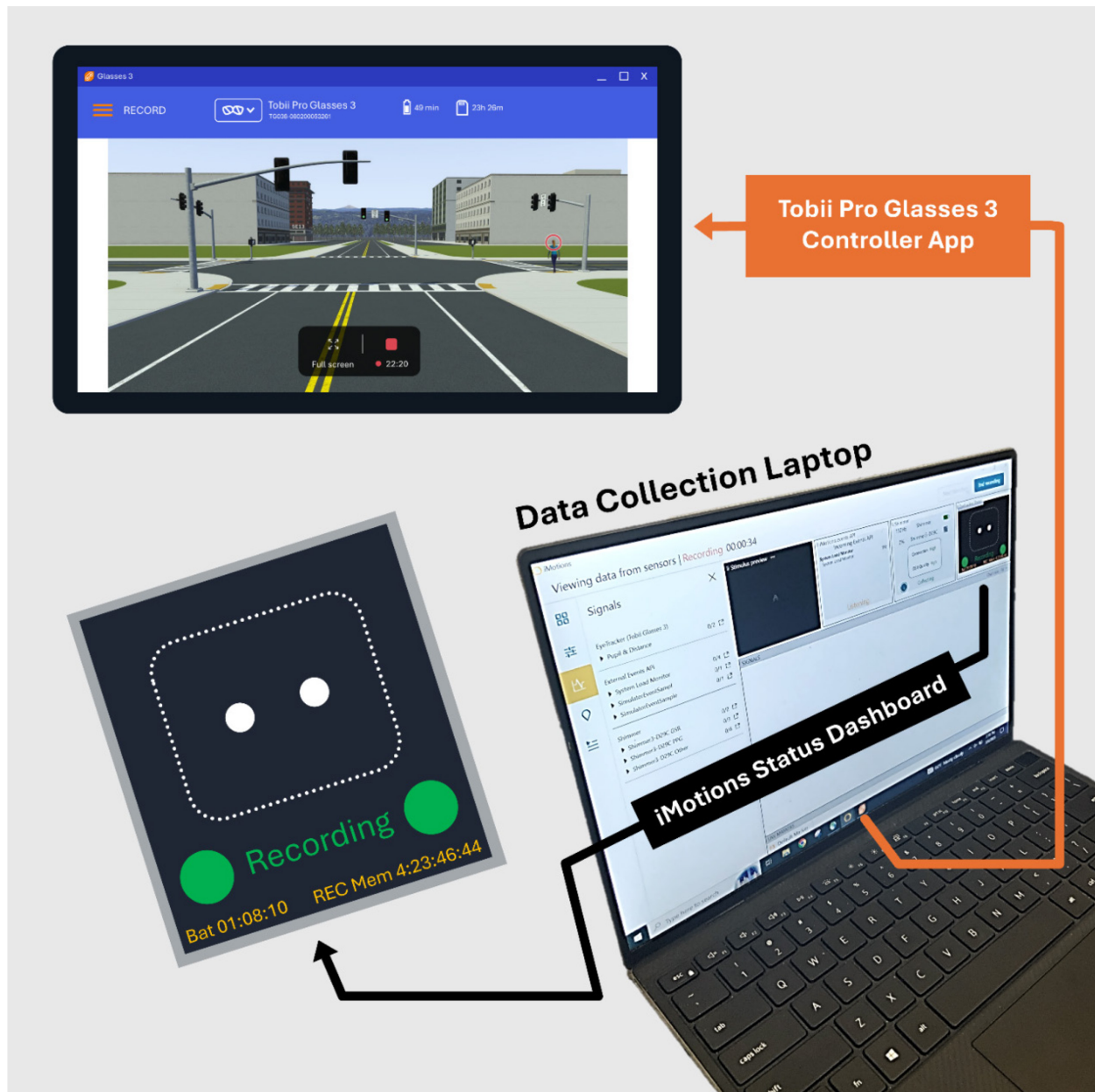


Figure 4.6. Data Collection Laptop & Status Dashboards

4.1.2 Experimental Design

This section provides an overview of the experimental design employed in the driving simulator study. First, a list of the research questions explored in the study is provided. This is followed by a description of the experimental variables (independent and dependent), as well as a description of the factorial design, counterbalancing, and presentation of driving scenarios. Finally, the section concludes with a description of the process used to design and develop the virtual environments for the study.

4.1.2.1 *Research Questions*

The objective of the driving simulator study is to help increase understanding of how the experimental variables (i.e., leading pedestrian intervals (LPI), the presence of a pedestrian, curb extensions (CE), and no turn on red (NTOR) sign) influence speed and visual attention. Research questions were developed to guide the experimental design of the driving simulator study. Below is a list of the research questions of interest for the simulator study.

1. Is the driver's turning speed and approach speed influenced by the LPI, presence of a pedestrian, Curb Extension, and NTOR Sign?
2. Is the driver's visual attention on the pedestrian influenced by the LPI, presence of a pedestrian, Curb Extension, and NTOR Sign?

4.1.2.2 *Experimental Variables*

The experimental variables selected for the driving simulator study were guided by the research questions mentioned in section 4.1.2.1. Described below are the independent and dependent variables selected for the driving simulator study.

Independent Variables - Four independent variables were included in the experiment: 5 Second LPI, Curb Extension, NTOR Sign, and Pedestrian. Each of these four independent variables have two levels (present vs not present) as shown in Table 4.1. For a detailed description of the design standards that were referenced when modeling the independent variables in the virtual environments of the driving simulator study, please see section 4.1.2.5.

Table 4.1. Independent Variables & Levels

Independent Variables	Levels
 5 Second LPI	2 Levels: Present & Not Present
 Curb Extension	2 Levels: Present & Not Present
 No Turn on Red (NTOR) Sign	2 Levels: Present & Not Present
 Pedestrian	2 Levels: Present & Not Present

Dependent Variables - Two dependent variables were collected and analyzed in the driving simulator study. These included vehicle speed (turning speed and approach speed) and visual attention (total fixation duration). The vehicle speed data is collected from the full cab driving simulator and its data acquisition system (SimObserver) at the operator workstation described in section 4.1.1.1. and the visual attention data is collected from the eye tracking glasses described in section 4.1.1.2.

4.1.2.3 *Within-Subjects Factorial Design*

A within-subjects factorial design was chosen for the driving simulator study to enable exploration of how subjects respond to all possible combinations of the independent variable levels and to gain insights regarding the variables' individual main effects and interaction effects. The factorial design for the four independent variables yielded a total of 16 scenarios (2 x 2 x 2 x 2). These 16 scenarios consisted of right-turn maneuvers at signalized intersections.

3D models (referred to as geocoded scenarios) of Broadway & 14th Avenue and Broadway & 21st Avenue in Portland, Oregon (2 of the 11 intersections studied in the conflict-based field study) were created in RoadRunner R2023b (Update 7) and presented in the experiment as 4 additional scenarios simulating right turn maneuvers at each of the two intersections with a pedestrian present and with no pedestrian present.

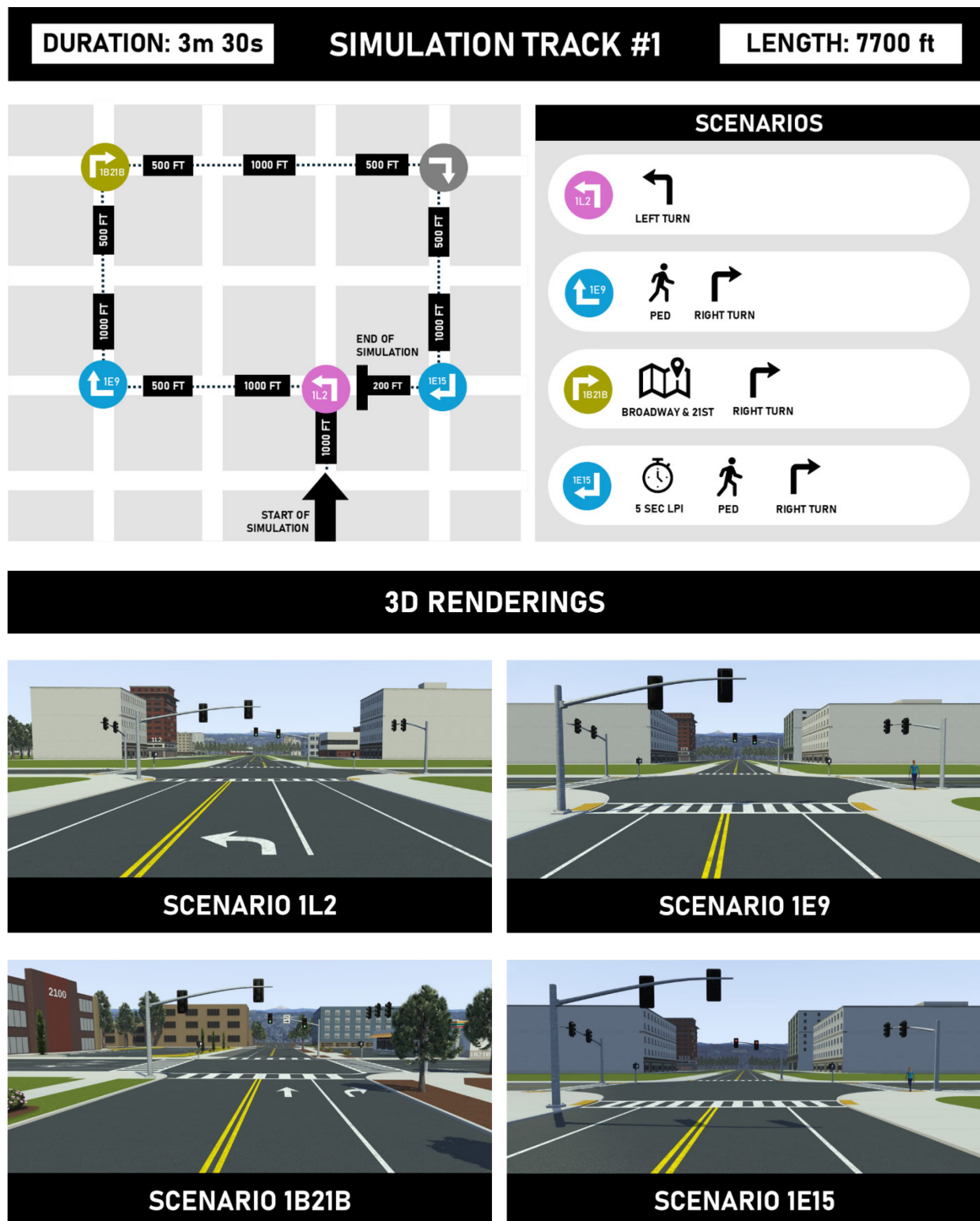
Because the main focus of the driving simulator study was on the right turn maneuvers due to them being more applicable to the independent variables, and due to limitations on the total duration of the driving simulator experiment to decrease the chances of simulator sickness, only 4 additional scenarios simulating left turn maneuvers were presented in the experiment. These 4 scenarios consisted of left turn maneuvers with 2 independent variables (5 Second LPI and Pedestrian) with 2 levels (present vs not present).

Therefore, a total of 24 scenarios were presented in the driving simulator study (16 scenarios consisted of right turns, 4 scenarios consisted of geocoded scenarios, and 4 scenarios consisted of left turns). Each of the 24 scenarios was assigned an ID number for easy identification when designing the virtual environments and when randomly ordering the scenarios. For example, right turn scenarios were assigned (E1 through E16), digital twin scenarios were assigned (B14A/B and B21A/B), and left turn scenarios were assigned (L1 through L4).

As shown in Table 4.2, each of the 6 simulation tracks contained a total of 4 scenarios. Figure 4.7 shows a sample visualization of the route and scenarios that subjects were presented with during simulation track #1, as well as the length (feet) and estimated duration (minutes and seconds) of the track. See Appendix D for sample visualizations of all remaining simulation tracks (tracks #2 to #6). The duration of each simulation track varied per subject, but on average, it took subjects approximately 5 minutes to complete each simulation track. The order in which each of the 6 simulation tracks was presented to each research subject was randomized to control for potential order effects in the within-subjects factorial design of the driving simulator study.

Table 4.2. Driving Simulator Scenarios

Simulation Track	Scenarios & Description
Simulation Track #1	Scenario 1L2 (left turn with no variables). Scenario 1E9 (right turn with a pedestrian). Scenario 1B21B (right turn at Broadway & 21st with no pedestrian). Scenario 1E15 (right turn with an LPI and a pedestrian).
Simulation Track #2	Scenario 2E14 (right turn with a curb extension and a pedestrian). Scenario 2L1 (left turn with an LPI and a pedestrian). Scenario 2E6 (right turn with no variables). Scenario 2E10 (right turn with an NTOR sign).
Simulation Track #3	Scenario 3B14A (right turn at Broadway & 14th with a pedestrian). Scenario 3E4 (right turn with an LPI, pedestrian, and a NTOR sign). Scenario 3E7 (right turn with an LPI). Scenario 3E16 (right turn with a curb extension and an NTOR sign).
Simulation Track #4	Scenario 4E5 (right turn with a curb extension, pedestrian, and NTOR sign). Scenario 4B21A (right turn at Broadway & 21st with a pedestrian). Scenario 4L4 (left turn with a pedestrian). Scenario 4E1 (right turn with LPI, curb extension, pedestrian, NTOR sign).
Simulation Track #5	Scenario 5E13 (right turn with a pedestrian and an NTOR sign). Scenario 5E11 (right turn with an LPI and a curb extension). Scenario 5E2 (right turn with an LPI, a curb extension, and a pedestrian). Scenario 5L3 (left turn with an LPI).
Simulation Track #6	Scenario 6E3 (right turn with an LPI, a curb extension, and a NTOR sign). Scenario 6E12 (right turn with an LPI and a NTOR sign). Scenario 6E8 (right turn with a curb extension). Scenario 6B14B (right turn at Broadway & 14th with no pedestrian).



4.1.2.4 Modeling of Virtual Environments

This section provides an overview of how the virtual environments for the driving simulator study were designed, modeled, and tested.

Design Manuals

During the design phase of the virtual environments, the researchers referenced city, state, and national design manuals (e.g. PBOT, 2022; ODOT, 2025a; NACTO, 2013; FHWA, 2023; AASHTO, 2018; Fisher et al., 2011).

Roadway Geometry:

- **Right Turn Scenarios:** The intersection approaches for the right turn scenarios consisted of two 11 ft travel lanes in each direction, two 9 ft parking lanes in each direction, and an 8 ft sidewalk with an 8 ft buffer strip on both sides of the road. Additionally, the intersections had a 30 ft curb radius, and a 20 ft crosswalk setback. Crosswalk width was 9.35 ft. See Figure 4.8 for an example.

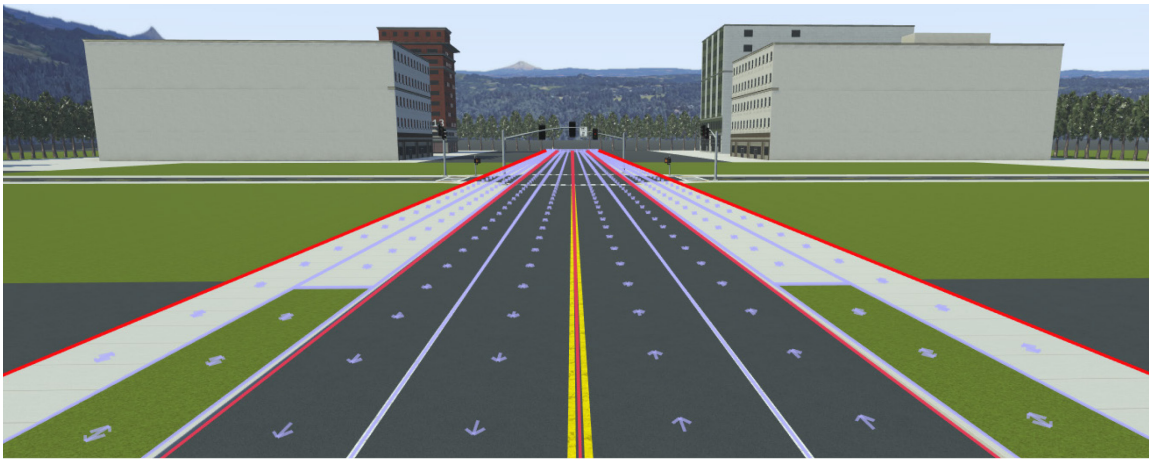


Figure 4.8. Sample Roadway Geometry of a Right Turn Scenario

- **Left Turn Scenarios:** The intersection approaches for left turn scenarios consisted of two 11 ft travel lanes in each direction, an 11 ft dedicated left turn lane, two 9 ft parking lanes in each direction, and an 8 ft sidewalk with an 8 ft buffer strip on both sides of the road. The intersections had a 30 ft curb radius, and a 20 ft crosswalk setback. Crosswalk width was 9.35 ft. See Figure 4.9 for an example.

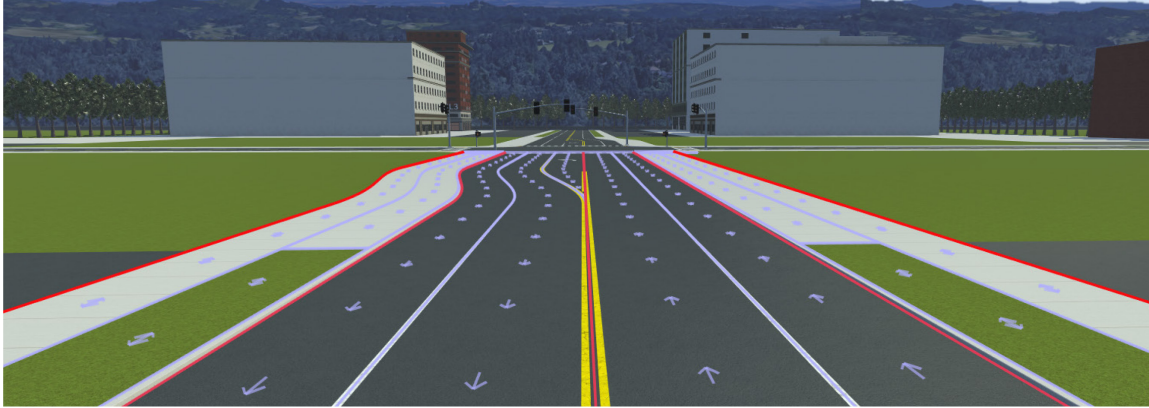


Figure 4.9. Sample Roadway Geometry of a Left Turn Scenario

- **Geocoded Scenarios:** The intersection approaches for the geocoded scenarios consisted of 3D models of the existing conditions of NE Broadway & 21st Avenue and NE Broadway & 14th Avenue in Portland, Oregon. For both intersections, the approximate dimensions of the roadway and surrounding buildings, softscape, and hardscape were measured using Google Earth's measure tool, then 2D satellite imagery from Google Earth was scaled and 3D modeled in RoadRunner R2023b.
 - **NE Broadway & 21st Avenue:** The 21st Avenue approach consisted of two 11 ft travel lanes in each direction, an 11 ft dedicated right turn lane, two 9 ft parking lanes in each direction, and a 6.5 ft sidewalk with an 8 ft buffer strip. The NE Broadway approach consisted of three 11 ft travel lanes in one direction, a 5 ft bike lane in one direction, two 9 ft parking lanes, and a 12 ft sidewalk on both sides of the street. The intersection had a 15 ft curb radius and no crosswalk setback. Crosswalk width was 13 ft. See Figures 4.10 (aerial view) and 4.12 (street view) for a comparison of the 3D model and the existing conditions.

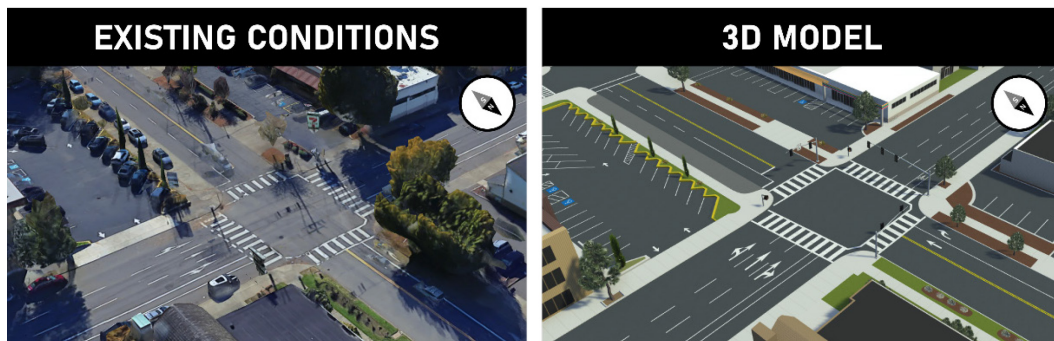


Figure 4.10. NE Broadway & 21st Avenue (Aerial View)

- **NE Broadway & 14th Avenue:** The 14th Avenue approach consisted of two 11 ft travel lanes in each direction, two 9 ft parking lanes in each direction, and an 8 ft sidewalk with an 8 ft buffer strip. The NE Broadway approach consisted of three 11 ft travel lanes in one direction, a 5 ft bike lane in one

direction, two 9 ft parking lanes, and a 12 ft sidewalk on both sides of the street. The intersection had a curb extension that was approximately 15 ft long, 2 ft narrower than the 9 ft parking lane, with a 15 ft curb radius, and no crosswalk setback. Crosswalk width was 16 ft. See Figures 4.11 (aerial view) and 4.13 (street view) for a comparison of the 3D model and the existing conditions.



Figure 4.11. NE Broadway & 14th Avenue (Aerial View)



Figure 4.12. NE Broadway & 21st Avenue (Street View)



Figure 4.13. NE Broadway & 14th Avenue (Street View)

Independent Variables:

- Leading Pedestrian Interval (LPI):*** According to the 11th Edition of the MUTCD, the minimum duration of an LPI is 3 seconds. And according to FHWA's 28 Proven Safety Countermeasures (Albee & Bobitz, 2021), the duration of an LPI ranges from 3-7 seconds. Researchers decided to focus on a 5-second LPI. This choice was made to study the midpoint duration of an LPI. Figure 4.14 shows a sample LPI scenario.



Figure 4.14. Sample LPI Scenario

- Curb Extension (CE):*** According to the NACTO Urban Street Design Guide (NACTO, 2013), the length of a curb extension should at least be equal to the width of the crosswalk, and the curb extension should generally be 1–2 ft narrower than the parking lane. For this experiment, researchers decided to follow a similar design to that of a real-life curb extension like the one found on the northeast corner of NE Broadway & 12th Avenue in Portland, Oregon. The CE modeled in the experiment was 30 ft long and 1.5 ft narrower than the 9 ft parking lane. To maintain consistency across all the scenarios in the experiment, the curb extension was modeled to have a 30 ft curb radius, and a 20 ft crosswalk setback. Figure 4.15 shows an aerial view of a sample curb extension scenario.



Figure 4.15. Sample Curb Extension Scenario (Aerial View)

- No Turn on Red (NTOR) Sign:*** According to the 11th Edition of the MUTCD, where a right turn on a circular red signal indication is to be prohibited, a NO TURN ON RED (R10-11, R10-11b) word message sign shall be used. And a NO TURN ON RED (symbolic circular red) (R10-11a) sign shall be used when the approach is controlled by both circular red and red arrow indications. Because no

red arrow indications were used in the experiment, researchers decided to use an R10-11 sign.

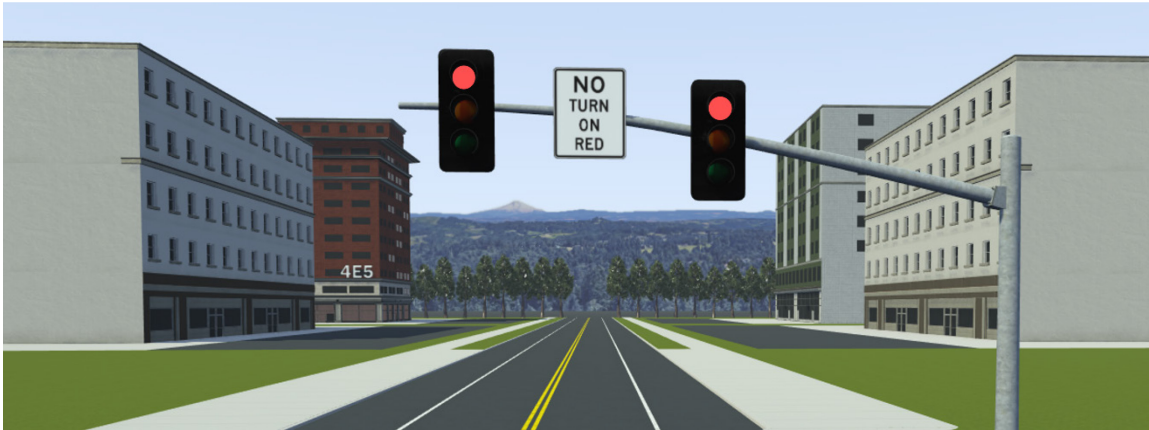


Figure 4.16. Sample NTOR (R10-11) Sign Scenario

- ***Pedestrian:*** The pedestrian used in the simulator experiment was modeled with a walking speed of 4 ft/s. The pedestrian signal head was a one-section pedestrian signal head without countdown display with the UPRaised HAND and WALKING PERSON arranged side-by-side. According to the MUTCD, at locations where an LPI is used, the minimum time for the WALK interval should be the time provided for the LPI plus 7 seconds. Thus, in scenarios where a 5 second LPI was present, the total duration of the WALK interval was 12 seconds. And at scenarios where no LPI was present, the total duration of the WALK interval was 7 seconds. The LPI allowed the ped to walk for 20 ft before the signal turned green (5s LPI x 4 ft/s average walking speed = 20 ft). When no CEs were present, the LPI allowed the ped to reach the middle lane (9 ft of parking lane + 11 ft of 1st travel lane) and when CEs were present, the LPI allowed the ped to reach past the middle of the 2nd travel lane (1.5 ft of parking lane + 11 ft of 1st travel lane + 7.5 ft of 2nd travel lane).



Figure 4.17. Sample Pedestrian at Scenario

Design Strategies to Mitigate Simulator Sickness

The way that a virtual environment is designed can influence simulator sickness. Design characteristics such as roads with curves, complex city environments, high speed roadways, and turning maneuvers at intersections have all been associated with increased dropout rates in driving simulation studies due to simulator sickness (Park et al., 2006; Almallah et al., 2021). Because this driving simulator study was specifically interested in studying how the 3 countermeasures (LPI, CE, and NTOR) impact driver turning behavior at signalized intersections, turning scenarios could not be avoided. To counteract the impacts of turning scenarios, straight long segments of road were provided in between turning scenarios to mitigate the risk of simulator sickness. Other strategies included minimizing the complexity of the scenery and dynamic objects presented in the virtual environment (i.e., minimizing visual clutter), providing enough sight distance at intersections (i.e., 200 ft buffer zone with no obstructions at all corners of the intersection), and setting a speed limit of 25 mph. These design strategies were based on best practices from OSU's more than 20 driving simulator studies since 2010 (Danilla et al., 2025; Chai et al., 2024; Fink et al., 2024b; Hurwitz et al., 2024; Jashami et al., 2019), and best practices from the Handbook of Driving Simulation (Fisher et al., 2011) and from researchers in the driving simulator community (Almallah et al., 2021, Dużmańska et al., 2018; Karl et al., 2013; Reed Jones, 2011; Park et al., 2006).

Design Software

The development of virtual environments was divided into 3 phases: 3D modeling, dynamic modeling, and testing. See Figure 4.2 in section 4.1.1.1 of this chapter for a visual summary of the development workflow that was used to model and test the virtual environments for the driving simulator study. Each of these phases leveraged two pieces of software, RoadRunner (3D modeling) and SimCreatorDX (dynamic modeling and testing).

RoadRunner: In previous simulator studies conducted at OSU, 3D modeling software like Blender and SketchUp were used. In 2024, the OSU Driving & Bicycling Simulator Laboratory began implementing RoadRunner by MathWorks as the primary software used to develop static 3D environments for simulator studies. This driving simulator study is the first one to implement RoadRunner in the lab's 15-year history. RoadRunner allowed OSU researchers to streamline the 3D modeling process through its user-friendly interface for roadway design and its extensive asset library with more than a hundred pre-built and customizable assets (e.g. road and highway signs, traffic signals, road surface markings, trees, buildings, barriers, material textures, props, etc.). The software allows for easy customization of roads and the pre-built asset library provides hundreds of 3D props and signage options with standard sizes and design characteristics that match those found in the MUTCD. This software allowed researchers to model the roadway networks, scenery, and traffic control devices needed to build the driving simulator study's virtual environments. Figure 4.18 shows an OSU researcher working with RoadRunner R2023b (Update 7). Then, the environment was converted using a widget to a specific extension compatible with SimCreatorDX and Fusion 2.



Figure 4.18. OSU Researcher Working with RoadRunner

SimCreatorDX: As described in section 4.1.1.1 and shown in Figure 4.2, SimCreatorDX by Realtime Technologies was used to model the dynamic scenarios of the driving simulator study. A C++ code was developed to model the traffic signal timing and pedestrian signal timing required for the LPI. The C++ code also allowed for easy customization of pedestrian walking speed, delay, and crossing trajectory, as well as customization of ambient vehicle speed (25 mph) and driving trajectory. The software was installed in a host computer that was connected to OSU's desktop simulator (Figure 4.1), which provided a convenient way to test and fine-tune all the scenarios for the experiment. Figure 4.19 shows an OSU researcher working with SimCreatorDX to model the walking speed, delay, and trajectory of a pedestrian at a signalized intersection.

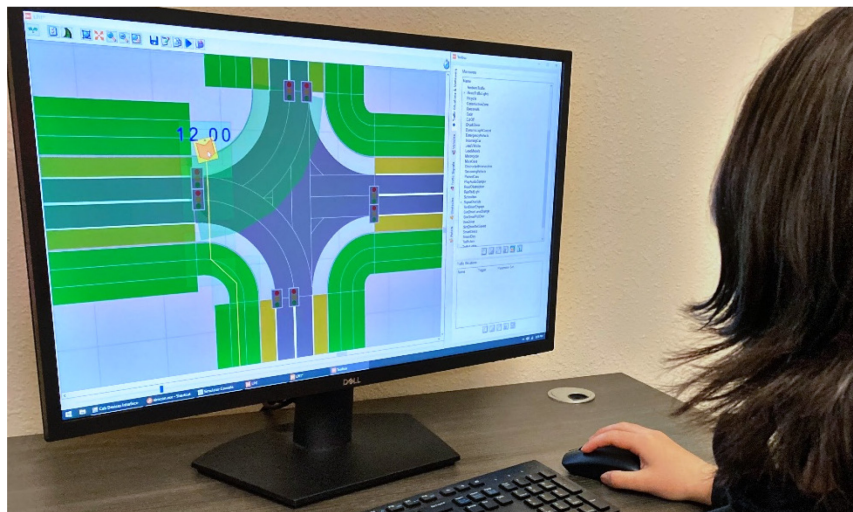


Figure 4.19. OSU Researcher Working with SimCreatorDX

Completed Simulation Scenarios: Once all 24 scenarios were tested and fine-tuned in the desktop simulator, the completed files were transferred to OSU's full-cab driving simulator for beta-testing and for conducting the actual experiment (see Figure 4.7 and

Appendix D for renderings of all 24 completed scenarios). When designing the virtual environments for the driving simulator study, a deliberate effort was made to match transportation design standards and real-life examples as closely as possible.

4.1.3 Experimental Procedure

This section provides a description of the step-by-step procedure used in the driving simulator experiment conducted at Oregon State University's Driving & Bicycling Simulator Laboratory. The experiment lasted approximately 1 hour and was broken down into 6 different phases (informed consent, pre-drive survey, practice drive, wearable equipment, experimental drive, and post-drive survey). Figure 4.20 shows a summary of the different phases that research subjects went through during the driving simulator experiment.

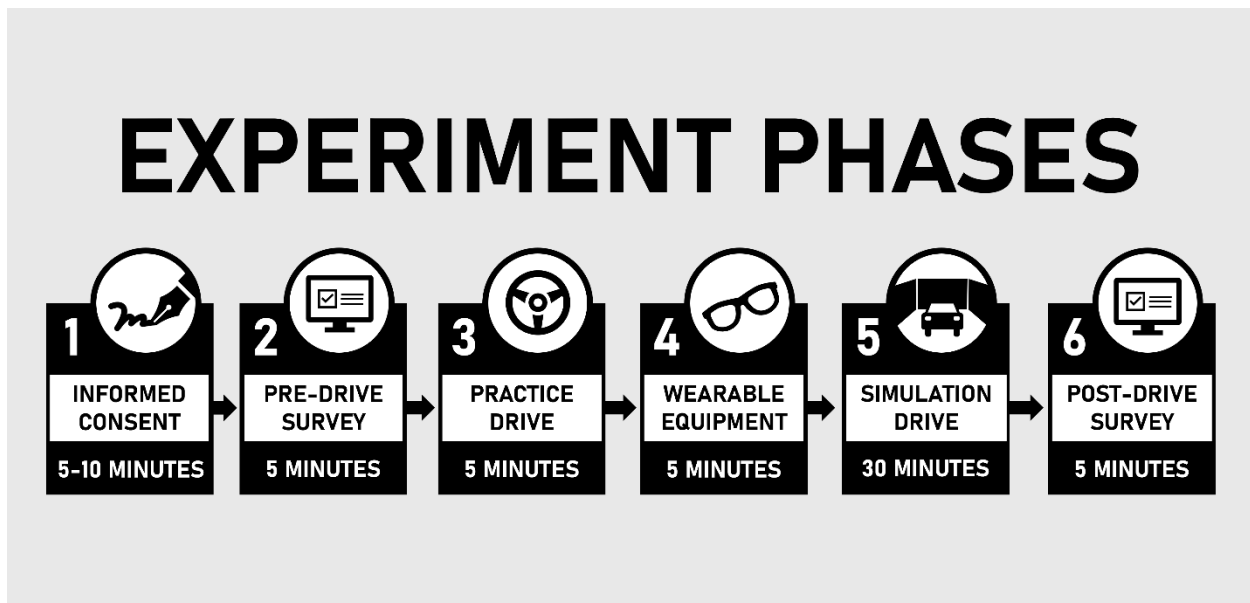


Figure 4.20. Driving Simulator Experiment Phases

1. Informed Consent

Consent was obtained from all subjects prior to beginning any experimental procedures. An Institutional Review Board (IRB) approved consent document was presented and explained to the subject upon arrival at the laboratory. The document included an overview of the driving simulator study, as well as any potential risks and benefits associated with their participation in the study. After signing the consent document, subjects then engaged with the experimental activities.

2. Pre-Drive Survey

After subjects completed the consent document, they were asked to complete a 5-minute pre-drive survey on a desktop computer at the laboratory. In this survey, subjects provided some demographic information (e.g., age, gender, race/ethnicity, income, highest level of completed education, etc.). They also shared the type of motor vehicle that they drive, whether they had

participated in a simulator experiment in the past (if yes, whether they experienced simulator sickness), and their history with motion sickness.

3. Practice Drive

After completing the pre-drive survey the subject entered the simulator vehicle for a 5-minute practice drive. During this practice drive subjects got a chance to become familiar with the simulator mechanics, virtual displays, and instructional signage as they navigated a simulation environment with no experimental variables. This allowed subjects to get situated within the vehicle and to adjust, as needed, the vehicle seat, rearview mirror, and steering wheel to optimize comfort and driving performance. Subjects were instructed to obey all traffic laws and drive as they normally would in their day-to-day life. This drive also allowed subjects to confirm if they are prone to simulator sickness. In the event that a subject experienced simulator sickness or discomfort during the practice drive they were encouraged not to proceed with the study and were compensated for their participation.

4. Wearable Equipment

After completing the practice drive, subjects were asked to exit the vehicle so that they could be equipped with the wearable equipment for the driving simulator experiment. The wearable equipment included a pair of eye-tracking glasses (Figure 4.5). Once the subjects were equipped with the eye tracking glasses, these were paired to the data collection laptop and calibrated as described in section 4.1.1.2. Once the eye tracking glasses were ready to go the subjects were asked to return back into the vehicle to begin the simulation drive.

5. Simulation Drive

The simulation drive was divided into 6 simulation tracks containing 4 different scenarios each (a total of 24). At the end of each track, participants were instructed to stop the vehicle, notify the researcher if they were experiencing any simulator sickness, confirm if they would like to proceed with the next simulation track, or withdraw from the study in case of any simulator sickness. The simulation drive lasted approximately 30 minutes.

6. Post-Drive Survey

As the final phase of the experiment, subjects were asked to exit the vehicle, remove the wearable equipment, and complete a post-drive survey. This survey allowed the researchers to collect additional information specific to the subject's behavior choices when navigating the virtual environment as well as their level of comfort across the various scenarios. Subjects were also asked if they experienced any simulator sickness throughout the experiment. Once participants successfully completed the post-drive survey, they received \$20 compensation and were thanked for their participation in the driving simulator study.

4.1.4 Data Processing

This section provides a description of how the raw data collected from the driving simulator experiment was processed for analysis. The main datasets include speed data collected from the full cab driving simulator and visual attention data collected from the eye tracking glasses.

4.1.4.1 Simulator Speed

As soon as a simulation file was loaded, the driving simulator's data acquisition system (SimObserver Pro) began collecting video data that was synchronized with vehicle data such as the vehicle's speed, position, acceleration, and braking patterns, among many other performance measures. This data was captured by SimObserver Pro at a rate of 60 Hz and processed in a software called Data Distillery by Realtime Technologies. Figure 4.21 shows an example of the raw data captured from the simulator.

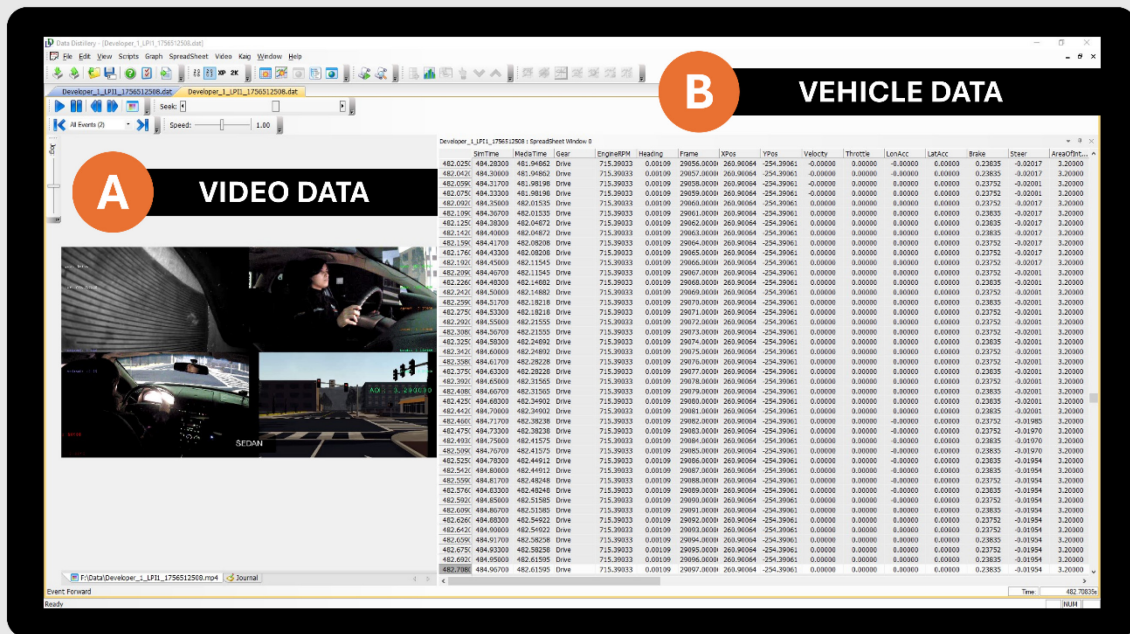


Figure 4.21. Raw Data Captured from Driving Simulator

During the development of the dynamic environments in SimCreatorDX, OSU researchers incorporated data collection markers at the intersections of all 24 scenarios. These markers allowed researchers to streamline data processing by allowing for automatic segmentation of the raw data. At each intersection, a total of 3 markers (aka sensors) were placed on the virtual roadway to automatically segment the approach speed and turning speed of the vehicle.

As shown in Figure 4.22, the first marker was located 50 ft away from the intersection and signaled the start of the raw data pertaining to the approach speed. The second marker was located on the outside edge of crosswalk #1 (farthest from center of the intersection) and signaled the end of the raw data pertaining to the approach speed and the start of the raw data pertaining to the turning speed. Finally, the third marker was located on the outside edge of crosswalk #2 (farthest from center of the intersection) and signaled the end of the raw data pertaining to the turning speed. Note: SimCreatorDX simplifies roadway geometry and lane markings from the 3D virtual environment as 2D lines, therefore, crosswalks are depicted as one line below traffic signal head symbols.

This line represents the outside edge of the crosswalk (the edge that is farthest from the center of the intersection).

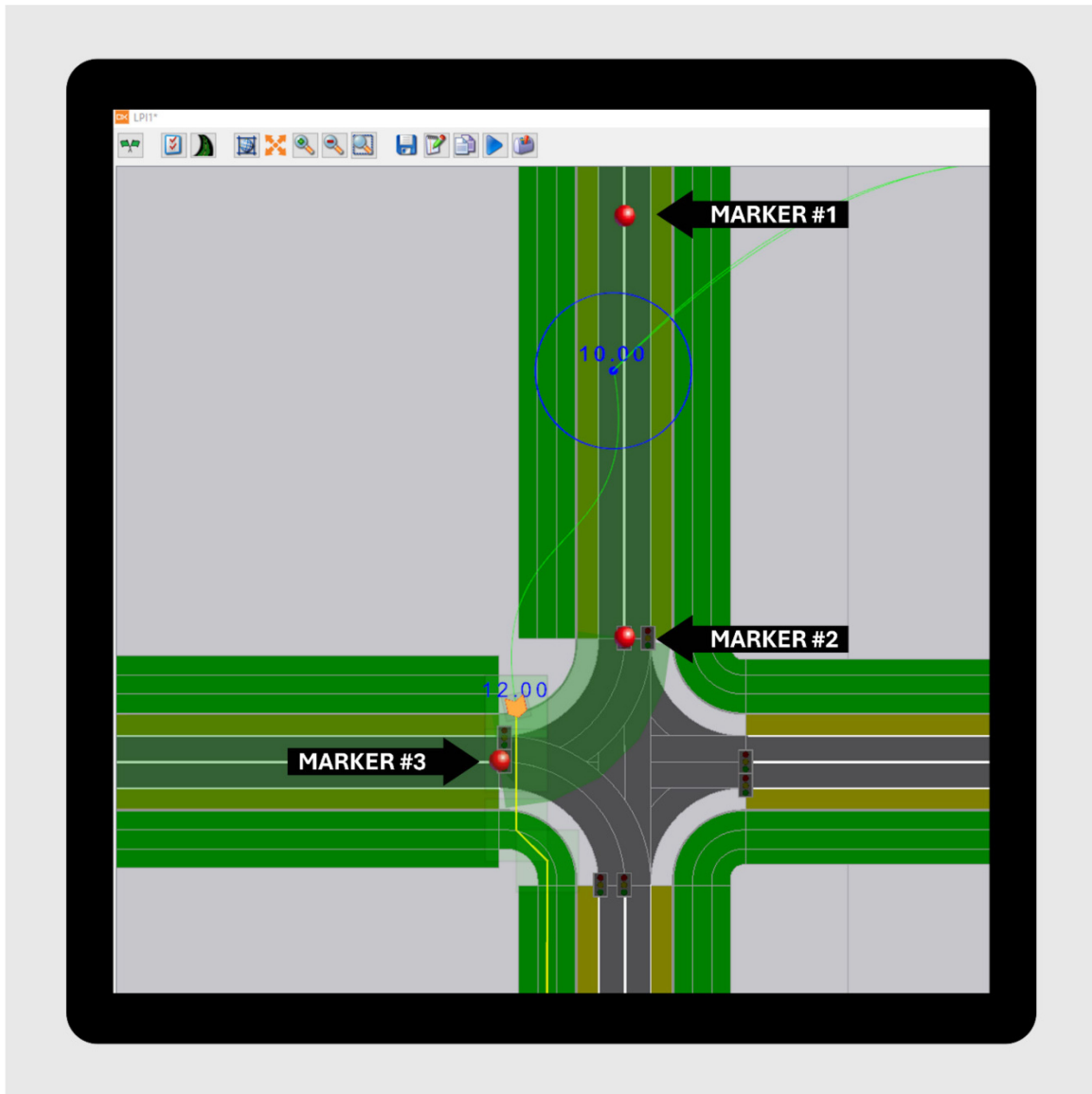


Figure 4.22. Data Collection Markers for Segmenting Speed Data

From the 58 subjects (29 male + 29 female) that participated in the experiment, raw vehicle data from only 44 subjects (24 male + 20 female) was used because 14 subjects withdrew from the study due to simulator sickness (5 male and 9 female). As previously mentioned, each subject completed a total of 6 simulation tracks. Across 44 subjects, this resulted in a total of 264 individual files with more than 20,000 rows of data per file (~5,280,000 rows of data to work with). Using Python, OSU researchers developed a code that combined all 264 .dat files.

Finally, an excel spreadsheet summarizing the descriptive statistics (mean and standard deviation) of the approach speed and turning speed for all 44 subjects across all 24

scenarios was created. Later on, the descriptive statistics were organized and visualized by right turn scenarios, digital twin scenarios, and left turn scenarios as presented in the results chapter. Figure 4.23 shows a summary of the steps used for processing the speed data.

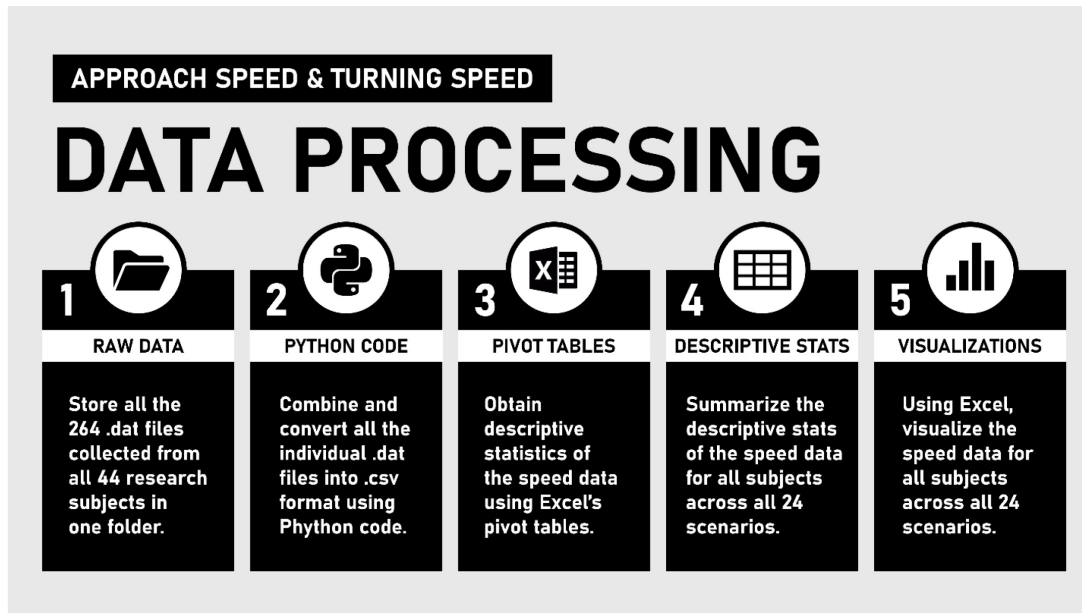


Figure 4.23. Steps for Speed Data Processing

4.1.4.2 Speed Validation

To validate the speeds collected in the driving simulator, speed data from the two real-world intersections modeled in the simulator (Broadway & 14th Avenue and Broadway & 21st Avenue) was collected using video data. To prevent the simulator turning speeds from being influenced by the presence of a pedestrian, only the turning speeds from geocoded scenarios with “no pedestrian present” were included in the analysis. Similarly, to ensure that the speeds collected from the video data in the field were consistent with the speeds collected from the simulator, the vehicle observations collected in the field included only turning vehicles travelling at free-flow speeds and those that did not conflict with pedestrians, bicyclists, or other vehicles.

Because the signal phase in which turning vehicles completed their turn influences turning speed, the research team looked at the proportion of drivers that turned on green and those that turned on Red during the simulation for each intersection. At Broadway & 14th Avenue, from the 44 simulator subjects, 34 turned on Red (77%) and 10 turned on Green (23%). At Broadway & 21st Avenue, from the 44 simulator subjects, 29 turned on Red (66%) and 15 turned on Green (34%). To replicate the simulator conditions, speed data for the same proportion of turning vehicles was collected from the video data in the field (the sample size was 100 vehicles per intersection). At Broadway & 14th Avenue, from the 100 vehicle observations, 77 turned on Red (77%) and 23 turned on Green (23%). At Broadway & 21st Avenue, from the 100 vehicle observations, 66 turned on Red

(66%) and 34 turned on Green (34%). The data transcribed consisted of video data collected across two weekdays (August 20-21, 2024) from 7 AM – 8 PM.

To transcribe the video data, a graduate research assistant (GRA) collected 2 timestamps per vehicle in hour:minutes:seconds. Timestamp #1 was the moment the rear bumper of the vehicle touched the stop bar, and the Timestamp #2 was the moment the rear bumper touched the stop bar of the approach the vehicle turned into. See Figure 4.24 for an example of the timestamps collected at both intersections.

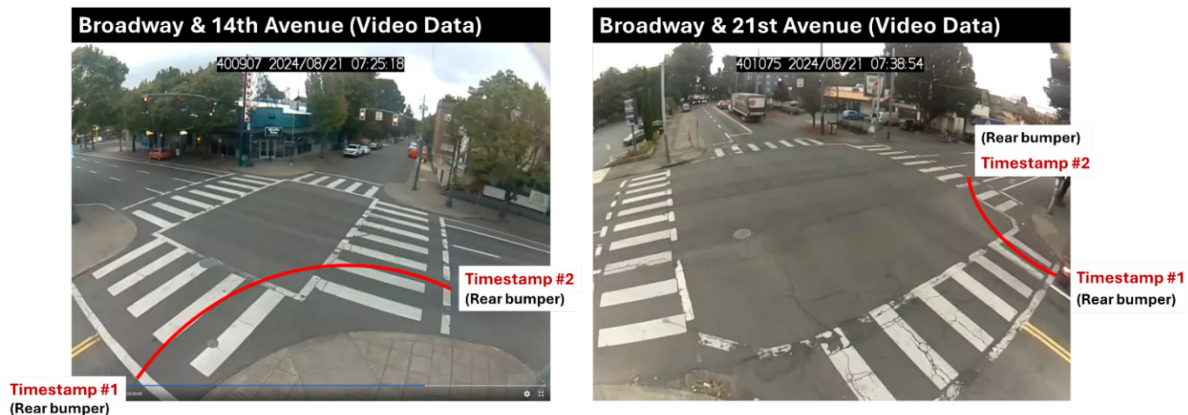


Figure 4.24. Timestamps Collected from Video Data

The timestamps collected by the GRA were reviewed by a group of undergraduate research assistants (URAs) for quality control. Inter Rater Reliability (IRR) scores were generated from comparing the timestamps collected by the GRA and those collected by the URAs. For Broadway & 14th Ave, the IRR score was 95.3%. And for Broadway & 21st Ave, the IRR score was 93.3%. From this comparison, the timestamps for which disagreement from both groups existed were double checked and corrected, then final datasets for each intersection were created.

To obtain the distance that turning vehicles travelled when making their turn, the arc length of the turning movement for each intersection (42 ft for Broadway & 14th Ave and 40 ft for Broadway & 21st Ave) was estimated using Google Earth Pro as shown in Figure 4.25. And individual vehicle speeds were calculated by dividing distance (arc length in feet) over time (difference between the two timestamps in seconds), then converted from feet per second (ft/s) to miles per hour (mph) using conversion factor 0.681818. Finally, the mean turning speed per intersection was obtained by getting the average of all 100 individual vehicle observations.

For a description of how the simulator speeds were collected, see Section 4.1.4.1. For a comparison of the speeds collected in the simulator and those collected in the field, see section 4.2.3.1 of the results chapter.



Figure 4.25. Arc Length Estimation Per Intersection

4.1.4.3 Visual Attention

As described in section 4.1.1.2, visual attention data in the form of video data overlaid with the subject's gaze (moving circle) was collected using eye tracking glasses. This data was later transcribed by defining Areas of Interest (AOI) through the eye tracking glasses module of a software called iMotions, as shown in Figure 4.26.

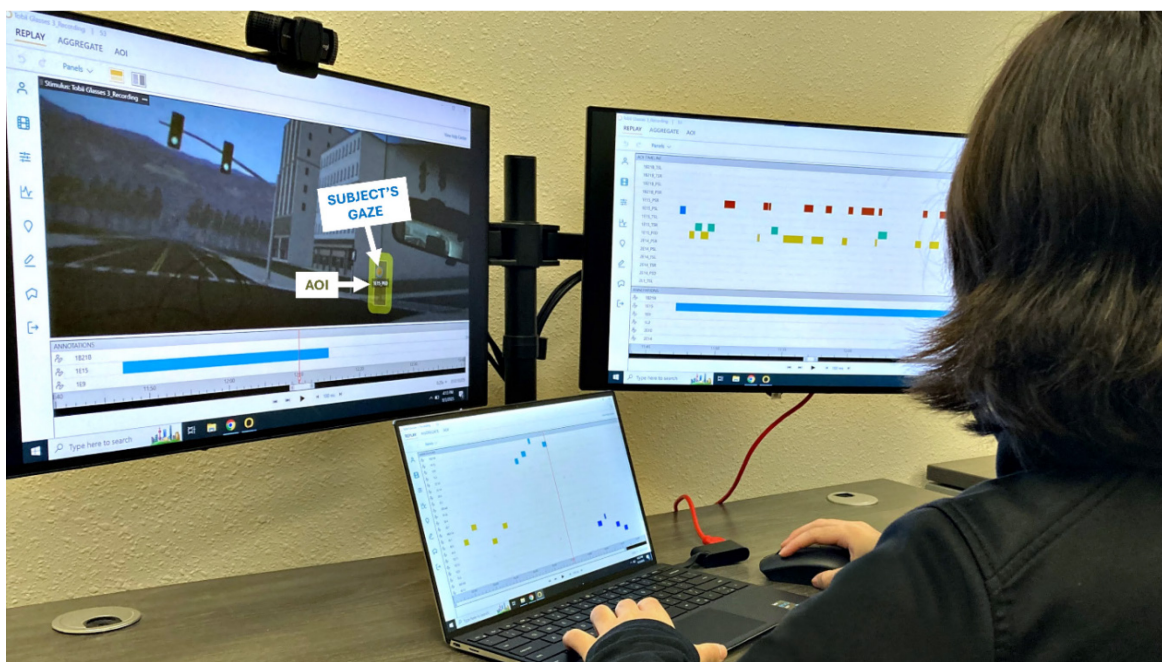


Figure 4.26. Visual Attention Data Transcription

The final analyzed sample for the visual attention dataset consisted of data from 33 subjects with 24 scenarios each (792 scenarios total). During 85 of these 792 scenarios, visual attention data did not get collected due to technical issues. Therefore, the final number of scenarios transcribed in iMotions was 707 scenarios across all 33 subjects. This data was transcribed by a group of graduate and undergraduate research assistants. A total of 4 AOIs were transcribed in this study (Pedestrian, NTOR Sign, Traffic Signal,

and Pedestrian Signal). Two separate AOIs were transcribed for the left and right pedestrian signal head and traffic signal head, and the results obtained from each pair were later combined to obtain the final result for the “Traffic Signal” and “Pedestrian Signal” AOIs. Per subject, research assistants transcribed a total of approximately 116 AOIs. A total of 3,425 AOIs were transcribed across all 33 subjects. Once the AOIs were transcribed, the iMotions software generated visual attention metrics for each AOI. The metric used for visual attention in this study is Total Fixation Duration (TFD), which iMotions defines as the total time in seconds the respondent spent fixating at the AOI. Descriptive statistics and visualizations of the TFD on each of the 4 AOIs across all 24 scenarios are shown in the results chapter.

As shown in Figure 4.27, across all scenarios (right turns, geocoded, and left turns), the data transcription for the visual attention data per scenario, started from the moment the driver reached a reference point (the end of the grass buffer strip) located 200 ft away from the intersection to the moment when the driver completed their turn and the pedestrian signal (circled in red) was out of sight. Shown by the orange dashed arrow is the path that turning vehicles followed. A sensor was placed 150 ft away from all intersections so that drivers were always presented with a red signal indication before making a turn. As soon as vehicles reached another sensor located 25 ft away from the intersection, drivers were given a ~12 second delay before the signal turned green (when no LPI was present), and a ~17 second delay before the signal turned green (when a 5 second LPI was present). These 12-17 seconds of wait time gave drivers enough time to scan the intersection (i.e., fixate on certain AOIs) and use their personal judgement to decide whether to wait for the green or turn on red. Although all subjects were provided with these same conditions across all scenarios, the total time that individual subjects spent at the intersection before making the turn varied from subject to subject, as some drivers would choose to turn on red while others would choose to wait for the green. The total time that subjects spent scanning the intersection and any associated AOIs before turning, may have influenced the mean TFD results for the AOIs studied in the experiment. However, because TFD is measured in milliseconds, valuable insights regarding which AOIs subjects fixated on the most, can still be acquired.

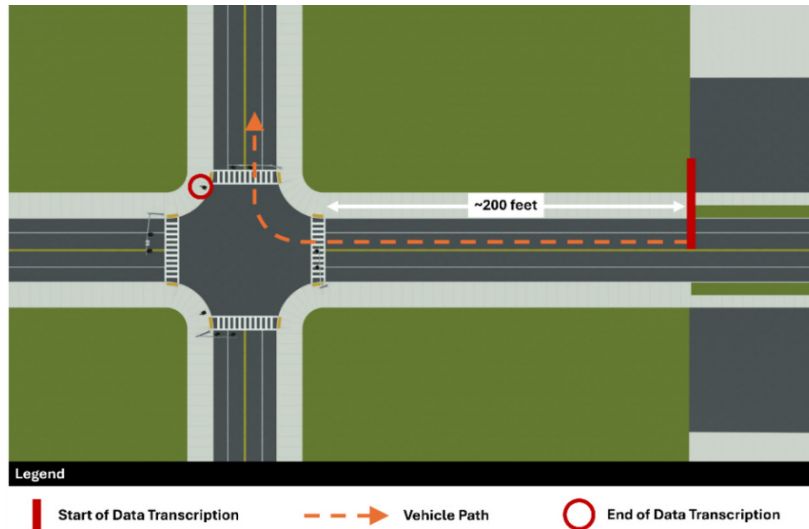


Figure 4.27. Example Start and End of Visual Attention Data Transcription

4.2 RESULTS

This section provides the results obtained from the driving simulator study. The chapter includes a description of the experiment's sample size, survey results, speed results, visual attention results, stress level results, decision making results, and simulator validation.

4.2.1 Subjects

4.2.1.1 Recruitment

An Institutional Review Board (IRB) application was submitted and approved (IRB Study No: HE-2023-529) for the driving simulator study. Subject recruitment consisted of paper-based and digital methods such as flyers, listservs, and email newsletter advertisements. A total of 58 subjects (29 male and 29 female) from Corvallis, Oregon and its surrounding communities participated in the driving simulator study. The age of subjects ranged from 18 to 78 years old and consisted of licensed drivers with at least 1 year of driving experience.

4.2.1.2 Total Sample Size

A total of 58 subjects (29 male and 29 female) participated in the driving simulator study. During the experiment, 14 subjects withdrew from the study because 10 of them experienced simulator sickness at the end of the practice drive, and 4 of them experienced simulator sickness after the third simulation track. This brought down the total sample size to 44 subjects ($AA = 33$, $SD = 17$), including 24 males ($AA = 31$, $SD = 17$) and 20 females ($AA = 36$, $SD = 18$).

4.2.1.3 Sample Size Per Dataset

The final analyzed sample for the two datasets (speed and visual attention) was different because of data loss due to some technical issues. Table 4.3 shows a summary of the total sample size and final analyzed samples from the driving simulator study.

Table 4.3. Sample Size of Driving Simulator Study

Data Type	Number of Subjects
Total Enrolled	58 subjects (29 male, 29 female)
Simulator Sickness	14 subjects (5 male, 9 female)
Total Sample Size	44 subjects (24 male, 20 female)
Data Lost	Speed Data (no data lost), Visual Attention Data (11 subjects)
Final Analyzed Sample (Speed Data)	44 subjects (24 male, 20 female)
Final Analyzed Sample (Visual Attention Data)	33 subjects (19 male, 14 female)

Speed - From the 58 subjects (29 male, 29 female) that participated in the driving simulator study, speed data from only 44 subjects (AA = 33, SD = 17), including 24 males (AA = 31, SD = 17) and 20 females (AA = 36, SD = 18), was analyzed because 14 subjects (5 male, 9 female, AA = 51, SD = 15) withdrew from the study due to simulator sickness.

Visual Attention - From the 44 subjects that did not experience simulator sickness, visual attention data from only 33 subjects was analyzed because eye-tracking data could not be collected from 11 subjects due to technical issues. The final analyzed sample for the visual attention dataset included the usable data from the 33 subjects (AA = 31, SD = 17), including 19 males (AA = 32, SD = 18) and 14 females (AA = 29, SD = 16). The average calibration accuracy of the data collected from the eye tracking glasses for the 33 subjects was 90.2%.

4.2.2 Survey

This section provides the results from the pre-drive and post-drive surveys that research subjects responded to during their participation in the driving simulator study.

4.2.2.1 Pre-Drive Survey

Before engaging with the driving simulator, research subjects were asked to complete a 5-minute pre-drive survey that collected data regarding the subjects' demographics, driving behavior, and their history with simulation experiments and motion sickness. Table 4.4 shows the results obtained from the usable subjects.

Table 4.4. Pre-Drive Survey Results

Question	Answer – Number of Subjects (Percentage)
Gender	Male — 24 subjects (54.5%) Female — 20 subjects (45.5%) Non-Binary — 0 subjects (0.0%) Other — 0 subjects (0.0%) Prefer Not to Answer — 0 subjects (0.0%)
Age	18 to 24 years old — 26 subjects (59.1%) 25 to 34 years old — 2 subjects (4.5%) 35 to 44 years old — 2 subjects (4.5%) 45 to 54 years old — 8 subjects (18.2%) 55 to 64 years old — 4 subjects (9.1%) 65+ years old — 2 subjects (4.5%)
Race or Ethnicity	Asian — 4 subjects (9.1%) White or Caucasian — 30 subjects (68.2%) Hispanic or Latino/a/x — 5 subjects (11.4%) Native Hawaiian or Other Pacific Islander — 1 subject (2.3%) American Indian or Alaska Native — 0 subjects (0.0%) Black or African American — 0 subjects (0.0%) Other — 4 subjects (9.1%)
What is your annual household income?	Less than \$25,000 — 8 subjects (18.2%) \$25,001 - \$50,000 — 3 subjects (6.8%) \$50,001 - \$75,000 — 3 subjects (6.8%) \$75,001 - \$100,000 — 3 subjects (6.8%) \$100,001 - \$200,000 — 15 subjects (34.1%) More than \$200,000 — 5 subjects (11.4%) Prefer Not to Answer — 7 subjects (15.9%)
What is the highest level of education you have completed?	Some High School or Less — 0 subjects (0.0%) High School Diploma or GED — 7 subjects (15.9%) Some College — 18 subjects (40.9%) Two-Year Degree — 2 subjects (4.5%) Four-Year Degree — 6 subjects (13.6%) Master's Degree — 9 subjects (20.5%) Doctorate Degree — 2 subjects (4.5%) No Response — 0 subjects (0.0%)
How many years have you been a licensed driver?	0 to 5 years — 23 subjects (52.3%) 6 to 10 years — 3 subjects (6.8%) 11 to 15 years — 0 subjects (0.0%) 16 to 20 years — 2 subjects (4.5%) 20+ years — 16 subjects (36.4%) No Response — 0 subjects (0.0%)

Question	Answer – Number of Subjects (Percentage)
In which state did you first obtain your driver's license?	Oregon — 20 subjects (45.5%) Other — 24 subjects (54.5%) No Response — 0 subjects (0.0%)
How many miles did you drive last year?	0 to 5,000 miles — 11 subjects (25.0%) 5,001 to 10,000 miles — 16 subjects (36.4%) 10,001 to 15,000 miles — 10 subjects (22.7%) 15,001 to 20,000 miles — 4 subjects (9.1%) More than 20,000 miles — 3 subjects (6.8%) No Response — 0 subjects (0.0%)
What type of motor vehicle do you typically drive?	Passenger Car — 25 subjects (56.8%) SUV — 15 subjects (34.1%) Pickup Truck — 4 subjects (9.1%) Van — 0 subjects (0.0%) Heavy Vehicle — 0 subjects (0.0%) No Response — 0 subjects (0.0%)
How often do you drive in a typical week?	0 times per week — 4 subjects (9.1%) 1 time per week — 7 subjects (15.9%) 2 to 4 times per week — 14 subjects (31.8%) 5 to 10 times per week — 14 subjects (31.8%) More than 10 times per week — 5 subjects (11.4%) No Response — 0 subjects (0.0%)
Are you color blind?	Yes — 1 subject (2.3%) No — 43 subjects (97.7%) No Response — 0 subjects (0.0%)
What, if any, corrective eyewear do you wear while driving?	Glasses — 13 subjects (29.5%) Contacts — 4 subjects (9.1%) None — 27 subjects (61.4%)
Do you experience Motion sickness? (a.k.a. travel sickness)	Yes — 1 subject (2.3%) No — 43 subjects (97.7%) No Response — 0 subjects (0.0%)
Have you participated in other simulator experiments?	Yes — 14 subjects (31.8%) No — 30 subjects (68.2%) No Response — 0 (0.0%)

4.2.2.2 *Post-Drive Survey*

After completing the driving simulator experiment, research subjects were asked to complete a 5-minute post-drive survey. This survey allowed the researchers to collect additional information specific to the subject's behavior choices when navigating the virtual environment, as well as their level of comfort across the various scenarios. Table 4.5 shows the results obtained from the survey. Note: The post-drive survey results do not include responses from the 14 subjects that experienced simulator sickness.

Table 4.5. Post-Drive Survey Results

Question	Answer – Number of Subjects (Percentage)
Did you notice the pedestrian "WALK" signal activate first before the traffic signal turned green?	Yes – 44 subjects (100.0%) No – 0 subjects (0.0%)
Are you familiar with the law regarding right turns on red?	Yes – 42 subjects (95.5%) No – 2 subjects (4.5%)
Before this experiment, how familiar or unfamiliar were you with LPIs?	Very Unfamiliar – 1 subject (2.3%) Unfamiliar – 7 subjects (15.9%) Somewhat Familiar – 8 subjects (18.2%) Familiar – 13 subjects (29.5%) Very Familiar – 15 subjects (34.1%)
Before this experiment, how familiar or unfamiliar were you with NTOR Signs?	Very Unfamiliar – 0 subjects (0.0%) Unfamiliar – 0 subjects (0.0%) Somewhat Familiar – 2 subjects (4.5%) Familiar – 16 subjects (36.4%) Very Familiar – 26 subjects (59.1%)
Before this experiment, how familiar or unfamiliar were you with Curb Extensions?	Very Unfamiliar – 3 subjects (6.8%) Unfamiliar – 5 subjects (11.4%) Somewhat Familiar – 9 subjects (20.5%) Familiar – 11 subjects (25.0%) Very Familiar – 16 subjects (36.4%)
On a scale from 1 (Not at all) to 5 (Very Much), how much did LPIs improved pedestrian visibility and your yielding behavior towards pedestrians?	1 – 1 subject (2.3%) 2 – 0 subjects (0.0%) 3 – 5 subjects (11.4%) 4 – 17 subjects (38.6%) 5 – 21 subjects (47.7%)
On a scale from 1 (Not at all) to 5 (Very Much), how much did NTOR Signs improved pedestrian visibility and your yielding behavior towards pedestrians?	1 – 2 subjects (4.5%) 2 – 1 subjects (2.3%) 3 – 7 subjects (15.9%) 4 – 13 subjects (29.5%) 5 – 21 subjects (47.7%)
On a scale from 1 (Not at all) to 5 (Very Much), how much did Curb Extensions improved pedestrian visibility and your yielding behavior towards pedestrians?	1 – 2 subjects (4.5%) 2 – 5 subjects (11.4%) 3 – 14 subjects (31.8%) 4 – 10 subjects (22.7%) 5 – 13 subjects (29.5%)
On a scale from 1 (Very Uncomfortable) to 5 (Very Comfortable), how would you rate your comfort level when turning at intersections with curb extensions?	1 – 1 subject (2.3%) 2 – 5 subjects (11.4%) 3 – 13 subjects (29.5%) 4 – 17 subjects (38.6%) 5 – 6 subjects (13.6%)

Question	Answer – Number of Subjects (Percentage)
	No Response – 2 subjects (4.5%)
During the experiment, was your vehicle involved in a crash or near-miss with a pedestrian?	Yes, Crash ⁸ – 1 subject (2.3%) Yes, Near-Miss – 8 subjects (18.2%) No – 35 subjects (79.5%)
If involved in a crash / near-miss. How did it happen?	Failed to see pedestrian – 0 subjects (0.0%) Failed to yield to pedestrian – 3 subjects (6.8%) Failed to stop before turning – 0 subjects (0.0%) Other ⁹ – 6 subjects (13.6%)
Based on your experience in the simulator, please rank the (Top 1) treatment or treatment combination that you believe help improve pedestrian safety the most?	LPI – 4 subjects (9.1%) NTOR Sign – 5 subjects (11.4%) Curb Extension – 1 subject (2.3%) All Three Combined – 24 subjects (54.5%) LPI + Curb Extension – 3 subjects (6.8%) LPI + NTOR Sign – 7 subjects (15.9%) NTOR Signs + Curb Extensions – 0 subjects (0.0%)
On a scale from 1 (Very Unlikely) to 5 (Very Likely), please rate how likely or unlikely you are to behave in the real-world the same way you behaved in the simulator.	1 – 0 subjects (0.0%) 2 – 3 subjects (6.8%) 3 – 4 subjects (9.1%) 4 – 24 subjects (54.5%) 5 – 13 subjects (29.5%)

⁸ This refers to a crash with a pedestrian, the one subject that answered yes misinterpreted the question. They climbed on top of a curb extension and considered this a crash. From rewatching the video, no pedestrian was present when this happened.

⁹ A total of 5 of 6 subjects described in the “other” option behaviors that match “failed to yield to pedestrian”. The 6th subject was the same subject mentioned in footnote 1, they wrote “the turn was too sharp”.

4.2.3 Speed

This section provides the results of the turning speed and approach speed collected from 44 research subjects in the driving simulator, organized and visualized by right turn scenarios, geocoded scenarios, and left turn scenarios.

4.2.3.1 Right Turn Scenarios

Included in this section are descriptive statistics (mean and standard deviation), as well as box plot visualizations for the turning speed and approach speed collected from the driving simulator at 16 right turn scenarios (2x2x2x2).

Table 4.6. Turning Speed in miles per hour (mph) at Right Turn Scenarios

Right Turn Scenarios (Variables)	Mean	Standard Deviation (SD)
Scenario 1E9 (pedestrian only)	11.8 mph	3.6 mph
Scenario 1E15 (LPI + pedestrian)	12.5 mph	3.4 mph
Scenario 2E14 (curb extension + pedestrian)	10.2 mph	3.0 mph
Scenario 2E6 (no variables)	13.8 mph	2.5 mph
Scenario 2E10 (NTOR sign only)	13.1 mph	3.3 mph
Scenario 3E4 (LPI + pedestrian + NTOR sign)	12.5 mph	3.1 mph
Scenario 3E7 (LPI only)	13.5 mph	2.5 mph
Scenario 3E16 (curb extension + NTOR sign)	11.3 mph	3.3 mph
Scenario 4E5 (curb extension + pedestrian + NTOR sign)	10.2 mph	3.0 mph
Scenario 4E1 (LPI + curb extension + pedestrian + NTOR sign)	10.6 mph	3.1 mph
Scenario 5E13 (pedestrian + NTOR sign)	11.7 mph	2.7 mph
Scenario 5E11 (LPI + curb extension)	11.4 mph	2.7 mph
Scenario 5E2 (LPI + curb extension + pedestrian)	10.3 mph	3.5 mph
Scenario 6E3 (LPI + curb extension + NTOR sign)	10.7 mph	3.2 mph
Scenario 6E12 (LPI + NTOR sign)	12.9 mph	2.7 mph
Scenario 6E8 (curb extension only)	11.5 mph	2.7 mph

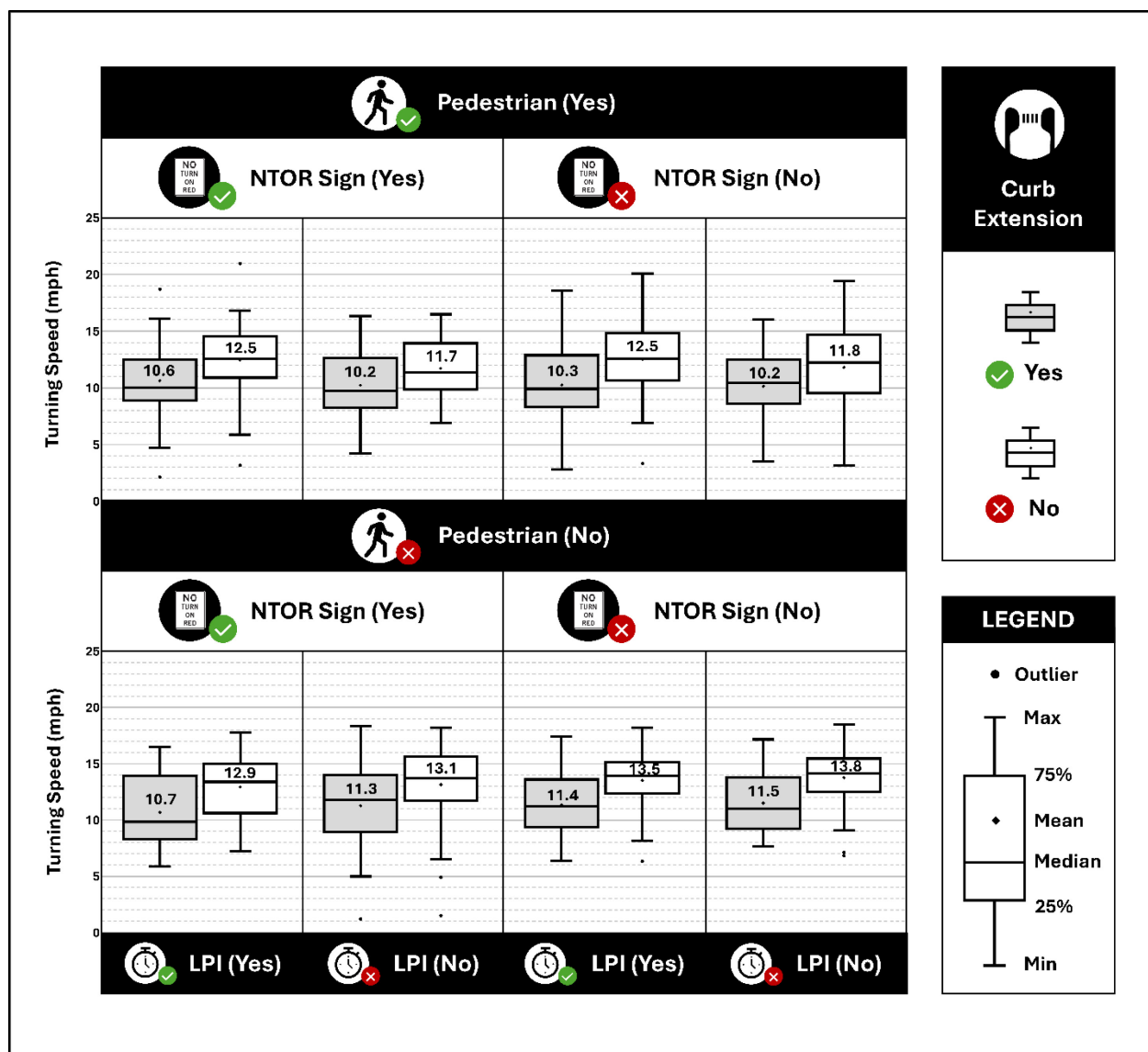


Figure 4.28. Turning Speed at Right Turn Scenarios

As shown in Table 4.6 and Figure 4.28, the highest mean turning speed was 13.8 mph ($SD = 2.5$), when drivers navigated the intersection in the absence of all independent variables (no curb extension, no LPI, no NTOR sign, and no pedestrian). The lowest mean turning speed was 10.2 mph ($SD = 3.0$), when drivers navigated the intersection with a curb extension and a pedestrian. Each boxplot in Figure 4.28 shows the distribution of the vehicle turning speed collected at the 16 intersections that were presented to research subjects during right turn scenarios. As shown by the box plots, the independent variables that had the most impact on vehicle turning speed across all 16 scenarios were the “curb extension” and “pedestrian” variables. When no other variables were present, curb extensions decreased the mean turning speed by 2.3 mph. And when no other variables were present, having a pedestrian at the intersection decreased the mean turning speed by 2 mph. Although the NTOR sign and LPI had less impact on turning speed compared to the curb extension and the pedestrian, when no other variables

were present, the NTOR sign decreased the mean turning speed by 0.7 mph and the LPI decreased the mean turning speed by 0.3 mph.

Table 4.7. Approach Speed in miles per hour (mph) at Right Turn Scenarios

Right Turn Scenarios (Variables)	Mean	Standard Deviation (SD)
Scenario 1E9 (pedestrian only)	6.3 mph	2.6 mph
Scenario 1E15 (LPI + pedestrian)	6.4 mph	2.8 mph
Scenario 2E14 (curb extension + pedestrian)	6.7 mph	2.7 mph
Scenario 2E6 (no variables)	8.1 mph	2.7 mph
Scenario 2E10 (NTOR sign only)	7.1 mph	3.4 mph
Scenario 3E4 (LPI + pedestrian + NTOR sign)	4.7 mph	1.4 mph
Scenario 3E7 (LPI only)	8.4 mph	3.2 mph
Scenario 3E16 (curb extension + NTOR sign)	6.6 mph	1.4 mph
Scenario 4E5 (curb extension + pedestrian + NTOR sign)	5.6 mph	0.7 mph
Scenario 4E1 (LPI + curb extension + pedestrian + NTOR sign)	5.8 mph	4.1 mph
Scenario 5E13 (pedestrian + NTOR sign)	4.7 mph	0.6 mph
Scenario 5E11 (LPI + curb extension)	7.9 mph	2.6 mph
Scenario 5E2 (LPI + curb extension + pedestrian)	5.5 mph	2.0 mph
Scenario 6E3 (LPI + curb extension + NTOR sign)	5.0 mph	1.2 mph
Scenario 6E12 (LPI + NTOR sign)	4.7 mph	0.6 mph
Scenario 6E8 (curb extension only)	7.7 mph	2.3 mph

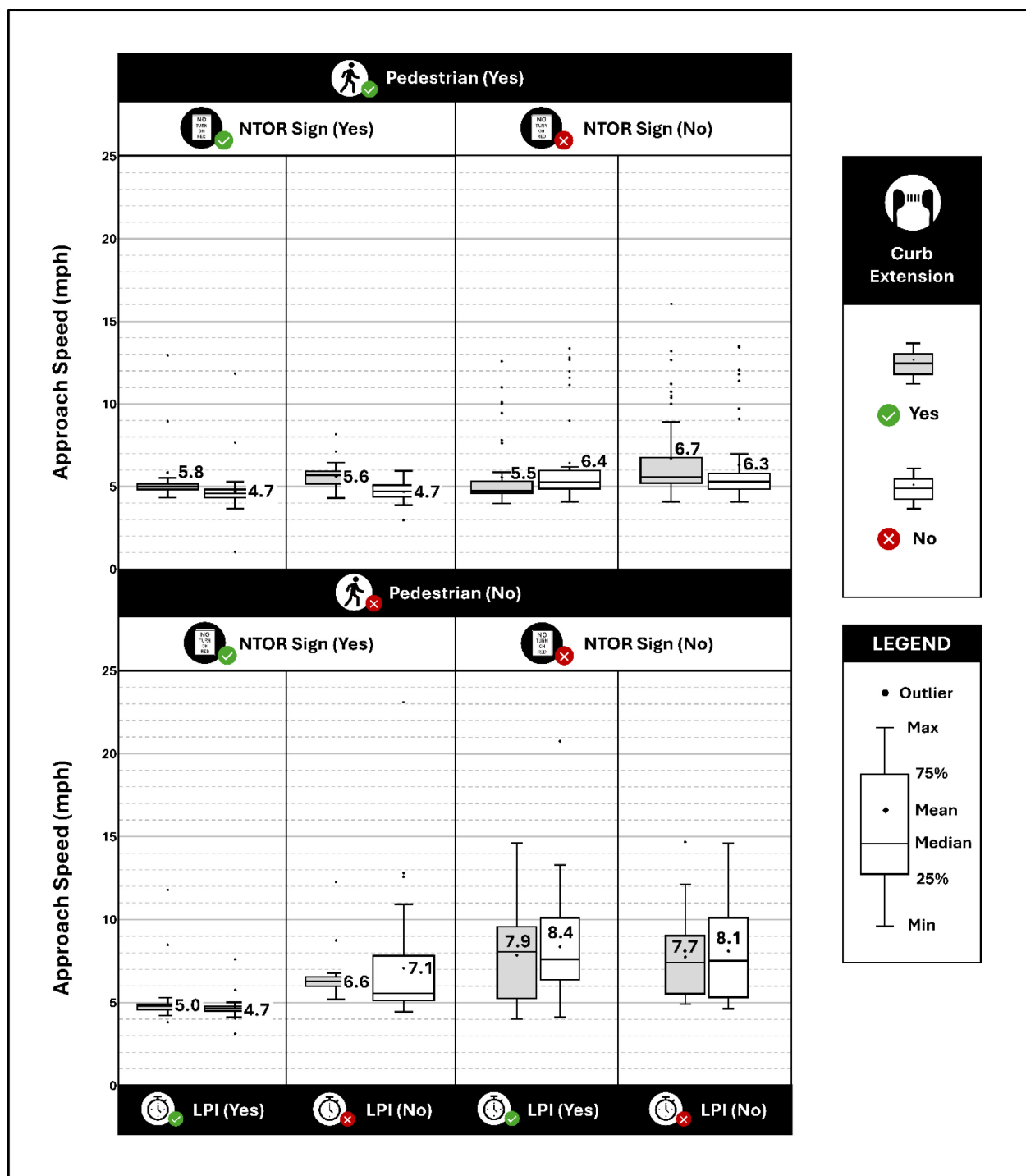


Figure 4.29. Approach Speed at Right Turn Scenarios

In terms of the approach speed, as shown in Table 4.7 and Figure 4.29, the highest mean approach speed was 8.4 mph (SD = 3.2), and the lowest approach speed was 4.7 mph (SD = 0.6). When no other variables were present, having a pedestrian at the intersection decreased the vehicle approach speed by 1.8 mph; the NTOR sign decreased the approach

speed by 1.0 mph; the curb extension decreased the approach speed by 0.4 mph; and the LPI increased the approach speed by 0.3 mph.

4.2.3.2 Geocoded Scenarios

Included in this section are descriptive statistics (mean and standard deviation), as well as box plot visualizations for the turning speed and approach speed collected from the driving simulator at 4 geocoded scenarios.

Table 4.8. Turning Speed & Approach Speed in miles per hour (mph) at Geocoded Scenarios

Geocoded Scenarios (Variables)	Turning Speed (Mean)	Turning Speed (SD)	Approach Speed (Mean)	Approach Speed (SD)
Scenario 1B21B (right turn at Broadway & 21st Avenue with no pedestrian)	11.5 mph	2.2 mph	8.9 mph	3.3 mph
Scenario 3B14A (right turn at Broadway & 14th Avenue with a pedestrian)	9.6 mph	2.7 mph	5.5 mph	1.9 mph
Scenario 4B21A (right turn at Broadway & 21st Avenue with a pedestrian)	9.4 mph	3.1 mph	5.4 mph	2.3 mph
Scenario 6B14B (right turn at Broadway & 14th Avenue with no pedestrian)	11.0 mph	2.5 mph	8.6 mph	2.7 mph

As shown in Table 4.8 and Figure 4.30, the mean turning speed at Broadway and 14th Avenue (curb extension + LPI) was 11.0 mph (SD = 2.5) when there was no pedestrian present, and 9.6 mph (SD = 2.7) when there was a pedestrian present. The mean approach speed at Broadway and 14th Avenue (curb extension + LPI) was 8.6 mph (SD = 2.7) when there was no pedestrian present, and 5.5 mph (SD = 1.9) when there was a pedestrian present. On Broadway and 21st Avenue (no curb extension + no LPI), the mean turning speed was 11.5 mph (SD = 2.2) when there was no pedestrian present, and 9.4 mph (SD = 3.1) when there was a pedestrian present. Lastly, the mean approach speed at Broadway and 21st Avenue was 8.9 mph (SD = 3.3) when there was no pedestrian present and 5.4 mph (SD = 2.3) when there was a pedestrian present.

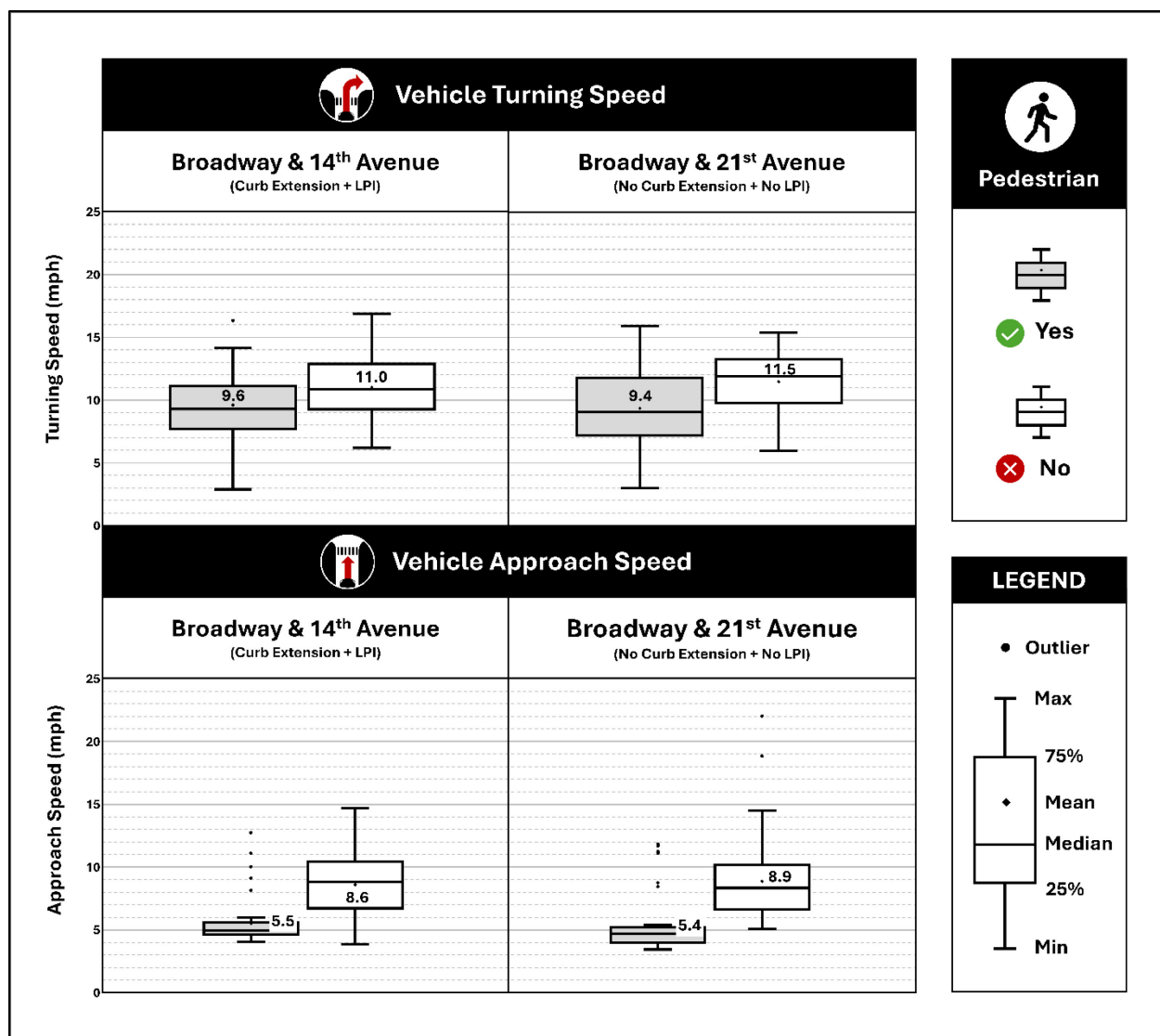


Figure 4.30. Turning Speed & Approach Speed at Geocoded Scenarios

4.2.3.3 Left Turn Scenarios

Included in this section are descriptive statistics (mean and standard deviation), as well as box plot visualizations for the turning speed and approach speed collected from the driving simulator at 4 left turn scenarios.

Table 4.9. Turning Speed & Approach Speed in miles per hour (mph) at Left Turn Scenarios

Left Turn Scenarios (Variables)	Turning Speed (Mean)	Turning Speed (SD)	Approach Speed (Mean)	Approach Speed (SD)
Scenario 1L2 (left turn with no variables)	13.9 mph	3.1 mph	6.7 mph	3.2 mph
Scenario 2L1 (left turn with an LPI and a pedestrian)	13.6 mph	2.3 mph	5.8 mph	2.6 mph
Scenario 4L4 (left turn with a pedestrian)	12.8 mph	2.6 mph	5.6 mph	0.6 mph
Scenario 5L3 (left turn with an LPI)	14.4 mph	2.5 mph	5.7 mph	2.5 mph

As shown in Table 4.9 and Figure 4.31, the mean turning speed was 13.9 mph (SD = 3.1) at the left turn scenario where no pedestrian and no LPI were present; 12.8 mph (SD = 2.6) at the left turn scenario where only a pedestrian was present; 14.4 mph (SD = 2.5) at the left turn scenario where only an LPI was present; and 13.6 mph (SD = 2.3) at the left turn scenario where both an LPI and a pedestrian were present. Additionally, the mean approach speed was 6.7 mph (SD = 3.2) at the left turn scenario where no pedestrian and no LPI were present; 5.6 mph (SD = 0.6) at the left turn scenario where only a pedestrian was present; 5.7 mph (SD = 2.5) at the left turn scenario where only an LPI was present; and 5.8 mph (SD = 2.6) at the left turn scenario where both an LPI and a pedestrian were present.

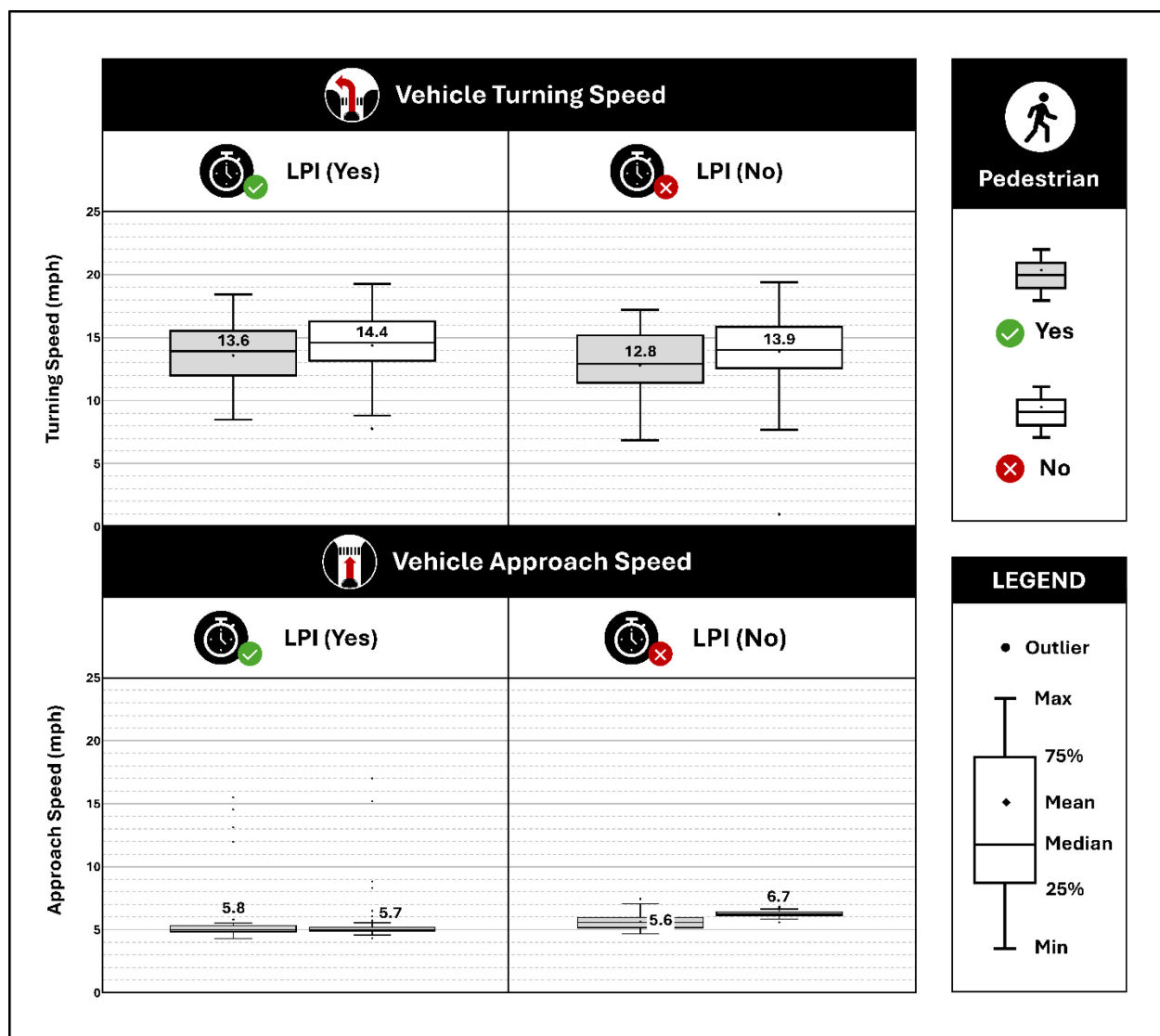


Figure 4.31. Turning Speed & Approach Speed at Left Turn Scenarios

4.2.3.4 Statistical Modeling

A statistical model was developed for the right turn scenarios, to evaluate the speed data as a dependent variable. The linear mixed model (LMM) technique was selected given its ability to handle repeated sampling of subjects to best account for the random effects and minimize Type I error rates (Jashami et al., 2019). The sample size for this measurement was 44 subjects, which is greater than the minimum required (20 subjects) for an LMM analysis (Jashami et al., 2019). The independent variables of NTOR Sign, LPI, Pedestrian, and Curb Extension were considered in the analysis. The subject number was considered as a random effect, and all statistical analyses were performed at a 95% confidence level using Python (Jashami et al., 2024b). The output from the first model (turning speed) is shown in Table 4.10, and the output from the second model (approach speed) is shown in Table 4.11.

Table 4.10. Results of LMM on Turning Speed in mph at Right Turn Scenarios

Variable	Estimate	Standard Error	P-Value
Subject Random Effect (Variance)	5.50	1.22	<0.001*
Constant	13.44	0.38	<0.001*
No Turn on Red Sign (Yes)	-0.31	0.11	0.006*
Leading Pedestrian Interval (Yes)	0.12	0.11	0.280
Presence of Pedestrian (Yes)	-0.81	0.11	<0.001*
Curb Extension (Yes)	-1.99	0.11	<0.001*

Summary Statistics: $R^2 = 76.65\%$, BIC = 2664.30, -2 Log Likelihood = 2651.26

* Statistically significant at $\alpha = 0.05$

The results of the LMM on the turning speed showed that all the variables were statistically significant (p-value < 0.05), except for the LPI. The presence of a curb extension decreased the turning speed by 1.99 mph (p-value < 0.001) compared to the baseline condition (13.44 mph). The presence of a pedestrian decreased the turning speed by 0.81 mph (p-value < 0.001) compared to the baseline condition. The presence of a NTOR Sign decreased the turning speed by 0.31 mph (p-value = 0.006) compared to the baseline condition. And the presence of an LPI increased the turning speed by 0.12 mph (p-value = 0.280) compared to the baseline condition; however, this was not statistically significant. The random effects for subjects were statistically significant (p-value < 0.001), supporting the use of a linear mixed effects model rather than ordinary linear regression.

Table 4.11. Results of LMM on Approach Speed in mph at Right Turn Scenarios

Variable	Estimate	Standard Error	P-Value
Subject Random Effect (Variance)	1.32	0.32	<0.001*
Constant	7.77	0.22	<0.001*
No Turn on Red Sign (Yes)	-1.62	0.12	<0.001*
Leading Pedestrian Interval (Yes)	-0.56	0.12	<0.001*
Presence of Pedestrian (Yes)	-1.14	0.12	<0.001*
Curb Extension (Yes)	0.10	0.12	0.388

Summary Statistics: $R^2 = 53.28\%$, BIC = 2644.69, -2 Log Likelihood = 2631.64

* Statistically significant at $\alpha = 0.05$

The results of the LMM on the approach speed showed that all the variables were statistically significant (p-value < 0.05), except for the curb extension. The presence of an NTOR Sign decreased the approach speed by 1.62 mph (p-value < 0.001) compared to the baseline condition (7.77 mph). The presence of a pedestrian decreased the approach

speed by 1.14 mph (p-value < 0.001) compared to the baseline condition. The presence of an LPI decreased the approach speed by 0.56 mph (p-value < 0.001) compared to the baseline condition. And the presence of a curb extension increased the approach speed by 0.10 mph compared to the baseline condition; however, this was not statistically significant (p-value = 0.388). The random effects for subjects were statistically significant (p-value < 0.001).

4.2.3.5 *Speed Validation (Simulator vs Field)*

To gain insights regarding how the turning speeds collected from the driving simulator compared to those collected in the field, a speed validation was conducted for both Broadway & 14th Avenue and Broadway & 21st Avenue (the 2 geocoded intersections modeled in the driving simulator). From the turning speed data collected from the 44 driving simulator participants during geocoded scenarios (with no pedestrian present), the research team looked at the proportion of drivers that turned on green and those that turned on Red for each intersection. To replicate the simulator conditions, speed data for the same proportion of turning vehicles was collected in the field using video data (sample size for the field data was 100 vehicle observations per intersection). Section 4.1.4.2. provides a detailed description of how this data was transcribed.

As shown in Figure 4.32, at Broadway & 14th Avenue, the difference in mean turning speed when comparing both data sources (simulator vs field) was 0.1 mph. And at Broadway & 21st Avenue, the difference in mean turning speed when comparing both data sources was 1.3 mph. Overall, when accounting for the signal phase in which drivers completed their turn, the speeds observed at Broadway & 14th Avenue were slightly higher in the simulator; and at Broadway & 21st Avenue, the speeds were slightly higher in the field. However, for both intersections, the speed difference is less than 1.5 mph. Inter Rater Reliability (IRR) scores for the video data transcribed at both intersections were 95.3% and 93.3%, respectively.

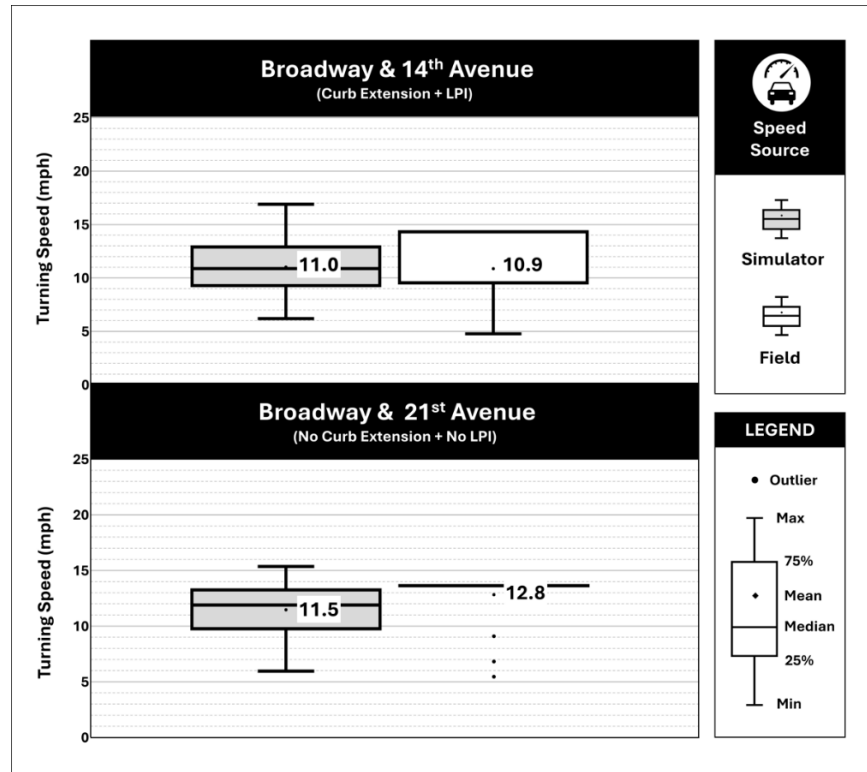


Figure 4.32. Speed Validation (Simulator vs Field)

4.2.4 Visual Attention

This section provides the results obtained from visual attention data from 33 subjects on 4 areas of interest (Pedestrian, NTOR Sign, Pedestrian Signal, and Traffic Signal) at all 24 scenarios, organized and visualized by right turn scenarios, geocoded scenarios, and left turn scenarios. Descriptive statistics (mean and standard deviation) and box plot visualizations of the “Total Fixation Duration (TFD)” on each of the 4 Areas of Interest (AOI) across all 24 scenarios are shown in this section. TFD represents the total time in seconds that the driver’s eyes produce fixations within a particular AOI. As described in section 4.1.4.3, visual attention data per scenario (i.e., intersection) was transcribed from the moment the driver reached a reference point located 200 ft away from the intersection to the moment when the driver completed their turn and the pedestrian signal was out of sight.

4.2.4.1 Right Turn Scenarios

Included in this section are descriptive statistics (mean and standard deviation), as well as box plot visualizations of the “Total Fixation Duration (TFD)” in seconds, on each of the 4 AOIs, collected from the eye tracking glasses of 33 subjects at 16 right turn scenarios (2x2x2x2).

Table 4.12. Total Fixation Duration in Seconds (s) on AOIs at Right Turn Scenarios

Right Turn Scenarios (Variables)	Pedestrian AOI	NTOR Sign AOI	Ped Signal AOI	Traffic Signal AOI
Scenario 1E9 (ped only)	Mean = 2.5s, SD = 2.2s	Not Applicable	Mean = 0.7s, SD = 0.8s	Mean = 1.2s, SD = 1.2s
Scenario 1E15 (LPI + ped)	Mean = 1.8s, SD = 1.3s	Not Applicable	Mean = 1.0s, SD = 1.1s	Mean = 0.8s, SD = 0.8s
Scenario 2E14 (CE + ped)	Mean = 1.7s, SD = 1.3s	Not Applicable	Mean = 1.1s, SD = 1.2s	Mean = 1.2s, SD = 1.6s
Scenario 2E6 (no variables)	Not Applicable	Not Applicable	Mean = 0.5s, SD = 0.6s	Mean = 1.1s, SD = 1.4s
Scenario 2E10 (NTOR sign only)	Not Applicable	Mean = 2.3s, SD = 2.3s	Mean = 0.4s, SD = 0.7s	Mean = 1.1s, SD = 1.0s
Scenario 3E4 (LPI + ped + NTOR sign)	Mean = 1.7s, SD = 1.4s	Mean = 2.1s, SD = 2.1s	Mean = 0.6s, SD = 0.5s	Mean = 1.2s, SD = 1.3s
Scenario 3E7 (LPI only)	Not Applicable	Not Applicable	Mean = 0.5s, SD = 0.6s	Mean = 1.2s, SD = 1.7s
Scenario 3E16 (CE + NTOR sign)	Not Applicable	Mean = 2.1s, SD = 1.7s	Mean = 0.6s, SD = 0.7s	Mean = 1.2s, SD = 1.2s
Scenario 4E5 (CE + ped + NTOR sign)	Mean = 2.2s, SD = 1.6s	Mean = 1.3s, SD = 1.4s	Mean = 0.8s, SD = 0.7s	Mean = 1.1s, SD = 1.7s
Scenario 4E1 (LPI + CE + ped + NTOR sign)	Mean = 1.6s, SD = 1.3s	Mean = 1.6s, SD = 1.6s	Mean = 1.0s, SD = 0.8s	Mean = 1.8s, SD = 1.8s
Scenario 5E13 (ped + NTOR sign)	Mean = 2.7s, SD = 1.9s	Mean = 1.7s, SD = 1.6s	Mean = 0.5s, SD = 0.6s	Mean = 1.4s, SD = 1.4s
Scenario 5E11 (LPI + CE)	Not Applicable	Not Applicable	Mean = 0.4s, SD = 0.5s	Mean = 0.9s, SD = 1.0s
Scenario 5E2 (LPI + CE + ped)	Mean = 1.7s, SD = 1.4s	Not Applicable	Mean = 1.1s, SD = 1.1s	Mean = 1.3s, SD = 1.4s
Scenario 6E3 (LPI + CE + NTOR sign)	Not Applicable	Mean = 2.8s, SD = 2.5s	Mean = 0.7s, SD = 0.7s	Mean = 2.0s, SD = 2.0s
Scenario 6E12 (LPI + NTOR sign)	Not Applicable	Mean = 2.7s, SD = 2.5s	Mean = 0.6s, SD = 0.6s	Mean = 1.7s, SD = 1.7s
Scenario 6E8 (CE only)	Not Applicable	Not Applicable	Mean = 0.4s, SD = 0.4s	Mean = 1.4s, SD = 1.9s

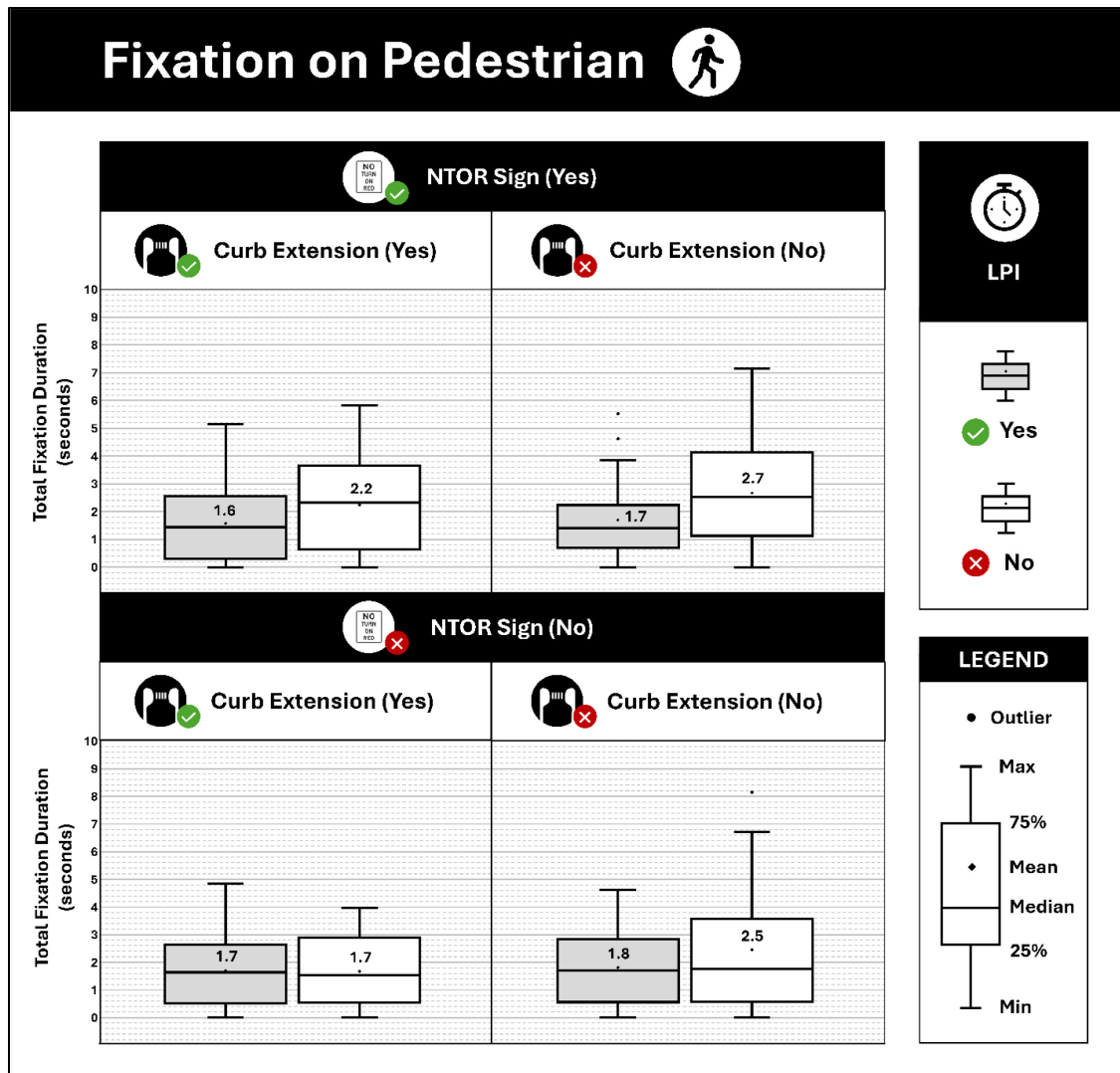


Figure 4.33. Total Fixation Duration (seconds) on Pedestrian

As shown in Table 4.12 and Figure 4.33, the highest mean TFD on the “Pedestrian AOI” was 2.7 seconds ($SD = 1.9$) when no variables were present besides the NTOR sign. And the lowest mean TFD on the pedestrian was 1.6 seconds ($SD = 1.3$), when all variables were present (NTOR Sign + Curb Extension + LPI). Each boxplot shown in Figure 4.33 shows the distribution of the TFD collected from the eye tracking glasses of 33 research subjects at 16 right turn scenarios. As shown by the box plots, when no variables were present, the mean TDF on the pedestrian was 2.5 seconds ($SD = 2.2$). And when all variables were present, the mean TFD on the pedestrian was 1.6 seconds ($SD = 1.3$). When no other variables are present, we can observe that the mean TFD on the pedestrian is 0.7 seconds lower when there is an LPI. When no other variables are present, we can observe that the TFD on the pedestrian is 0.8 seconds lower when there is a curb extension. And when no other variables are present, we can observe that the TFD on the pedestrian is 0.2 seconds higher when there is a NTOR sign.

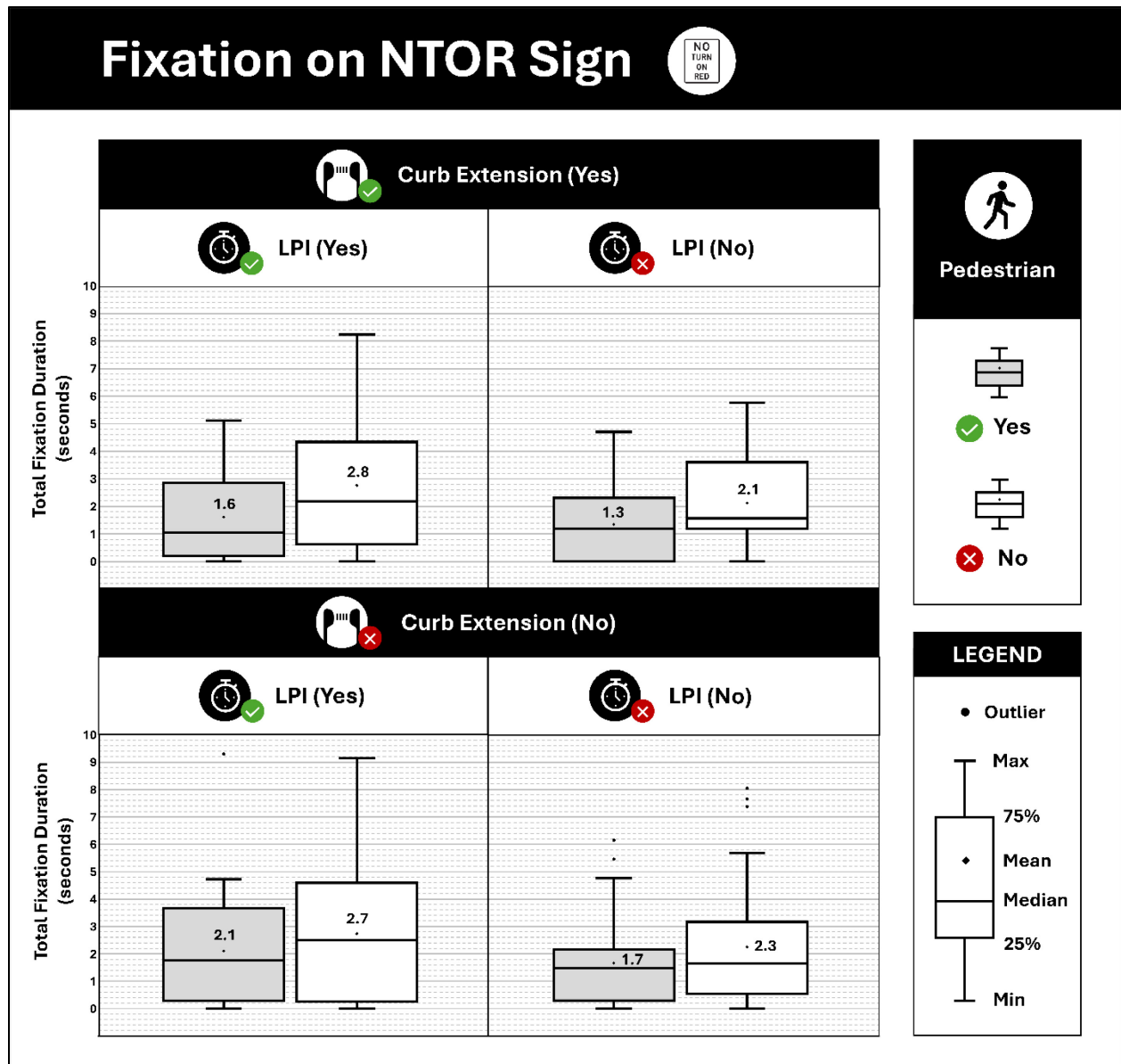


Figure 4.34. Total Fixation Duration (seconds) on NTOR Sign

As shown in Table 4.12 and Figure 4.34, the highest mean TFD on the “NTOR Sign AOI” was 2.8 seconds ($SD = 2.5$), when all variables were present, except for the pedestrian. And the lowest mean TFD on the NTOR Sign was 1.3 seconds ($SD = 1.4$), when all variables were present, except for the LPI. As shown by the box plots, when no variables were present, the mean TFD on the NTOR Sign was 2.3 seconds ($SD = 2.3$). And when all variables were present, the mean TFD on the NTOR Sign was 1.6 seconds ($SD = 1.6$). Additionally, we can observe that when no other variables are present, the mean TFD on the NTOR Sign is 0.4 seconds higher when there is an LPI. When no other variables are present, the mean TFD on the NTOR Sign is 0.2 seconds lower when there is a curb extension. And when no other variables are present, the mean TFD on the NTOR Sign is 0.6 seconds lower when there is a pedestrian.

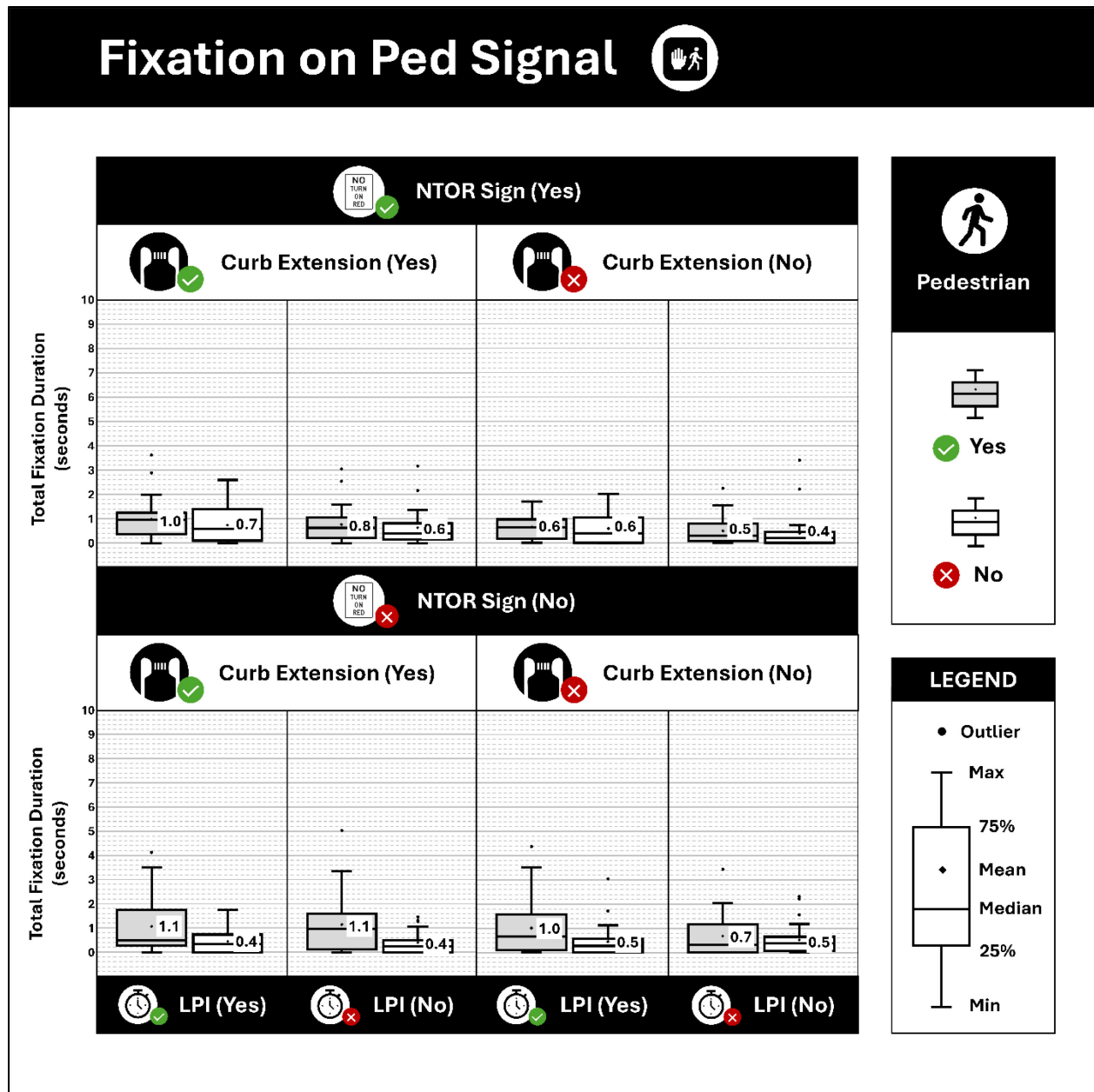


Figure 4.35. Total Fixation Duration (seconds) on Ped Signal

As shown in Table 4.12 and Figure 4.35, the highest mean TFD on the “Ped Signal AOI” was 1.1 seconds ($SD = 1.1$), when all variables, except for the NTOR Sign were present. And the lowest mean TFD on the ped signal was 0.4 seconds ($SD = 0.4$), when no variables, except for the curb extension were present. As shown by the box plots, when no variables were present, the mean TFD on the ped signal was 0.5 seconds ($SD = 0.6$). And when all variables were present, the mean TFD on the ped signal was 1.0 seconds ($SD = 0.8$).

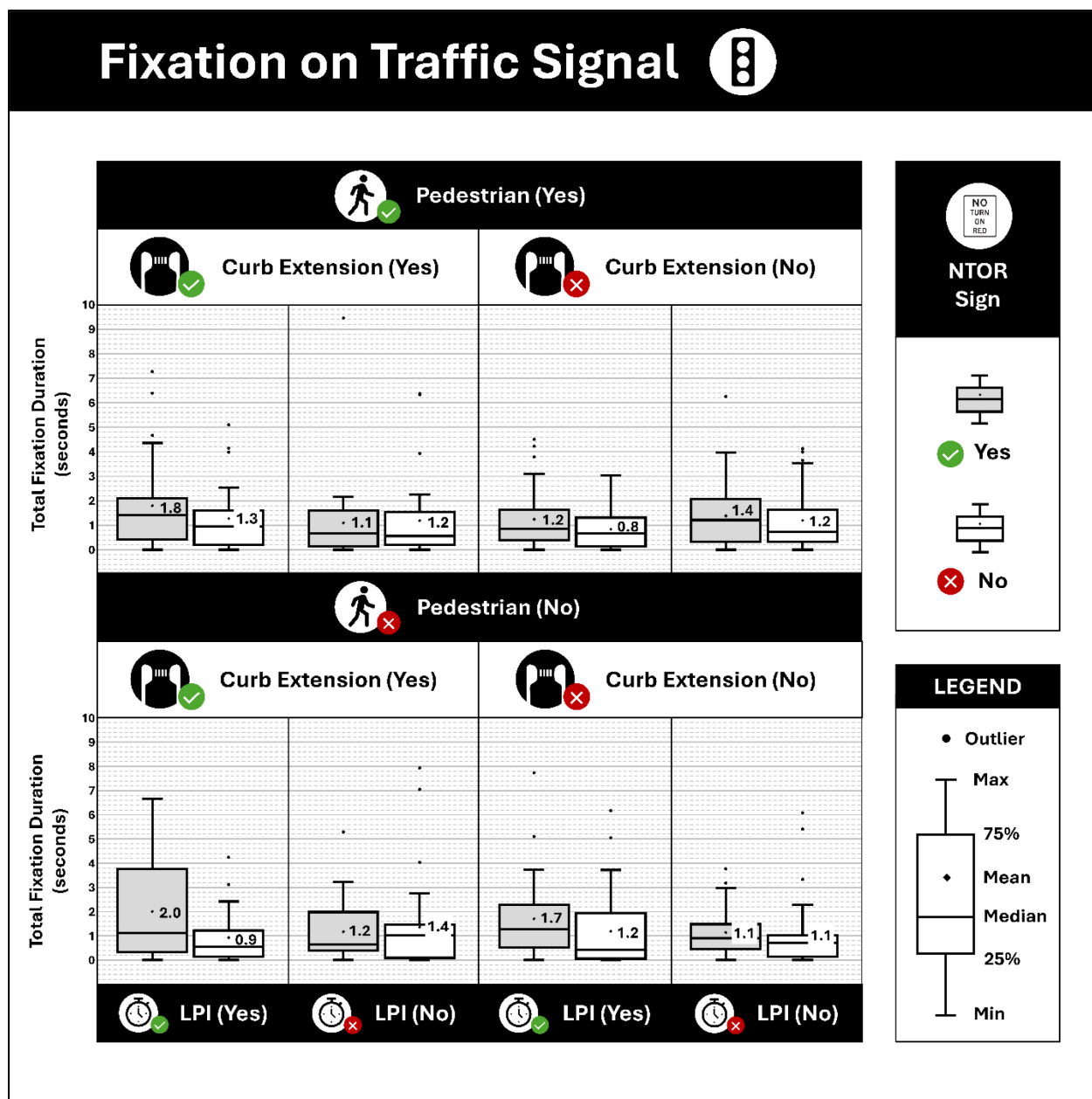


Figure 4.36. Total Fixation Duration (seconds) on Traffic Signal

As shown in Table 4.12 and Figure 4.36, the highest mean TFD on the “Traffic Signal AOl” was 2.0 seconds (SD = 2.0), when all variables, except for the pedestrian were present. And the lowest mean TDF on the traffic signal was 0.8 seconds (SD = 0.8), when an LPI and a pedestrian were present. As shown by the box plots, when no other variables were present, the mean TFD on the traffic signal was 1.1 seconds (SD = 1.4). And when all variables were present, the mean TFD on the traffic signal was 1.8 seconds (SD = 1.8).

4.2.4.2 Geocoded Scenarios

Included in this section are descriptive statistics (mean and standard deviation), as well as box plot visualizations of the “Total Fixation Duration (TFD)” in seconds, on each of the 4 AOIs, collected from the eye tracking glasses at 4 geocoded scenarios.

Table 4.13. Total Fixation Duration in Seconds (s) on AOIs at Geocoded Scenarios

Geocoded Scenarios (Variables)	Pedestrian AOI	NTOR Sign AOI	Ped Signal AOI	Traffic Signal AOI
Scenario 1B21B (right turn at Broadway & 21st Avenue with no pedestrian)	Not Applicable	Not Applicable	Mean = 0.3s, SD = 0.4s	Mean = 0.9s, SD = 1.4s
Scenario 3B14A (right turn at Broadway & 14th Avenue with a pedestrian)	Mean = 3.2s, SD = 2.3s	Not Applicable	Mean = 1.1s, SD = 1.0s	Mean = 0.7s, SD = 0.6s
Scenario 4B21A (right turn at Broadway & 21st Avenue with a pedestrian)	Mean = 3.7s, SD = 2.8s	Not Applicable	Mean = 0.7s, SD = 0.8s	Mean = 0.8s, SD = 1.2s
Scenario 6B14B (right turn at Broadway & 14th Avenue with no pedestrian)	Not Applicable	Not Applicable	Mean = 0.6s, SD = 0.6	Mean = 0.6s, SD = 1.0s

Each boxplot shown in Figure 4.37 shows the distribution of the TFD collected from the eye tracking glasses of 33 research subjects at 4 geocoded scenarios. As shown in Table 4.13 and Figure 4.37, when a pedestrian was present, the AOI with the highest mean TFD at Broadway & 14th Avenue (Curb Extension + LPI) was the pedestrian AOI with 3.2 seconds (SD=2.3), followed by the ped signal AOI with 1.1 seconds (SD=1.0), and the traffic signal AOI with 0.7 seconds (SD=0.6). When no pedestrian was present, there was no difference between the mean TFD on the ped signal and the traffic signal, the mean TFD was equal to 0.6 seconds (SD=0.6 and 1.0, respectively). At Broadway & 21st Avenue (No Curb Extension + No LPI), when a pedestrian was present, the AOI with the highest TFD was the pedestrian AOI with 3.7 seconds (SD=2.8), followed by the traffic signal AOI with 0.8 seconds (SD=1.2), and the ped signal AOI with 0.7 seconds (SD=0.8). On the other hand, when no pedestrian was present, the mean TFD on the ped signal was 0.3 seconds (SD=0.4), and the mean TFD on the traffic signal was 0.9 seconds (SD=1.4).

AOI Fixation at Geocoded Scenarios

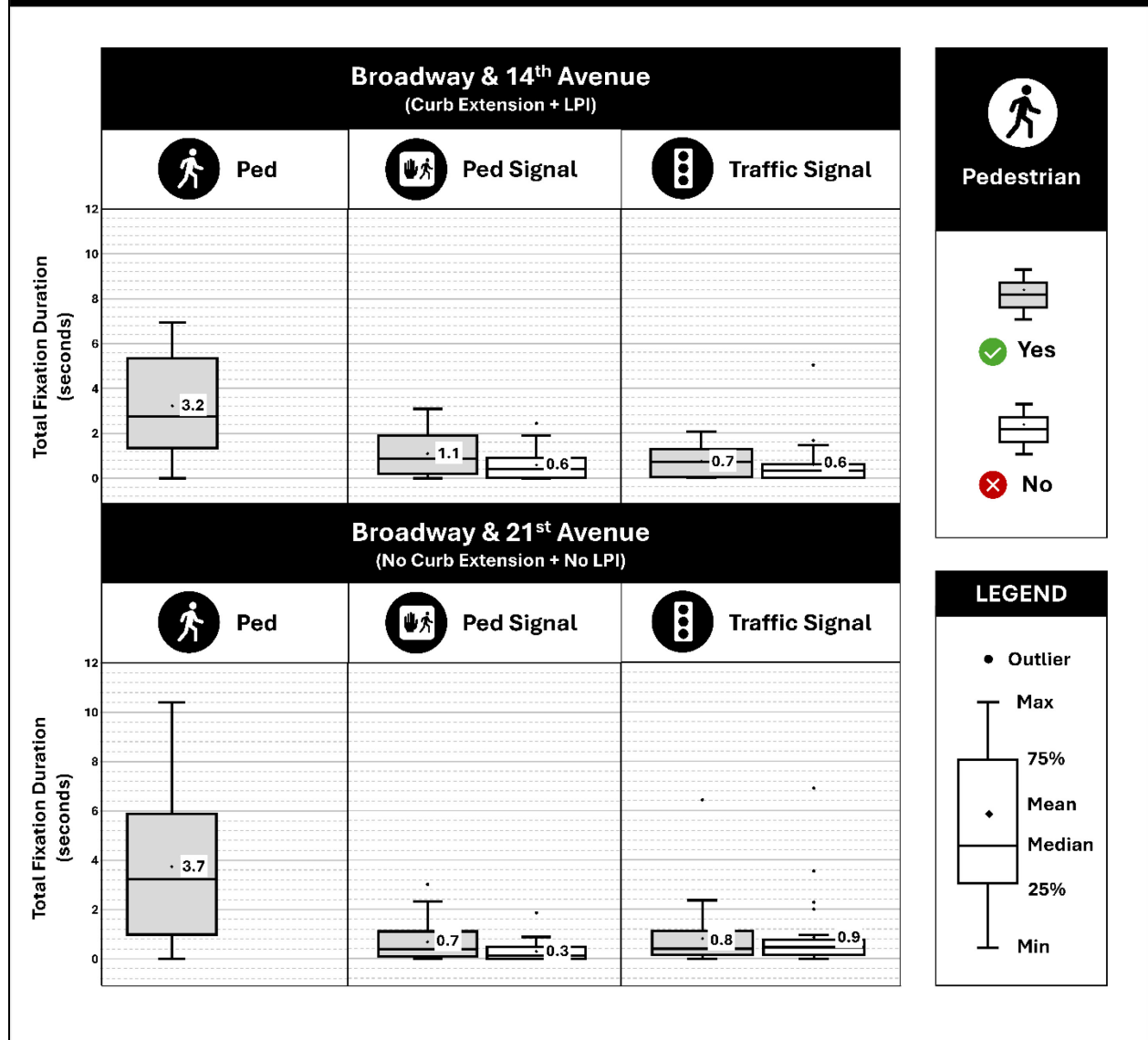


Figure 4.37. Total Fixation Duration (All AOIs) at Geocoded Scenarios

4.2.4.3 Left Turn Scenarios

Included in this section are descriptive statistics (mean and standard deviation), as well as box plot visualizations of the “Total Fixation Duration (TFD)” in seconds, on each of the 4 AOIs, collected from the eye tracking glasses at 4 left turn scenarios.

Table 4.14. Total Fixation Duration in Seconds (s) on AOIs at Left Turn Scenarios

Left Turn Scenarios (Variables)	Pedestrian AOI	NTOR Sign AOI	Ped Signal AOI	Traffic Signal AOI
Scenario 1L2 (left turn with no variables)	Not Applicable	Not Applicable	Mean = 0.2s, SD = 0.4s	Mean = 2.8s, SD = 2.4s
Scenario 2L1 (left turn with an LPI and a pedestrian)	Mean = 1.9s, SD = 1.5s	Not Applicable	Mean = 0.4s, SD = 0.6s	Mean = 2.3s, SD = 2.2s
Scenario 4L4 (left turn with a pedestrian)	Mean = 2.9s, SD = 1.9s	Not Applicable	Mean = 0.3s, SD = 0.5s	Mean = 0.9s, SD = 1.2s
Scenario 5L3 (left turn with an LPI)	Not Applicable	Not Applicable	Mean = 0.3s, SD = 0.4s	Mean = 1.7s, SD = 1.2s

Each boxplot shown in Figure 4.38 shows the distribution of the TFD collected from the eye tracking glasses of 33 research subjects at 4 left turn scenarios. As shown in Table 4.14 and Figure 4.38, in left turn scenarios with an LPI and a pedestrian, the AOI with the highest mean TFD was the traffic signal AOI with 2.3 seconds (SD=2.2), followed by the pedestrian AOI with 1.9 seconds (SD=1.5), and the ped signal AOI with 0.4 seconds (SD=0.6). On the other hand, when an LPI with no pedestrian was present, the AOI with the highest mean TFD was the traffic signal AOI with 1.7 seconds (SD=1.2), followed by the ped signal AOI with 0.3 seconds (SD=0.4). Additionally, when a pedestrian with no LPI was present, the AOI with the highest mean TFD was the pedestrian AOI with 2.9 seconds (SD=1.9), followed by the traffic signal AOI with 0.9 seconds (SD=1.2), and the ped signal AOI with 0.3 seconds (SD=0.5). And lastly, when no pedestrian with no LPI was present, the AOI with the highest mean TFD was the traffic signal AOI with 2.8 seconds (SD=2.4), followed by the ped signal AOI with 0.2 seconds (SD=0.4).

AOI Fixation at Left Turn Scenarios

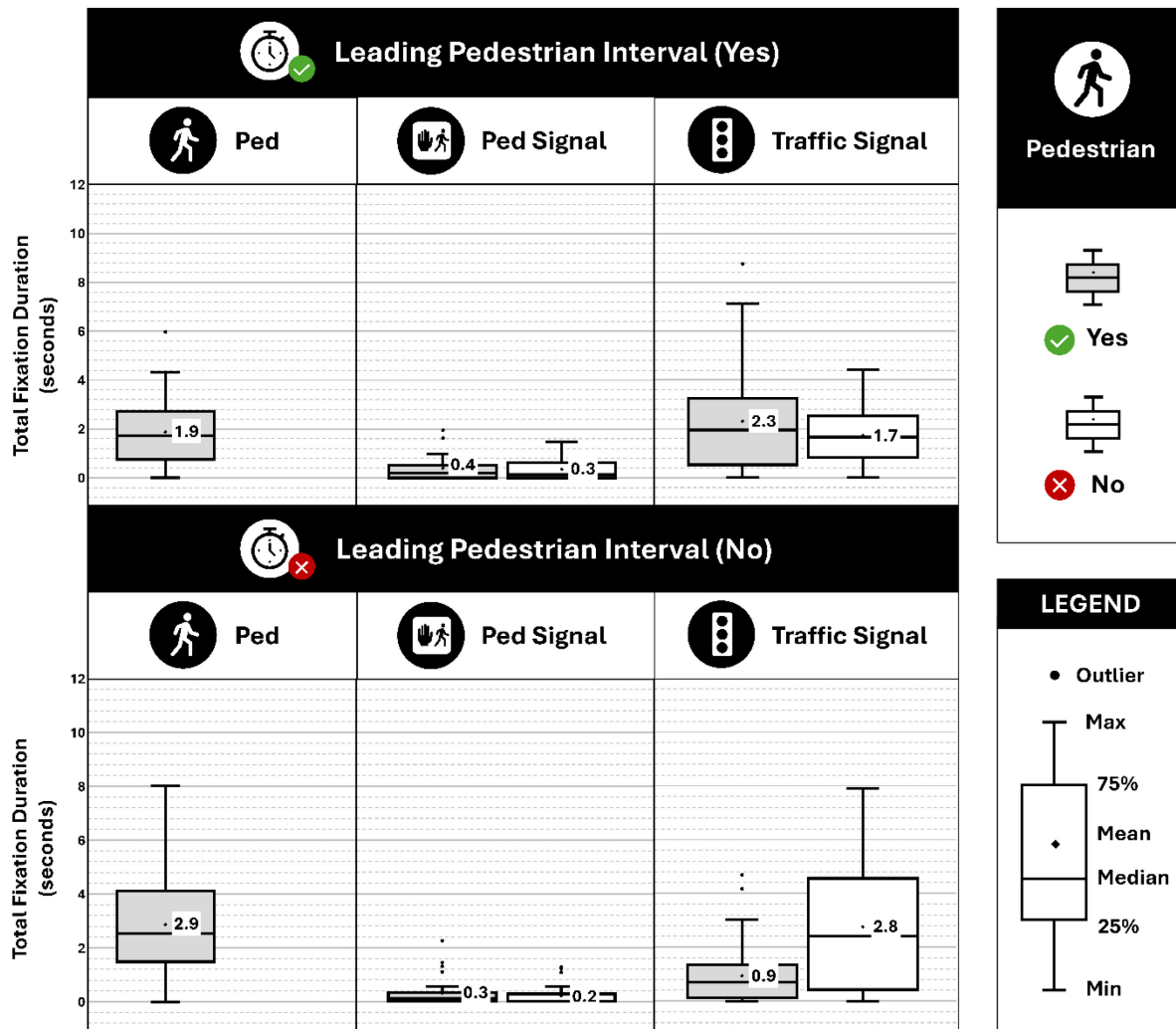


Figure 4.38. Total Fixation Duration (All AOIs) at Left Turn Scenarios

4.2.4.4 Statistical Modeling

A statistical model was developed for the right turn scenarios to evaluate the Total Fixation Duration (TFD) as a dependent variable for each of the AOIs (NTOR Sign AOI, Pedestrian AOI, Pedestrian Signal AOI, Traffic Signal AOI). It is reasonable to expect correlated error terms across equations (e.g., unobserved factors influencing total fixation duration may affect all four areas of interest within the same observation), in which case seemingly unrelated regression (SUR) yields more efficient estimates by explicitly accounting for correlated error terms than using four standard linear regressions for each AOI (Gupta et al., 2022). To that end, the mixed effects seemingly unrelated regression

(SUR) technique was selected. The independent variables of NTOR Sign, LPI, Pedestrian, and Curb Extension were considered in the estimate of the “TFD” dependent variable. Subjects were considered as random effects, and all statistical analyses were performed at a 95% confidence level using Python. The model output is shown in Table 4.15.

Table 4.15. Results of SUR on Total Fixation Duration at Right Turn Scenarios

Equation	Term	Coefficient	Standard Error	P-Value
<u>NTOR Sign AOI</u>	<u>Constant</u>	2.36	0.31	<0.001*
NTOR Sign AOI	Curb Extension (Yes)	-0.23	0.20	0.255
NTOR Sign AOI	Leading Pedestrian Interval (Yes)	0.45	0.23	0.044*
NTOR Sign AOI	Pedestrian (Yes)	-0.79	0.21	<0.001*
<u>Pedestrian AOI</u>	<u>Constant</u>	2.36	0.30	<0.001*
Pedestrian AOI	Curb Extension (Yes)	-0.37	0.16	0.022*
Pedestrian AOI	Leading Pedestrian Interval (Yes)	-0.56	0.14	<0.001*
Pedestrian AOI	No Turn on Red Sign (Yes)	0.15	0.15	0.300
<u>Ped Signal AOI</u>	<u>Constant</u>	0.41	0.09	<0.001*
Ped Signal AOI	Curb Extension (Yes)	0.17	0.05	0.001*
Ped Signal AOI	Leading Pedestrian Interval (Yes)	0.11	0.06	0.047*
Ped Signal AOI	No Turn on Red Sign (Yes)	-0.06	0.07	0.343
Ped Signal AOI	Pedestrian (Yes)	0.33	0.08	<0.001*
<u>Traffic Signal AOI</u>	<u>Constant</u>	1.01	0.17	<0.001*
Traffic Signal AOI	Curb Extension (Yes)	0.14	0.11	0.216
Traffic Signal AOI	Leading Pedestrian Interval (Yes)	0.18	0.08	0.030*
Traffic Signal AOI	No Turn on Red Sign (Yes)	0.31	0.12	0.011*
Traffic Signal AOI	Pedestrian (Yes)	-0.07	0.11	0.526

* Statistically significant at $\alpha = 0.05$

Table 4.15 shows the results of the SUR model on the Total Fixation Duration (TFD) at right turn scenarios across 4 areas of interest (NTOR Sign, Pedestrian, Ped Signal, Traffic Signal).

Curb Extension (CE): The largest CE effect was a decrease in TFD on the Pedestrian AOI by 0.37 s ($p = 0.022$). CE also decreased TFD on the NTOR Sign AOI by 0.23 s (not significant; $p = 0.255$) and increased TFD on the Ped Signal AOI by 0.17 s ($p = 0.001$). The smallest effect was on the Traffic Signal AOI (+0.14 s, not significant; $p = 0.216$).

Leading Pedestrian Interval (LPI): The largest LPI effect was a decrease in TFD on the Pedestrian AOI by 0.56 s ($p < 0.001$). LPI also increased TFD on the NTOR Sign AOI by

0.45 s ($p = 0.044$), on the Traffic Signal AOI by 0.18 s ($p = 0.030$), and on the Ped Signal AOI by 0.11 s ($p = 0.047$). The smallest effect was on the Ped Signal AOI (+0.11 s).

No Turn on Red (NTOR) Sign: The largest NTOR effect was an increase in TFD on the Traffic Signal AOI by 0.31 s ($p = 0.011$). NTOR had a small, non-significant increase on the Pedestrian AOI (0.15 s, $p = 0.300$) and the smallest, non-significant decrease on the Ped Signal AOI (0.06 s, $p = 0.343$).

Presence of Pedestrian (Ped): The largest Ped effect was a decrease in TFD on the NTOR Sign AOI by 0.79 s ($p < 0.001$). Ped also increased TFD on the Ped Signal AOI by 0.33 s ($p < 0.001$) and had the smallest, non-significant decrease on the Traffic Signal AOI (0.07 s, $p = 0.526$).

Figure 4.39 shows an error bar plot of the four AOIs. As shown in Table 4.15 and the non-overlapping error bars circled in Figure 4.35, the variables that influenced TFD on the AOIs the most were the NTOR sign, the LPI, and the pedestrian. The NTOR sign increased fixation on the traffic signal; the LPI decreased fixation on the pedestrian; and the pedestrian increased fixation on the ped signal and decreased fixation on the NTOR sign.

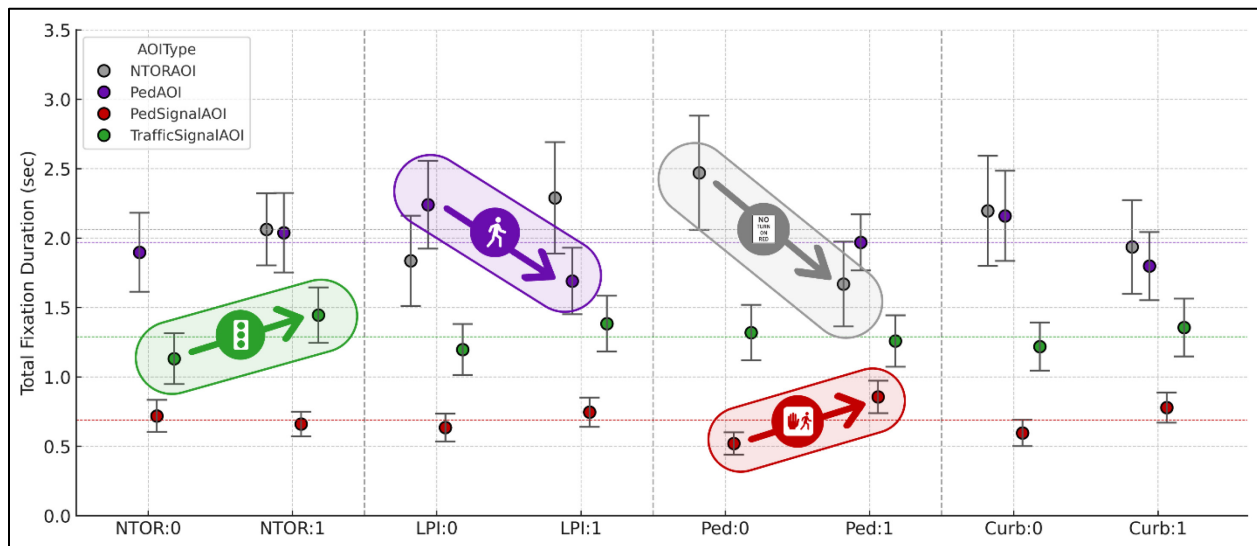


Figure 4.39. Error Bar Plot of SUR Model Results

4.3 SUMMARY

Key findings were identified from the speed data and visual attention data collected from the driving simulator study conducted at Oregon State University. The research questions that guided the driving simulator study included: 1) Is the driver's turning speed and approach speed influenced by the LPI, Curb Extension, and NTOR Sign?; and 2) Is the driver's visual attention on the pedestrian influenced by the LPI, Curb Extension, and NTOR Sign?. Summarized below are some of the key findings identified for each of the research questions.

4.3.1 Key Findings

Speed: To answer research question 1, speed data (turning speed and approach speed) were collected from the driving simulator. Results from the LMMs performed on the speed data for right turn scenarios indicated that the presence of a curb extension, pedestrian, and NTOR sign was each associated with a statistically significant decrease in turning speed. Similarly, the presence of an NTOR sign, pedestrian, and LPI was each associated with a statistically significant decrease in approach speed.

Visual Attention: To answer research question 2, visual attention data (total fixation duration in seconds) was collected from eye-tracking glasses as subjects drove the simulation environment. Results from the SUR model performed on the visual attention data for right turn scenarios across 4 different AOIs (NTOR Sign, Pedestrian, Ped Signal, and Traffic Signal) showed that all independent variables (NTOR sign, pedestrian, LPI, and CE) had statistically significant effects on the fixation duration of at least one AOI. For example, the NTOR sign increased fixation on the traffic signal; pedestrian presence increased fixation on the ped signal but decreased fixation on the NTOR sign; the LPI decreased fixation on the pedestrian but increased fixation on the ped signal, NTOR sign, and traffic signal; and the CE decreased fixation on the pedestrian but increased fixation on the ped signal.

4.3.2 Limitations

Although the simulator study offers valuable insights into driver behavior at signalized intersections, limitations must be acknowledged. Due to constraints in time and resources, a limited number of independent variables and variable levels were used in the experiment. The timing of LPIs can vary from 3-7 seconds; the design of CEs can vary in size and shape; walking speeds can vary from person to person; and NTOR Signs can be static (R10-11, R10-11a, R10-11b) or blank-out signs. This study focused on a 5 second LPI, a 30 ft long CE; a pedestrian walking speed of 4 ft/s, and an R10-11 sign. Future research could focus on studying the effects from different variations of LPI timing, CE design, pedestrian walking speeds, and NTOR signs. Second, because the experiment was conducted in a simulated environment, speeds tend to differ slightly from those observed in the field. However, the relative validity provided by driving simulators allows researchers to still differentiate the effects of experimental variables (Islam et al., 2016; Rudin-Brown et al., 2009). Finally, repeated measures can lead to learning and fatigue effects, and simulator sickness can occur at any point during the simulation, resulting in smaller sample sizes due to subject withdrawal. Simulation sickness needs to be detected as early as possible.

5.0 LPI SUITABILITY ASSESSMENT TOOL

5.1 TOOL DEVELOPMENT

As part of this research, an LPI suitability assessment tool was developed to help the Oregon Department of Transportation (ODOT) quantitatively assess its traffic signal inventory to produce a priority list of signals suitable for LPI. The tool is intended to identify which locations may be suitable for LPIs but is not intended to supersede engineering judgement and assessment based on site-specific crash history, signal operations, geometry, etc.

5.1.1 LPI Research, Policy, and Guidelines

This tool was developed using Eschen et al (2025)’s framework as a foundation. The tool was informed with findings from this research; research studies like Eschen et al (2025), Raha et al (2025), Craig & Morris (2025), Jashami et al (2024a), Raha et al (2024), Saeidi-Razavi & Furth (2023), Mase (2023), Saneinejad & Lo (2019), Furth & Saeidi-Razavi (2019), Sharma et al (2017), Lin et al (2017), among others; guidance provided by the MUTCD (FHWA, 2023), NACTO (2020), and FHWA (2019); as well as LPI policy and guidelines developed by cities and state departments of transportation, such as the Florida Department of Transportation (FDOT, 2025), City of Phoenix Street Transportation Department (Eschen et al., 2025), North Carolina Department of Transportation (NCDOT, 2025), Texas Department of Transportation (TxDOT, 2024), City of Bellevue Transportation Department (City of Bellevue, 2023), Pennsylvania Department of Transportation (PennDOT, 2021), California Department of Transportation (CalTrans, 2021); Maryland Department of Transportation State Highway Administration (MDOT SHA, 2020), Seattle Department of Transportation (SDOT, 2019), among others.

5.1.2 How the Tool Works

The tool consists of a worksheet that guides the analyst through a series of questions for the intersection under consideration (Table 5.1) and each associated crosswalk (Table 5.2). Following Eschen et al. (2025)’s recommendation to implement LPIs as crosswalk pairs (North-South and East-West) to ensure consistency of Accessible Pedestrian Signal (APS) prompts to cross a given street; the combined score for each of the crosswalks (Table 5.3) is entered into a suitability matrix (Table 5.4) as a crosswalk pairing. Based on the suitability matrix scores of crosswalk pairings, an LPI is determined to be Optional (low expected safety benefit), Considered (moderate expected safety benefit), or Recommended (high expected safety benefit). The LPI Suitability Assessment Tool is divided in two parts: Part 1 – Intersection Level and Part 2 – Crosswalk Level. Tables 5.1 and 5.2 explain why each factor is important and cite relevant research and LPI guidelines/policy from other jurisdictions. Figure 5.1 shows instructions on how to conduct an LPI suitability assessment using the tool. A template of the tool and an example of how the tool was used to assess the suitability of an LPI at Broadway & 21st Avenue in Portland, Oregon is found on Appendix E and F, respectively. Disclaimer: The tool template

developed in this research is designed to provide results only for 4-leg intersections with 4 marked crosswalks (not 3-leg intersections).

LPI Suitability Assessment

To use the tool, follow these 5 steps:

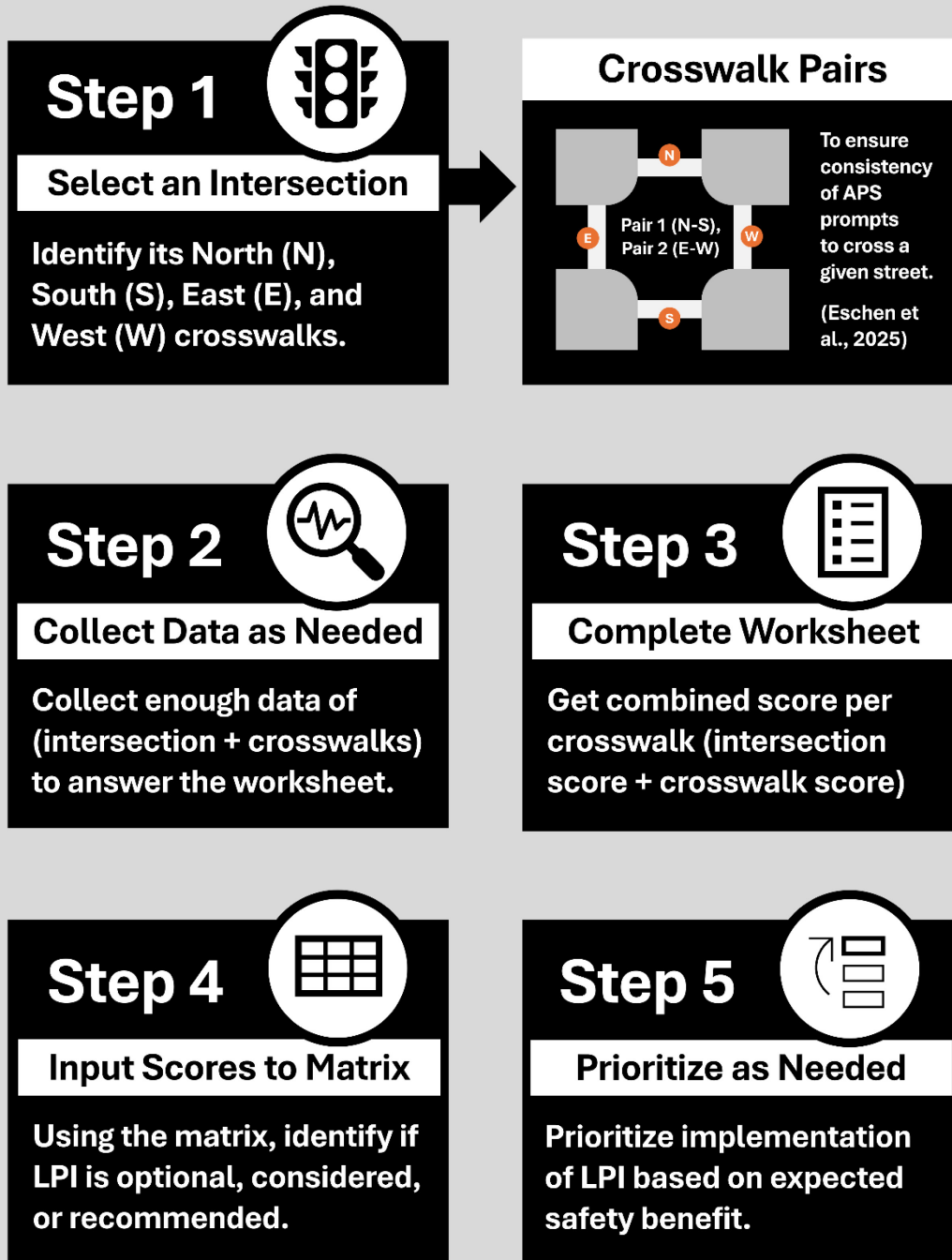


Figure 5.1. How to Use the LPI Suitability Assessment Tool

Table 5.1. LPI Suitability Assessment Tool (Part 1 - Intersection Level)

Factor	Score	Score Allocation	Why This Factor is Important
 Crash History	0 to 60 points	How many crashes between pedestrians and turning vehicles have occurred in the last 5 years? • None = 0 points. • 1 crash = 20 points. • 2 crashes = 40 points. • ≥ 3 crashes = 60 points.	One or more pedestrian crashes at a signalized intersection are a clear red flag for pedestrian safety. The LPI guidelines/policy from 5+ jurisdictions consider crash history as a factor for LPI implementation (Eschen et al., 2025; NCDOT, 2025; TxDOT, 2024; PennDOT, 2021; CalTrans, 2021; GDOT, 2021; MDOT SHA, 2020; FHWA, 2019; Lin et al., 2017).
 Accessible Pedestrian Signal (APS)	-30 to 60 points	Does the intersection have existing Accessible Pedestrian Signals (APS) at all 4 crosswalks? • No, there are no existing APS at all 4 crosswalks = -30 points. • No, but planning to install APS at all 4 crosswalks before LPI implementation = 30 points. • Yes, there are existing APS at all 4 crosswalks = 60 points.	According to the MUTCD, "If an LPI is used without accessible features, pedestrians with vision disabilities might begin crossing at the onset of the vehicular movement when vehicle operators are not expecting them to begin crossing" (FHWA, 2023). Legal precedents from lawsuits in New York City (NYCDOT, 2024) and Chicago (Department of Justice, 2021) reinforce the importance of providing APS in conjunction with LPIs. The LPI guidelines/policy from 5+ jurisdictions consider APS as a factor for LPI implementation (CA VEH, 2025; DDOT, 2025; FDOT, 2025; Arlington County, 2025; TxDOT, 2024; City of Bellevue, 2023; FHWA, 2019).
 Land Use Context	0 to 30 points	How far away is the intersection from at least one land use type or facility that attracts vulnerable road users? (e.g. school, assisted-living, transit stop/station, shops, park, multifamily housing, healthcare facility, or any other land use type or facility not listed but deemed appropriate based on engineering judgement). • Greater than a 3000 ft radius = 0 points. • Within a 2000 ft to 3000 ft radius = 10 points. • Within a 500 ft to 2000 ft radius	A signalized intersection's close proximity to these land-use types or facilities may increase the presence of vulnerable road users within the intersection. The LPI guidelines/policy from 5+ jurisdictions consider land-use context as a factor for LPI implementation (Eschen et al., 2025; NCDOT, 2025; PennDOT, 2021; GDOT, 2021; CalTrans, 2021; SDOT, 2019; Lin et al., 2017).

Factor	Score	Score Allocation	Why This Factor is Important
		= 20 points. • Within a 0 to 500 ft radius = 30 points.	
 Public Complaints	0 to 30 points	How many public complaints regarding pedestrian safety has the intersection received in the last 5 years? • None = 0 points. • 1 complaint = 10 points. • 2 complaints = 20 points. • ≥ 3 complaints = 30 points.	Public complaints not only highlight concerns from the public regarding pedestrian safety, but they can also provide insights regarding near-misses within the intersection. The LPI guidelines / policy from 3+ jurisdictions consider public complaints / requests as a factor for LPI implementation (NCDOT, 2025; PennDOT, 2021; Lin et al., 2017).
 Unique Case	-30 to 60 points	Based on engineering judgement, does the intersection have a unique case (something not already captured by the tool) that would influence the need for an LPI? Choose any score between -30 to 60 points , then identify and justify the unique case. Note: If no unique case is identified, enter 0 points .	An effort was made for this tool to capture the major factors that influence LPI implementation. However, it is possible that not all possible factors were captured, and an intersection's unique characteristics may also influence LPI implementation. This section allows evaluators to consider such factors and weigh them according to engineering judgement.
Summary:	240 points max	5 Intersection Level Factors	25+ Citations

Table 5.2. LPI Suitability Assessment Tool (Part 2 - Crosswalk Level)

Factor	Score	Score Allocation	Why This Factor is Important
 Pedestrian Volume	10 to 20 points	For each crosswalk, how many pedestrians use the crosswalk (in both directions) within at least one peak hour (morning, midday, or evening) during any day? • ≤ 25 pedestrians = 10 points. • ≥ 26 pedestrians = 20 points.	As pedestrian volume increases, pedestrian-vehicle interactions increase. The MUTCD (FHWA, 2023) and LPI guidelines/policy from 5+ jurisdictions consider pedestrian volume as a factor for LPI implementation (Eschen et al., 2025; NCDOT, 2025; TxDOT, 2024; WSDOT, 2024; CalTrans, 2021; MnDOT, 2021; MDOT SHA, 2020; FHWA, 2019; Lin et al., 2017).
 Vehicle Volume	0 to 20 points	For each crosswalk, how many right and left turning vehicles (if on a permissive phase) turn into the crosswalk during the same hour and day as the pedestrian volume? Note: If signal phasing separates right turning vehicles from peds, how many vehicles turn on red into the crosswalk? • Not applicable (e.g. no vehicles from parallel approach turning into the crosswalk / one-way) = 0 points. • ≤ 50 turning vehicles = 10 points. • ≥ 51 turning vehicles = 20 points.	As vehicle volume increases, pedestrian-vehicle interactions increase. The MUTCD (FHWA, 2023) and LPI guidelines/policy from 5+ jurisdictions consider turning vehicle volume as a factor for LPI implementation (Eschen et al., 2025; TxDOT, 2024; WSDOT, 2024; MnDOT, 2021; CalTrans, 2021; MDOT SHA, 2020; Lin et al., 2017).

Factor	Score	Score Allocation	Why This Factor is Important
 Speed Limit	0 to 30 points	What is the posted speed limit for the approach parallel to the crosswalk under consideration? • Not applicable (e.g. no vehicles from parallel approach turning into the crosswalk / one-way) = 0 points. • ≤ 25 mph = 10 points. • 30 mph = 20 points. • ≥ 35 mph = 30 points.	The risk of a pedestrian crash fatality increases as posted speed limit increases (Jashami et al., 2024a; NACTO, 2020; Turner et al., 2017). Vehicle turning speed is also a consideration of interest to promote pedestrian safety. There is evidence that smaller curb radii (Chai et al., 2024, Hurwitz et al., 2023) and the presence of Curb Extensions (per this research) can positively contribute to reducing turning speeds. LPI guidelines / policy from 5+ jurisdictions (Arlington County, 2025; GDOT, 2021; MnDOT, 2021; MDOT SHA, 2020; NACTO, 2013) recommend supplementing LPIs with traffic calming measures such as Curb Extensions.
 Crosswalk Length	10 to 30 points	How long (in feet) is the crosswalk under consideration? • ≤ 40 feet = 10 points. • 41 to 79 feet = 20 points. • ≥ 80 feet = 30 points.	As crosswalk length increases, pedestrian exposure increases. The MUTCD (FHWA, 2023) and LPI guidelines / policy from 2+ jurisdictions (NCDOT, 2025; CalTrans, 2021; FHWA, 2019) consider crosswalk length / crossing distance as a factor for LPI implementation and for determining LPI duration.
 Visibility Issues	0 to 60 points	Does the approach parallel to the crosswalk under consideration have any of the features listed below that could affect pedestrian visibility for turning vehicles? If more than one feature is present, add 10 points per feature (60 points max). • 1. No Pedestrian Visibility Issues Identified = 0 points. • 2. On-Street Parking at Corner with No Parking Restriction or Curb Extension = 10 points. • 3. Physical Obstruction (e.g. Vegetation, Street Furniture, Utilities, etc.) = 10 points. • 4. No Crosswalk Setback (i.e. crosswalk is very near the corner of the intersection) = 10 points.	The LPI guidelines/policy from 5+ jurisdictions consider visibility issues as a factor for LPI implementation (NCDOT, 2025; PennDOT, 2021; CalTrans, 2021; FHWA, 2019). On-street parking (FHWA, 2019); physical obstructions (NCDOT, 2025; PennDOT, 2021; CalTrans, 2021; FHWA, 2019); geometric characteristics (PennDOT, 2021; CalTrans, 2021; FHWA, 2019) like crosswalk setback (Hurwitz et al., 2023; Jacquemart, 2012), curb radius (Chai et al., 2024, Hurwitz et al., 2023; Singleton et al., 2023), skewed angle (Brewer et al., 2014); and poor lighting (PennDOT, 2021)

Factor	Score	Score Allocation	Why This Factor is Important
		• 5. Large Curb Radius (≥ 30 feet) = 10 points. • 6. Skewed Angle ($<75^\circ$) = 10 points. • 7. Poor or No Lighting = 10 points.	are commonly identified as features that affect pedestrian visibility.
 Turn Lane Configuration	0 to 30 points	What is the right turn lane configuration for the approach parallel to the crosswalk under consideration? • Not applicable (e.g. no vehicles from parallel approach turning right into the crosswalk / one-way) = 0 points. • Channelized Right-Turn Lane = 0 points. • Shared Thru/Right Turn Lane = 10 points. • Dedicated Right Turn Lane = 20 points. • Dual Right Turn Lane = 30 points.	The LPI guidelines/policy from 2+ jurisdictions consider turn lane configuration (especially dual right turn lanes due to visibility issues) as a factor for LPI implementation (NCDOT, 2025; CalTrans, 2021). Research studies like (Craig & Morris, 2025) recommend the implementation of dedicated right-turn lanes in conjunction with pedestrian safety countermeasures such as improving sightlines, advance stop lines, signage to alert drivers, and traffic calming to prevent pedestrian-vehicle conflicts at the secondary/parallel crosswalk.
 RTOR Restriction	0 to 20 points	Do the right turning vehicles turning into the crosswalk under consideration have a right-turn-on-red (RTOR) restriction? • No = 0 points. • Yes = 20 points.	To prevent non-yielding behaviors during the LPI, researchers (Day et al., 2025; Day et al., 2024; Day et al., 2023; Wolfgram et al., 2022; Sharma et al., 2017; Lin et al., 2017), the MUTCD (FHWA, 2023), FHWA (2019), and 5+ jurisdictions (Arlington County, 2025; TxDOT, 2024; WSDOT, 2024; GDOT, 2021; PennDOT, 2021; MDOT SHA, 2020) recommend prohibiting right turns on red during the LPI.
 Right Turn Phasing	0 to 30 points	What is the signal phasing for the right turn movement at the crosswalk under consideration? • Other (e.g. Protected, No Ped FYA, Split-Phasing, Protected / Permissive, N/A) = 0 points. • Permissive = 30 points.	The LPI guidelines/policy from 5+ jurisdictions consider signal phasing as a factor for LPI implementation (NCDOT, 2025; PennDOT, 2021; CalTrans, 2021; MDOT SHA, 2020; SDOT, 2019). LPI guidelines such as NCDOT (2025) provide a list of challenges, mitigation strategies, and other considerations related to signal phasing and LPIs.

Factor	Score	Score Allocation	Why This Factor is Important
 Left Turn Phasing	0 to 30 points	What is the signal phasing for the left turn movement at the crosswalk under consideration? • Other (e.g. Protected, No Ped FYA, Split-Phasing, Protected / Permissive, N/A) = 0 points. • Permissive = 30 points.	The LPI guidelines/policy from 5+ jurisdictions consider signal phasing as a factor for LPI implementation (NCDOT, 2025; PennDOT, 2021; CalTrans, 2021; MDOT SHA, 2020; SDOT, 2019). LPI policies such as SDOT (2019) recommend not implementing LPIs if leading protected / permissive left-turn phasing does not warrant being converted to lagging protected / permissive phasing. LPI guidelines such as NCDOT (2025) provide a list of challenges, mitigation strategies, and other considerations related to signal phasing and LPIs.
 Unique Case	-30 to 30 points	Based on engineering judgement, does the crosswalk under consideration have a unique case (something not already captured by the tool) that would influence the need for an LPI? Choose any score between -30 to 30 points for each applicable crosswalk, then identify and justify the unique case. Note: If no unique case is identified, enter 0 points.	An effort was made for this tool to capture the major factors that influence LPI implementation. However, it is possible that not all possible factors were captured, and a crosswalk's unique characteristics may also influence LPI implementation. This section allows evaluators to consider such factors and weigh them according to engineering judgement.
Summary:	300 points max	10 Crosswalk Level Factors	80+ Citations

Table 5.3. Combined Score Calculation

Assessment Scores	North Crosswalk	South Crosswalk	East Crosswalk	West Crosswalk
Intersection Score (Crash History + Accessible Pedestrian Signal (APS) + Land Use Context, Public Complaints, Unique Case).	0-240 points	0-240 points	0-240 points	0-240 points
Crosswalk Score (Pedestrian Volume + Vehicle Volume + Speed Limit + Crosswalk Length + Visibility Issues + Turn Lane Configuration + RTOR Restriction + Right Turn Phasing + Left Turn Phasing + Unique Case).	0-300 points	0-300 points	0-300 points	0-300 points
Combined Score (Intersection Score + Crosswalk Score)	0-540 points	0-540 points	0-540 points	0-540 points

Table 5.4. LPI Suitability Matrix

Combined Score	North or East Crosswalk (0-180 points)	North or East Crosswalk (181-361points)	North or East Crosswalk (362-540 points)
South or West Crosswalk (0-180 points)	Optional (Low Expected Safety Benefit)	Optional (Low Expected Safety Benefit)	Considered (Moderate Expected Safety Benefit)
South or West Crosswalk (181-361 points)	Optional (Low Expected Safety Benefit)	Considered (Moderate Expected Safety Benefit)	Recommended (High Expected Safety Benefit)
South or West Crosswalk (362-540 points)	Considered (Moderate Expected Safety Benefit)	Recommended (High Expected Safety Benefit)	Recommended (High Expected Safety Benefit)

5.1.3 Additional Guidance & Best Practices

The score allocations provided in the LPI suitability assessment tool provide insight into where LPIs are most frequently recommended (lowest score = least recommended, highest score = most recommended) based on research, policy, and guidelines from cities and state departments of transportation. The assessment can be conducted using inventory data from databases like ODOT TransGIS (ODOT, 2025b), field or virtual street view visits, and data collection efforts where necessary (e.g., pedestrian volume per crosswalk and turning vehicle volume per crosswalk). While the tool attempts to incorporate as many factors as possible while minimizing the need for complex and time-consuming data collection efforts to help streamline the assessment and prioritization process, specific details about the intersection and/or the crosswalks under consideration may elevate the need for an LPI. To provide a space for analysts to consider such details, both the intersection level assessment and the crosswalk level assessment of the tool include a “Unique Case” factor that allows analysts to account for unique factors not already captured by the tool and weigh them according to engineering judgement. For example, an agency may identify additional factors specific to the intersection or crosswalk(s) under consideration that are not already captured by the tool (e.g. presence of bicycle signals, long cycle lengths, etc.), or they may weigh a certain factor more heavily (e.g. crash history) and may use this section to customize the assessment per agency policies / best practices.

5.1.3.1 *Complementary Treatments*

Accessible Pedestrian Signal (APS) – To ensure LPIs are accessible to pedestrians with vision disabilities, the installation of APS is recommended (FDOT, 2025; TxDOT, 2024; FHWA, 2023; FHWA, 2019; City of Bellevue, 2023). Legal precedents from lawsuits in New York City (NYCDOT, 2024) and Chicago (Department of Justice, 2021) reinforce the importance of providing APS in conjunction with LPIs. Additionally, proactive steps, such as those from the State of California, are recommended. For example, the CalTrans (2021) LPI Implementation Guidelines mention that it is preferable for intersections to have crosswalk markings, APS, and pedestrian countdown signals before LPIs are implemented. And to provide clarity on LPI & APS implementation, California passed legislation related to LPI & APS implementation at state-owned signals on 10/03/25, through Senate Bill 671 (Chapter 326), which amends section 21450.5 of the CA Vehicle Code.

Curb Extension (CE) – CEs are often recommended as complementary treatments to LPIs (Arlington County, 2025; GDOT, 2021; MnDOT, 2021; MDOT SHA, 2020; NACTO, 2013). This research confirms that CEs decrease vehicle turning speed and shift conflicts from high/medium to low severity. For conflicts involving speed, both CEs & LPIs reduced conflicts, with the addition of the CE providing additional conflict reduction.

No Turn on Red (NTOR) Sign – Prohibiting right turns on red during the LPI, through complementary treatments such as static or blank-out NTOR signs is often recommended (NCDOT, 2025; TxDOT, 2024; FHWA, 2023; City of Bellevue, 2023; PennDOT, 2021; CalTrans, 2021; MDOT SHA, 2020; FHWA, 2019). This research found that the presence of an LPI increased fixation on the static NTOR (R10-11) sign. It was also

found that the NTOR sign decreased the approach and turning speed of vehicles. Although data regarding NTOR compliance was not collected in the field, and compliance data was not analyzed as part of the driving simulator experiment, the majority of simulator participants were observed to comply with NTOR. However, it must be noted that drivers may behave differently in a simulation environment because they know that they are being observed.

Turning Vehicles Yield to Pedestrians Sign – If right turns on red are not prohibited, the installation of a R10-15R sign is often recommended at intersections with LPIs, a dedicated turn lane, or a free-flow channelized turn lane (FDOT, 2025; NCDOT, 2025; PennDOT, 2021; MDOT SHA, 2020). R10-15L can be helpful for protected/permissive left turns that don't end concurrently (PennDOT, 2021).

5.1.4 How the Tool is Different

The tool developed in this research builds upon the work of Eschen et al. (2025), Saneinejad & Lo (2019), and Lin et al. (2017). Although each of these tools provide valuable criteria for determining LPI suitability, these tools were developed for jurisdictions outside of Oregon, such as the City of Phoenix (Eschen et al, 2025), the City of Toronto, Canada (Saneinejad & Lo, 2019), and the state of Florida (Lin et al, 2017). Included in Appendix G of this report is an example of each of the tools referenced in this research (Eschen et al., 2025; Saneinejad & Lo, 2019; and Lin et al., 2017).

This tool was adapted for the state of Oregon and supplemented with findings from this research, as well as a comprehensive review of existing literature and agency practices. While previous tools serve as a foundational example for determining the suitability of LPIs, this tool seeks to provide more comprehensive criteria for LPI suitability assessment, while minimizing the need for complex and time-consuming data collection efforts to help streamline the assessment and prioritization process.

This tool augments the criteria developed by previous tools by compiling a list of the most influential factors (15 total) as identified in the literature and by simplifying the scoring process in a way that practitioners can easily assess LPI suitability based on intersection and crosswalk characteristics. This tool considers a diverse range of factors at both the intersection level (5 total: crash history, accessible pedestrian signal (APS), land use context, public complaints, and unique case) and crosswalk level (10 total: pedestrian volume, vehicle volume, speed limit, crosswalk length, visibility issues, turn lane configuration, RTOR restriction, right turn phasing, left turn phasing, and unique case).

One primary thing that differentiates this LPI suitability assessment tool from previous tools is that this tool places emphasis on pedestrian safety as the core basis for LPI implementation. While previous tools consider vehicle-centric factors such as impacts on vehicular capacity, calculating such impacts may require additional time and resources from jurisdictions, which may delay LPI implementation. With shifts in thinking through initiatives like Vision Zero (Vision Zero Network, 2025), this tool embodies a forward-thinking approach towards LPI implementation, one that puts pedestrians at the forefront.

6.0 CONCLUSION & RECOMMENDATIONS

Improving pedestrian safety continues to be critically important to ODOT's mission to provide a safe and reliable multimodal transportation system. This research provides ODOT with refined tools to improve pedestrian safety at signalized intersections by developing enhanced guidance on when and where to implement Leading Pedestrian Intervals (LPI) either solely or in conjunction with complementary treatments such as Curb Extensions (CE), and NTOR signs. The guidance provided in this research was informed by four major tasks: 1) A Literature Review, 2) A Conflict-Based Field Study, 3) A Driving Simulator Study, and 4) An LPI Suitability Assessment Tool.

6.1 LITERATURE REVIEW

A literature review was conducted on 1) the relationship between LPIs and CEs on signalized intersection safety, 2) agency practices related to LPIs and CEs, 3) factors that impact LPI duration and effectiveness, and 4) recommended LPI supplements. In the literature, both LPIs and CEs were found to provide pedestrians with a head start to enter crosswalks at intersections. While LPIs are known for giving pedestrians a head start in time, CEs are known for giving pedestrians a head start in space. They both offer similar safety benefits and demonstrate strong potential to improve pedestrian safety at signalized intersections. To gain a better understanding of existing guidance related to LPIs and CEs across the United States, policy and guidelines from 10+ cities and state DOTs were reviewed. Factors such as corner radius, street furniture in sight triangle, lane configuration, crosswalk setback, approach and turning speeds, as well as signal operation plans and hardware, were identified as factors that may impact the duration and effectiveness of an LPI. Finally, research and guidance on recommended LPI supplements such as using "No Turn on Red" (NTOR) and Accessible Pedestrian Signals (APS) were also reviewed. The insights from the literature review informed the LPI suitability assessment tool developed in this research.

6.2 CONFLICT-BASED FIELD STUDY

A conflict-based field study was conducted to assess the frequency of pedestrian-vehicle conflicts (measured by Post Encroachment Time (PET)) and to explore how these conflicts differ between intersections with and without LPIs and CEs. A total of 300 potential sites were received from ODOT and local agencies, including Washington County, Clackamas County, and the City of Portland. From this initial list of sites, the project team prioritized sites that were at 4-legged intersections, and that were not close to a school (as the data collection would occur in the summer when the school is closed and therefore crossing volumes would be low). Ultimately, 11 intersections in Portland (10) and Lake Oswego (1) were selected. These sites were divided into 3 different groups: control sites (no LPIs or CEs), experimental sites (both LPIs and CEs), and before/after sites (no LPI or CE in 'before' period; LPI only in 'after' period). Two days of video data were collected at each intersection from 7 AM to 7 PM in August, September, and October 2024 (~264 hours).

For each intersection, 2 crosswalks (East & West or North & South) with 3 vehicular movements of interest were studied. These vehicular movements represent turning vehicles that must yield to pedestrians: 1) A left turn from the perpendicular lane, 2) an adjacent right turn from the approach of the study crosswalk to the perpendicular lane, and 3) a crossing right turn from the perpendicular lane to the approach of the study crosswalk. For each crosswalk, researchers collected the volume and travel direction of pedestrians, as well as the volume of vehicular turning movements across the crosswalk. In addition to volume data, pedestrian-vehicle conflicts with a PET of 5 seconds or less, as well as the speed of turning vehicles were also collected. Pedestrian-vehicle conflicts were summarized by 3 different PET severity ranges: low ($3.5 < \text{PET} < 5$), medium ($1.5 < \text{PET} < 3.5$), and high ($\text{PET} < 1.5$). Additionally, for most sites, conflicts with speeds below 7.97 mph were classified as low-speed conflicts, and those with higher speeds were classified as high-speed conflicts. For the 10th and Burnside site only, conflicts with speeds below 6 mph were classified as low-speed conflicts, and all others were classified as high-speed conflicts.

The findings from the conflict-based field study found, consistent with the literature, that LPIs reduce conflict frequency across exposure conditions and intersection types, while curb extensions show evidence of mitigating high-speed conflict frequency and shifting conflicts from high/medium to low severity.

6.3 DRIVING SIMULATOR STUDY

A driving simulator study was conducted to investigate driver behavior (speed and visual attention) when navigating signalized intersections with LPIs, CEs, NTOR signs, and pedestrians. The study was conducted using Oregon State University's full-cab driving simulator and a pair of eye-tracking glasses. A total of 58 subjects (29 male and 29 female) from Corvallis, Oregon and its surrounding communities participated in the study (14 of them experienced simulator sickness). The age of subjects ranged from 18 to 78 years old and consisted of licensed drivers with at least 1 year of driving experience. Four independent variables with two levels (present vs not present) were included in the experiment: an LPI (5 seconds), a CE (30 ft long), a static NTOR sign (R10-11), and a pedestrian (4 ft/s walking speed). A within-subjects factorial design was chosen to enable exploration of how subjects respond to all possible combinations of the independent variable levels. The factorial design for the four independent variables yielded a total of 16 scenarios ($2 \times 2 \times 2 \times 2$). These 16 scenarios consisted of right-turn maneuvers at signalized intersections. Additionally, geocoded scenarios of Broadway & 14th Avenue and Broadway & 21st Avenue in Portland, Oregon (2 of the 11 intersections studied in the conflict-based field study) were created and presented in the experiment as 4 additional scenarios simulating right turn maneuvers at each of the two intersections with a pedestrian present and with no pedestrian present. Four additional scenarios simulating left turns were presented. These 4 scenarios consisted of left turn maneuvers with two independent variables (5 second LPI and pedestrian) with two levels (present vs not present).

In total, 24 scenarios were presented to each subject (16 right turn scenarios, 4 geocoded scenarios, and 4 left turn scenarios). Results from a linear mixed model of speed data collected from right-turn scenarios indicated that the presence of a curb extension, a pedestrian, and an NTOR sign were each associated with a statistically significant decrease in turning speed. Similarly, the presence of an NTOR sign, a pedestrian, and an LPI were each associated with a

statistically significant decrease in approach speed. Results from a seemingly unrelated regression model performed on the visual attention data for right turn scenarios across 4 different AOIs (NTOR Sign, Pedestrian, Ped Signal, and Traffic Signal) showed that all independent variables (NTOR sign, pedestrian, LPI, and CE) had statistically significant effects on the fixation duration of at least one AOI. For example, the NTOR sign increased fixation on the traffic signal; pedestrian presence increased fixation on the ped signal but decreased fixation on the NTOR sign; the LPI decreased fixation on the pedestrian but increased fixation on the ped signal, NTOR sign, and traffic signal; and the CE decreased fixation on the pedestrian but increased fixation on the ped signal.

6.4 LPI SUITABILITY ASSESSMENT TOOL

An LPI suitability assessment tool was developed to help ODOT assess its traffic signal inventory to produce a priority list of signals suitable for LPI. This tool was developed using Eschen et al. (2025)'s framework as a foundation, and scoring criteria and allocations were informed by findings from this research; a comprehensive literature review on previous LPI research studies; LPI guidance from FHWA (2023), NACTO (2020), and FHWA (2019); as well as LPI policy and guidelines developed by 10+ cities and state departments of transportation in the United States. The tool consists of a worksheet that guides the analyst through a series of questions for the intersection under consideration and for each of the crosswalks associated with it. Following Eschen et al (2025)'s recommendation to implement LPIs as crosswalk pairs (North-South and East-West) to ensure consistency of APS prompts to cross a given street, combined scores for each of the crosswalks are entered into a suitability matrix as a crosswalk pairing. Based on the suitability matrix scores of crosswalk pairings, an LPI is determined to be Optional (low expected safety benefit), Considered (moderate expected safety benefit), or Recommended (high expected safety benefit). This report provides three versions of the tool: one showing the tool itself and the guidance that was referenced when deciding on factors and score allocations (Chapter 5.0), a second showing a template version of the tool (Appendix E), and a third showing an example of how the tool was used to assess the suitability of an LPI at Broadway & 21st Avenue in Portland, Oregon (Appendix F).

To use the tool, an analyst would follow 5 simple steps: 1) select an intersection and identify its north, south, east, and west crosswalks; 2) collect enough data from the intersection and each of the crosswalks to answer the questions listed in the worksheet; 3) complete the worksheet to get a combined score per crosswalk; 4) input the combined scores per crosswalk into the matrix to determine if an LPI is optional, considered, or recommended; and 5) prioritize LPI implementation based on expected safety benefit. Overall, this tool provides ODOT with a holistic, data-driven approach to determine LPI suitability through 5 intersection level factors and 10 crosswalk level factors. Disclaimer: The tool template developed in this research is designed to provide results only for 4-leg intersections with 4 marked crosswalks. For 3-leg intersections, use engineering judgement.

6.5 LIMITATIONS & FUTURE WORK

As previously noted, the guidance provided in this research was informed by four major tasks: a literature review, a conflict-based field study, a driving simulator study, and an LPI suitability assessment tool. Listed below are some of the limitations identified for each:

Literature Review: An effort was made to identify existing LPI policy and guidelines across all 50 states of the United States. However, only documentation from 10+ cities and state DOTs were identified, either because these were the only jurisdictions with published LPI policy/guidelines at the moment, or because it is harder to locate LPI guidance in the design and practice documentation of other jurisdictions not included in the literature review.

Conflict-Based Field Study: There were a number of limitations in the conflict frequency and conflict severity modelling. These included: limited sample size, short data collection window, only daytime hours observed, imbalanced conflict counts, limited true before-after pairs, severity model performance, and potential unobserved heterogeneity. These limitations suggest that results should be interpreted as directional evidence rather than precise effect sizes. Future research could consider the implications of LPIs on nighttime pedestrian safety to extend the application of these findings.

Driving Simulator Study: Due to constraints in time and resources, a limited number of independent variables and variable levels were used. The timing of LPIs can vary from 3-7 seconds; the design of CEs can vary in size and shape; walking speeds can vary from person to person; and NTOR Signs can be static (R10-11, R10-11a, R10-11b) or blank-out signs. Future research could focus on studying the effects from different variations of LPI timing, CE design, pedestrian walking speeds, and NTOR signs.

LPI Suitability Assessment Tool: Although an effort was made for the tool to be as comprehensive as possible, there could be other factors that impact LPI suitability that the tool might not account for. Engineering judgement must continue to be used when determining LPI suitability. Additionally, because the main objective of this research was to develop a tool specifically for LPIs, the tool does not provide a score for complementary LPI treatments. Future research could focus on developing a suitability assessment tool for each treatment or integrating a scoring system for all treatments within the same tool.

6.6 RECOMMENDATIONS FOR PRACTICE

This research found that CEs decrease vehicle turning speed and shift conflicts from high/medium to low severity. For conflicts involving speed, both CEs & LPIs reduced conflicts, with the addition of the CE providing additional conflict reduction. This research supports guidance provided in the 2025 ODOT Highway Design Manual (506.17) and the 2024 ODOT Traffic Manual (310.3), which mention that CEs help reduce crossing distances in areas with on-street parking, increase pedestrian visibility, help control vehicular speeds, add available space for curb ramps, can improve motor vehicle operations by reducing the time needed for a person to complete their crossing, and can be used to enforce the required distance of on-street parking from intersections stated in ORS 811.550(17) and ORS 811.550(18). This research also aligns with and supports the 2024 ODOT Traffic Signal Policy & Guidelines (5.1). At signalized intersections, we recommend considering LPIs in conjunction with CEs to decrease turning speeds and provide additional conflict reduction.

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