DEPARTMENT OF TRANSPORTATION

# Multi-Method Investigation of Pedestrian Safety Impacts of Right-Turn Lanes


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16. Abstract (Limit: 250 words)

The impact of dedicated right-turn lanes at signalized intersections on pedestrian safety has been relatively understudied, particularly for urban areas. The authors reviewed the research literature and pedestrian crash data analysis on right-turning vehicles, performed a field study with both in-person observation and video recordings of sites with dedicated right-turn lanes and right-turn through lanes in Saint Paul, MN, and conducted an urban driving simulation study with participants driving and turning through both simulated lane types. The results indicated that (1) lane count and traffic volume were significantly associated with risk to pedestrians from right-turning vehicles, (2) higher-volume intersections with dedicated right-turn lanes were riskier to pedestrians in terms of yielding rates, (3) the dedicated right-turn lanes at lower-volume sites were safer than their right-turn through-lane counterparts in terms of yielding likelihood, (4) dedicated right-turn lanes were associated with fewer high-speed turns, and (5) right-turn through lanes were associated with wider turns in both the field data and simulation data. Taken together, intersections with dedicated right-turn lanes could pose some risk to pedestrians at higher-volume intersections for stopping rates, while dedicated right-turn lanes were likely safer than right-turn through-lane counterparts at lower-volume intersections in terms of pedestrian safety. Future research should examine these findings with a wider range of traffic volumes and intersection types.

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# Multi-Method Investigation of Pedestrian Safety Impacts of Right-Turn Lanes

## Final Report

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# Table of Contents

# List of Figures

# List of Tables

# Executive Summary

Dedicated right-turn lanes reduce traffic delays on urban roads and typically result in a reduction in motor vehicle crashes for both urban and rural roadways. General guidelines for installing dedicated right-turn lanes focus on both through and turning traffic volumes, vehicle-vehicle crash rate and type, such as sideswipe and rear end crashes, and road and intersection type. However, the impact of dedicated right-turn lanes on pedestrian safety is relatively understudied but is important because of the vulnerability of pedestrians and the relatively high rate of pedestrian injuries and fatalities.

The objective of this study was to clarify the consequences to pedestrian safety posed by the features of conventional dedicated right-turn lanes, specifically in urban communities. The safety consequences for pedestrians were assessed by (1) looking at available public research and (2) observable human behavior in right-turn lanes both on urban roads in Minnesota, and (3) in a safe, simulated environment. This study incorporated three methods to effectively assess both the impacts of urban right-turn lanes on pedestrian safety, and any specific factors of these lanes that contribute to pedestrian risk.

The first method was a narrative review of the current state of the literature on right-turn lanes, and an audit of publicly available data on pedestrian crashes in Minnesota. The second method focused on field data collection in Saint Paul, MN. Careful site selection allowed the team to select locations that have features of right-turn lanes that were of interest to traffic engineers and safety experts. Once sites were selected, observation of turning vehicles directly measured how vehicles responded to pedestrians at right-turn lanes. Observations were complemented by concurrent camera recordings and video coding to capture a wider range of crossing conditions. The observations also included a longitudinal case study at the intersection of White Bear Ave and Larpenteur Ave from 2023 to 2025, before and after the installation of two dedicated right-turn lanes at that location. Finally, carefully constructed driving scenarios were designed in an immersive, full chassis driving simulator, during which participants drove through a realistic world and encountered potentially dangerous crossing scenarios with simulated pedestrians. These simulations measured and provided better understanding of the behavior of drivers, such as turning speed in the simulator, braking distance, and other measured variables.

The research team reviewed public data that was analyzed by Toole Design on MnDOT pedestrian crash data over four years (2016-2019), highlighting the subset of the analyzed data on right-turn crashes in urban and suburban centers. While lane type information was not defined in the dataset, other relevant characteristics that contribute to risk of crashes at signalized intersections were clarified. The general takeaway for urban signalized intersections and right-turn crashes with pedestrians was the risk of high-volume traffic, number of lanes, and other factors that lead to dense, complex traffic interactions with multiple conflict points. Presumably these environments lead drivers to attend to multiple events and stimuli on the roadway, which leaves less attention to allocate to pedestrians. The most complex of these intersections present a similar level of risk in suburban communities, except for those with even higher posted speeds. Finally, as the prior research literature indicated, the pedestrian crash-risk could be particularly salient at the secondary crosswalk as drivers accelerate to complete the turn and pedestrians frequently interact with turning drivers at this part of the intersection.

The camera data indicated that the presence of a dedicated right-turn lane is associated with more driver-pedestrian conflicts in most scenarios. Because of the mix of right-turning and straight maneuvers undertaken by drivers in a right-through lane, there appears to be a lower likelihood of a pedestrian encountering a right-turning driver while crossing. However, the longitudinal case study on White Bear Ave and Larpenteur Ave indicates that for relatively low vehicle volume and pedestrian volume intersections with a right-on-red permitted and relatively low pedestrian volumes, a dedicated right-turn lane can lead to a lower rate of conflict between right-turning drivers and pedestrians by allowing the continued flow of right-turning traffic. For secondary or parallel crosswalk stopping rates, there is increased likelihood of drivers stopping pedestrians when turning on a dedicated right-turn lane for lower-volume roadways, and a decreased likelihood of stopping for pedestrians when turning on a dedicated right-turn lane on higher-volume roadways. Finally, the presence of a dedicated right-turn lane is associated with a reduced rate of high-speed turns on higher-volume roadways.

For the simulation study, participants were exposed to dedicated right-turn lanes and right-turn through lanes in experimental blocks, and a simulated pedestrian was sometimes present at the turning intersection and sometimes this participant crossed the street. Driving through the right-turn through lanes tended to have greater changes in entry speed and wider turns, report greater mental demand and marginal statistical differences in the tendency to fully stop and have greater changes in speed.

Some of the key recommendations based on the research results include:

- In most situations, dedicated right-turn lanes are associated with a small increase in the rate of driver-pedestrian conflicts for both primary and secondary crosswalks. This is only a concern if pedestrian volume is very high.
- However, there are exceptions due to **annual average daily traffic (AADT)**.
    - The exception is when the following is true: right-on-red is permitted, the rate of pedestrians crossing is relatively low (e.g., up to about 4 to 5 crossings every two hours on average), and the daily vehicle volume is relatively low (up to 7000 AADT). If these are true, then a dedicated right-turn lane may reduce the rate of driver-pedestrian conflicts for legal crossings on the secondary crosswalk.
- For lower-volume roadways (up to 11000 AADT, based on the current dataset), dedicated right-turn lanes appear to be beneficial or neutral for pedestrian safety, depending on the measure.
- For higher-volume roadways (16000+ AADT based on the current dataset, both directions added together) dedicated right-turn lanes have mixed results for pedestrian safety.
    - Dedicated turn lanes on higher-volume roadways should be considered for pedestrian safety countermeasures for conflicts at the secondary/parallel crosswalk. These include improving sightlines, advance stop lines, signage to alert drivers, and traffic calming.

# Chapter 1: Introduction

## 1.1 Pedestrian Safety Impacts of Right-Turn Lanes

Dedicated right-turn lanes reduce traffic delays on urban roads (Potts et al., 2007) and typically result in a reduction in motor vehicle crashes for both urban and rural roadways (Harwood et al., 2003). General guidelines for installing dedicated right-turn lanes focus on both through and turning traffic volumes, vehicle-vehicle crash rate and type, such as sideswipe and rear-end crashes, along with road (e.g., speed) and intersection type (CH2M HILL, 2014). However, the impact of dedicated right-turn lanes on pedestrian safety is relatively understudied. The lack of clarity on these impacts is important because of the vulnerability of pedestrians and the relatively high rate of pedestrian injuries and fatalities, and because pedestrians are often predominantly members of a disadvantaged minority population (Smart & Klein, 2015). This consideration adds further value by fostering livable communities by determining the trade-off between efficiency in traffic flow with right-turn lanes versus the potential risk to pedestrian safety.

The objective of this study was to clarify the consequences to pedestrian safety posed by the features of conventional, dedicated right-turn lanes, specifically for urban communities. The safety consequences to pedestrians were assessed by looking at available public research and observable human behavior in right-turn lanes both on urban roads in Minnesota and in a safe, simulated environment. This study incorporated multiple methods to effectively assess both the impacts of urban right-turn lanes on pedestrian safety, and which specific factors of these lanes contribute to pedestrian risk.

### 1.1.1 Methods

#### 1.1.1.1 Research Investigation

The first method was a literature review and audit of publicly available pedestrian data on urban roadways in Minnesota. The review was a narrative review of the current state of the literature on right-turn lanes. The audit of publicly available data on pedestrian crashes illustrated pedestrian risk given the location and rate of pedestrian crashes, specifically whether these crashes happen disproportionately at low-speed, right-turn lanes.

#### 1.1.1.2 Field Study

The second method focused on field data collection, including a cross-sectional component and a longitudinal component. The cross-sectional approach first incorporated the selection of right-turn lanes around urban streets in Minnesota, specifically in Saint Paul, MN. Careful site selection allowed the team to select locations that have features of right-turn lanes that were of interest to traffic engineers and safety experts (e.g., lane length, signals, crosswalk marking types, refuge, channelized, slip lanes, etc.). Once sites were selected, observations were conducted of turning vehicles directly measuring how vehicles responded to pedestrians at right-turn lanes. These observations were complemented by concurrent camera recordings and video coding to capture a wider range of crossing conditions.

The cross-sectional field study was complemented by a field longitudinal case study, which employed similar methods to the cross-sectional field study. The longitudinal study focused on one site as a case study, examining only traffic camera data, and measured driver behavior and the outcome of driver-pedestrian conflicts before and after installation of a dedicated turn lane. This occurred at the signalized intersection of White Bear Ave and Larpenteur Ave in Saint Paul, MN.

#### 1.1.1.3 Driving Simulation

While camera footage and staged crossings can capture a significant number of data points, risky crossing scenarios, which may be more likely to lead to a pedestrian crash, are less likely to occur and are unsafe to attempt in a staged crossing. Therefore, carefully constructed driving scenarios are designed with the Human Factors Safety Laboratory (HFSL) immersive driving simulator, during which participants drive through a realistic world in a 2013 Ford Fusion chassis and encounter potentially dangerous crossing scenarios with simulated pedestrians. These simulations measure and provide better understanding of the behavior of drivers, such as turning speed in the simulator, braking distance, and other measured variables.

## 1.2 Research Literature

### 1.2.1 Pedestrian Fatalities

Pedestrian deaths are at a 30-year high nationally, accounting for 16% of total deaths in 2018 which is far higher than 12% just ten years ago (GHSA, 2019). This trend is mirrored in Minnesota and 2019 saw similar rates of fatal crashes as 2016, a year that claimed the lives of 60 pedestrians (see Figure 1.1, calculated from MN Crash Facts).

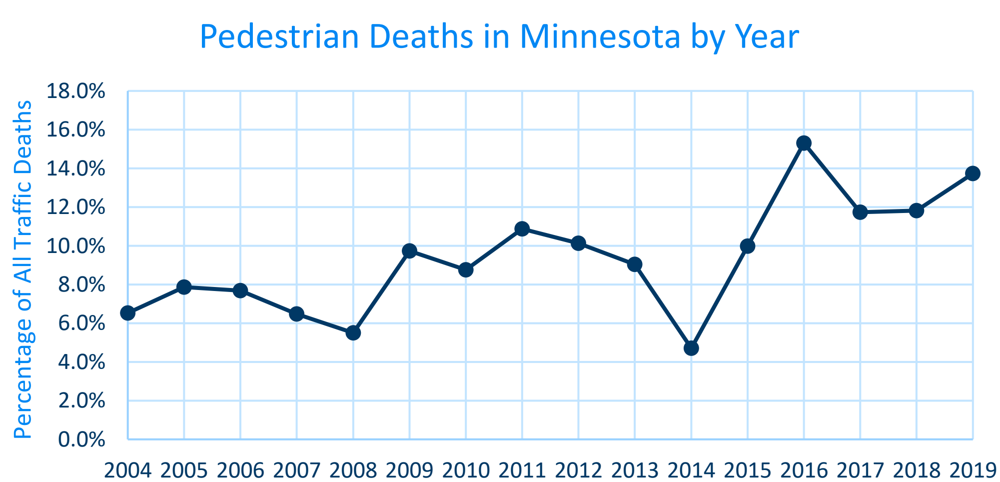


**Figure 1.1 Percentage of all fatal crashes represented by pedestrian fatalities in Minnesota by year.**

The pre-crash movement of vehicles and pedestrians in vehicle-pedestrian crashes vary depending on location. According to Minnesota Department of Public Safety (2019), 92% of pedestrian crashes occur in urban areas (as defined by population of 5,000 or greater people). Turning left or right at an intersection are the most frequent maneuvers, after the most common of traveling straight, for vehicles prior to striking a pedestrian. Given the pedestrian safety risk of turning vehicles, the implementation of turn-only lanes becomes potentially problematic. Dedicated right-turn lanes reduce traffic delays on urban roads (Potts et al., 2007) and typically results in a reduction in motor vehicle crashes for both urban and rural roadways, although the magnitude of the crash reduction is greater for rural compared to urban roadways, and unsignalized intersections compared to signalized intersections (Harwood et al., 2003). However, the safety impact of dedicated right-turn lanes on pedestrian safety is relatively understudied.

### 1.2.2 Right-Turning Vehicles

In a high-level analysis of issues related to perception, psychology, and safety in driver behavior, Summala (1996) observed that drivers turning right at T-intersections were less likely to visually observe aspects of the intersection relative to left-turning drivers, which suggests that drivers may pay less attention to unsafe conflicts at these intersections. This logic may apply to four leg intersections as well.

An analysis of pedestrian crash and injury data collected by NHSTA from 1994 to 1998 found that the proportion of vehicle pre-crash maneuvers were 48% for driving straight, 32% for right turns, and 10% for left turns (Roudsari et al., 2006). Moreover, Roudsari and colleagues (2006) found that the association between pre-crash maneuver and injury severity was driven by impact speed.

An analysis of crash data in Florida observed that right-turn crashes tended to increase with traffic volume along with number of lanes on the main road, along with the presence of exclusive left-turn lanes on the main road, suggesting heightened conflicts between left turning vehicles and right-turn movements (Abdel-Aty et al., 2006). In 2017, SHRP 2 Naturalistic Driving Study (NDS) data was used to examine risk to pedestrians and right-turn crashes (Wu et al., 2017). Under permitted right-turning conditions, drivers tended to have higher acceleration and less observance of potential threats and hazards, including pedestrians, whereas the presence of conflicting traffic led to greater odds of deceleration near the turning point. Furthermore, only 50% of drivers yielded to pedestrians when turning right, and the risk to pedestrians was highest during right-turn-on-red (RTOR) situations (Wu et al., 2017).

In Oregon, signalized intersections account for more than 24% of roadway fatalities, and 2% of roadway fatalities appear to occur because of right-turn crashes (Hurwitz et al., 2018). In response to this observation, Jashami (2020) and his colleagues reviewed five years of crash data across Oregon to assess factors attributing to crash severity for right-turn crashes at signalized intersections. The presence of a pedestrian-vehicle conflict had the highest association on the probability of a severe crash occurring while a vehicle turned right at a signalized intersection, which the author considered important because right turns are frequently permitted during pedestrian walk indications and drivers may not give the right of way to pedestrians, as indicated earlier. This may also be particularly problematic for dedicated right-turn only lanes.

Finally, an analysis of high-speed intersections (i.e., 45 mph speed limit or higher) in Louisiana from 2010 to 2019 found that the occurrence of right-turning drivers failing to yield the right-of-way to a pedestrian were significantly associated with pedestrian crashes (Hossain et al., 2024). While this association between failure to stop for a pedestrian when the pedestrian has the right-of-way and pedestrian crashes is established for high-speed intersections, it is not as clearly established for lower-speed signalized intersections. It is worth noting that low-speed uncontrolled intersections with no reported pedestrian crashes had higher rates of drivers stopping for pedestrians compared to sites with 2 or more pedestrian crashes in a 5-year period (Schneider et al., 2018).

### 1.2.3 Right-Turn Lanes

Right turn lanes were first introduced to speed the flow of traffic and decrease the risk of rear end collisions, as they got slowing vehicles out of the way of vehicles continuing straight (Potts et al., 2007). Where there is no right turn lane, right turners can delay traffic by up to 6 seconds and right turn lanes can reduce pedestrian related delays by up to six seconds (Potts et al., 2007). Studies focused on the interaction between cars turning right and pedestrians specifically identified three distinct dangers. There is danger to pedestrians due to traffic approaching at high speeds at unsignalized intersections or at signalized intersections when traffic signal is already green (Jiang et al., 2020; Fitzpatrick et al., 2006a; Fitzpatrick et al., 2006b). There is danger when traffic signal changes from red to green while both vehicles and pedestrians enter the intersection (Jiang et al., 2020; Van Houten et al., 2000; Hubbard et al., 2009). Finally, there is danger due to cars turning right on red (Retting 2002; Chadda & Schonfeld, 1985). These dangers all play differing roles in the overall safety of pedestrians based on the type of intersection. Jiang and colleagues (2020) describe the three primary forms of right turn lanes: "1) non-channelized right-only lanes, 2) non-channelized right-through lanes, and 3) channelized right-turn lanes."

The dangers of cars turning right on red and turning immediately after the traffic signal changes happens when cars do not yield the right of way to pedestrians. Though right turns on red have many benefits (increased traffic flow, lower fuel consumption, less tailpipe emission), there are cases where the safety risks outweigh them (Retting et al., 2002). There are a couple different approaches to solve the right of way issue. Retting and colleagues (2002) suggest that limiting when right turns on red are allowed would help reduce the safety concerns. In their study they found that limiting the allowed hours for right turn on red was more effective than signs that said, "No right turn when pedestrians are present." However, even during prohibited hours 19% of drivers continued to turn right. In comparison, turning right on red in the absence of signs occurred 85% to 88% of the time. Fu and colleagues (2019) discuss two places in each intersection where vehicle-pedestrian interactions occur. There is a crosswalk that the car crosses as it enters the intersection (primary interactions), and the crosswalk the car crosses as it leaves the intersection (secondary interactions). Not many studies have involved secondary interactions, but Fu et al. find that secondary interactions are more dangerous. For example, vehicle speeds were at a median of 2.14 m/s at the primary crosswalk, but 4.69 m/s at the secondary right crosswalk and 7.67 m/s at the secondary through crosswalk, and vehicles were typically decelerating toward the primary intersection, but accelerating through all secondary intersection types (right, left, through). A partial solution can be to implement lead pedestrian phase (LPI) in signal timing to let pedestrians begin to cross first, forcing the cars to give up the right of way as soon as the traffic signal turns green (Van Houten et al., 2000).

When looking at overall crash rates, Fitzpatrick and colleagues (2006a) found that the safest type of right turn lane was a shared right through lane due to its slower speeds, smaller surface area, and 90° turn angle. Slower speed allows drivers more time to see pedestrians, and pedestrians are more likely to survive crashes at slower speeds (Fitzpatrick et al., 2006b). Potts and colleagues (2013) examined crash data in Ontario, Canada from 1999-2005 and found that channelized right-turn lanes have similar pedestrian safety as non-channelized right-through lanes. They found that non-channelized right-only lanes have 70-80% more pedestrian crashes than either of the other two approaches. However, Jiang and colleagues (2020) argue that pedestrians are less safe in channelized right turn lanes, because they find higher speeds in channelized right turn lanes and lower speeds in non-channelized right turn lanes. Jiang et al. (2020) also notes that some drivers are unable to slow down sufficiently to yield the right of way due to the higher approach speeds when the turning radius increases at channelized right turn lanes.

Finally, a model of exposure, signalization, and geometry on occurrence of pedestrian injury was conducted on 1864 intersections in Canada, specifically Montreal. Straight green arrows, commercial entrances, and total number of lanes increased the rate of pedestrian injuries. Curb extensions, raised medians, all-red and half-red phases, and number of exclusive turn lanes decreased the rate of pedestrian injuries. The measure of exclusive turn lanes included both right- and left-turn only lanes, but the authors attributed the effect to primarily left-turn lanes, as each additional left turn lane reportedly reduced injuries by 14% (Stipancic, Miranda-Moreno, Strauss, & Labbe, 2020). One can infer that there was either little effect or a small positive effect of right-turn lanes on pedestrian safety at Montreal intersections.

## 1.3 Public Data Review

The research team reached out to MnDOT traffic safety data services in their Traffic Engineering division and was unsuccessful at retrieving the needed data for a primary analysis. However, the research team was able to retrieve a recent analysis conducted by Toole Design and funded by the Metropolitan Council, using MnDOT pedestrian crash data from 2016 to 2019. This year range is likely consistent with typical pedestrian and vehicle traffic patterns as it was just prior to the pandemic of 2020-2021. The data was constructed into crash trees to highlight the risk profiles of certain vehicle-pedestrian interaction scenarios. The research team had access to the data underlying the crash trees and was able to verify the scores. Unfortunately, the data here did not have information about road types and right-turn lanes. Furthermore, the categorization of communities were defined as either urban centers, urban areas, or rural communities, based on Thrive MSP 2040.

The analysis found that right turn pedestrian crashes were less frequent than left turn or straight crashes, and when they occurred, were less likely to result in death or serious injury than left or straight crashes. The riskiest scenarios related to right-turning vehicles in urban and suburban environments at signalized intersections are reported here, and given in **Appendix A** for suburban communities, and **Appendix B** for urban communities and urban centers. We highlight the riskiest scenarios because these conditions will likely be the most sensitive for whether a dedicated right-turn only lane can benefit or detract toward pedestrian risk. The currently presented analyses do not account for poverty level of the community in question.

For ***suburban*** communities (APPENDIX A), the highest risk of pedestrian crashes for signalized intersections are in the following order based on the generated risk score which looks at the ratio of severe right-turn pedestrian crashes per intersection:

1. Higher volume (7000+ ADT) intersections with speed limits between 35-50 MPH, with at least 1 transit stop in proximity to the intersection, and at least 4 or more lanes at the intersection. Risk score is 39.58.
2. Medium volume intersections (800-7000 ADT), all speeds, all locations, all lanes. Risk score is 12.11.
3. Higher volume (7000+ ADT) intersections with speed limits between 35-50 MPH, with at least 1 transit stop in proximity to the intersection, and 3 lanes at the intersection. Risk score is 11.84.
4. Higher volume (7000+ ADT) intersections with speed limits between 35-50 MPH, with no transit stop in proximity to the intersection, all lane counts. Risk score is 8.52.

For **urban centers** (APPENDIX B), the highest risk of pedestrian crashes for signalized intersections are in the following order based on the generated risk score which looks at the ratio of severe right-turn pedestrian crashes per intersection:

1. Higher volume (7000+ ADT) intersections with speed limits 30 MPH or less, with at least 1 transit stop in proximity to the intersection, and at least 4 or more lanes at the intersection. Risk score is 71.65.
2. Higher volume (7000+ ADT) intersections with speed limits 30 MPH or less, with no transit stop in proximity to the intersection, and all lane counts. Risk score is 68.72.
3. Higher volume (7000+ ADT) intersections with speed limits 30 MPH or less, with at least 1 transit stop in proximity to the intersection, and 1 to 2 lanes at the intersection. Risk score is 48.35.
4. Higher volume (7000+ ADT) intersections with speed limits 30 MPH or less, with at least 1 transit stop in proximity to the intersection, and 3 lanes at the intersection. Risk score is 17.70.

To summarize, Minnesota pedestrians appear to be most at risk for right-turning drivers in **suburban communities** at signalized intersections on higher speed limit roadways (35-50 MPH), and when there is a combination of high traffic volume and a transit stop with multiple lanes (3 to 4+ lanes), or when there is medium traffic volume (800 to 7000 ADT). For **urban centers** at signalized intersections, Minnesota pedestrians appear to be most at risk from right-turning vehicles at relatively low speed roadways (30 MPH or less) with higher traffic volumes (7000+ ADT), and the risk is highest when there is 4+ lanes and a transit stop in the vicinity. The elevated risk of transit stops may be due to the increase in pedestrian volume, the sight distance restriction posed by large buses, and the risk posed by traffic exposure to pedestrians with multiple lanes. The question of transit stops aside, lower speed roadways with high traffic volumes present both the highest risk to pedestrians for right-turning vehicles in urban areas, specifically urban centers, but these intersections also provide the most incentive to traffic engineers to place a dedicated right-turn only lane at these locations to improve traffic efficiency.

## 1.4 Conclusion

The relatively sparse published research indicates that dedicated right-turn only lanes have minimal or possibly positive impact on pedestrian safety (Stipancic et al., 2020), but circumstances which allow for greater acceleration/speed of the vehicle in a right turn lane may lead to greater risk to pedestrians (Fitzpatrick et al., 2006a; Jiang et al, 2020). Dedicated right-turn only lanes may facilitate this greater acceleration, particularly when pedestrians are at significant risk for being struck with right-turning vehicles in urban areas with high traffic volumes. Risky urban sites, particularly those with high traffic volumes, 4+ lanes and a transit stop, or 2-3 lanes without a transit stop, necessitate further study for the safety benefits of a dedicated right-turn only lane.

# Chapter 2: Field Observation Studies

## 2.1 Field Study 1 – Cross-Sectional Field Study

### 2.1.1 Cross-sectional Site Selection

The research team reviewed existing pedestrian crash analyses in each city. The team also worked with city, county, and state partners to review and agree upon key selection criteria, specifically prioritizing signalized sites within urban areas (e.g., Saint Paul, Minnesota) with moderate to high pedestrian volumes.

Half of the study sites selected were those with dedicated right-turn lanes. Additional considerations were the number of legs, as the ideal location would be a 4-leg intersection with a single approach in each direction with/without a right turn lane, and no presence of a lane that is used as a right-turn lane although not specifically designated as such.

The initial site candidates were dedicated right-turn lane sites because these sites and their implications for pedestrian safety are the central focus point of this study, and because there are very few such sites in the Saint Paul area. Sites without dedicated right-turn lanes would be selected based on both pedestrian volume and relative similarity and proximity to the selected dedicated right-turn only lane sites. The key right-turn lane type of interest in this study are non-channelized dedicated right-turn lanes as compared to right-through lanes, given that the consequences channelized right-turn lanes are arguably better understood by traffic engineers compared to non-channelized lanes, and right-through lanes are typical of intersections where right turns are permitted. The initial dedicated right-turn lane candidates in Saint Paul, MN are listed below.

1. White Bear & Suburban
2. Snelling & Marshall
3. Larpenteur & Edgerton
4. Cleveland & Marshall
5. Maryland & Payne
6. Cretin & Marshall
7. Fairview & Marshall

After initial consultation with the Technical Advisory Panel for the project, Snelling & Marshall, Marshall & Cleveland, and Maryland & Payne were marked as potential candidates moving forward due to an assumption that these sites had good pedestrian traffic volume.

#### 2.1.1.1 Pedestrian Traffic Volume Estimation

Working with MnDOT, the research team was able to retrieve estimates of pedestrian traffic volume from StreetLight Data, which generates a metric that compares estimates of pedestrian traffic volumes from a given list of comparison sites, called Pedestrian Index (PI). With PI, larger numbers suggest higher number of estimated pedestrians compared to the other sites within that year. Numbers do not reflect actual volume, just mathematical indices. Estimations are based on pings from active devices carried by pedestrians and other individuals, along with a proprietary modeling algorithm based on known factors of the roadway and geography to normalize and fit the data. The numbers are based on a 24-hour period and are also provided atop pedestrian open street map (OSM) layers of varying accuracy.

Besides the initial site list of dedicated right-turn only sites, new dedicated right-turn only site candidates were identified to provide a pedestrian volume estimation (via PI metric) from StreetLight Data, including three options from neighboring Minneapolis, Minnesota. Besides these dedicated right-turn candidates, a separate list of right-turn through lane sites (with no dedicated right-turn lanes present) was provided to gather estimates of pedestrian volumes. The list of dedicated right-turn only sites are provided in Table 2.1 and their associated pedestrian indices (PIs) and the list of right-turn through sites are provided Table 2.2. The legs in Table 2.1 for dedicated right-turn lanes were provided because not all legs of the intersection in question had right-turn lanes.

**Table 2.1 Dedicated Right-Turn Only Lane Pedestrian Volume Estimations from StreetLight Data**

| Street 1 | Street 2 | Leg | Pedestrian OSM Layer | Year: 2018 | Year: 2019 | Year: 2020 |
|---|---|---|---|---|---|---|
| Riverside | Cedar | N | bad | 1992 | 1837 | 1671 |
| Lowry | Penn | E | bad | 816 | 794 | 484 |
| Lowry | Penn | W | bad | 849 | 745 | 546 |
| Wabasha | Plato | W | good | 847 | 520 | 451 |
| Marshall | Snelling | W | good | 578 | 386 | 320 |
| Marshall | Cretin | N | good | 567 | 253 | 383 |
| Maryland | Payne | S | good | 159 | 188 | 121 |
| Snelling | Ford | S | good | 91 | 159 | 291 |
| Payne | Minnehaha | E | good | 174 | 144 | 294 |
| Marshall | Cleveland | S | good | 234 | 143 | 166 |
| Dale | Minnehaha | N | good | 376 | 128 | 192 |
| Marshall | Cleveland | N | good | 433 | 110 | 153 |
| Marshall | Snelling | N | good | 256 | 105 | 158 |
| Marshall | Snelling | S | good | 119 | 92 | 78 |
| Wabasha | Plato | N | good | 22 | 76 | 173 |
| Marshall | Fairview | N | good | 286 | 57 | 121 |
| Larpenteur | Edgerton | W | bad | 140 | 36 | 244 |
| Wabasha | Plato | E | good | 17 | 4 | 2 |
| White Bear Ave | Suburban | E | unsure / bad | 5 | 1 | 21 |

**Table 2.2 Right-Turn Through Lane Pedestrian Volume Estimations from StreetLight Data**

| Street 1 | Street 2 | Pedestrian OSM Layer | Year: 2018 | Year: 2019 | Year:2020 |
|---|---|---|---|---|---|
| Minnehaha | Arcade | unsure/bad | 3840 | 2570 | 2477 |
| Riverside | 21st | good | 2870 | 2388 | 2307 |
| Wabasha | Fillmore/Water | good | 3323 | 2230 | 2095 |
| Riverside | 20th | good | 3274 | 2361 | 1752 |
| Maryland | Hazelwood | unsure / bad | 1556 | 1373 | 1620 |
| Snelling | Highland Pkwy | unsure/bad | 735 | 821 | 1583 |
| Snelling | Randolph | unsure/bad | 1214 | 881 | 1549 |
| Marshall | Prior | good | 1290 | 855 | 1370 |
| Larpenteur | White Bear Ave | good | 2529 | 1328 | 1190 |
| Marshall | Otis | good | 1636 | 777 | 1096 |
| Maryland | Forest | good | 1128 | 702 | 1033 |
| Maryland | Earl | unsure | 992 | 508 | 775 |
| Dale | Maryland | unsure/bad | 790 | 359 | 555 |
| Maryland | Edgerton | good | 1153 | 481 | 549 |
| Maryland | Sylvan | unsure/bad | 792 | 383 | 449 |
| Maryland | Jackson | good | 1398 | 403 | 439 |
| Dale | Wheelock Pkwy | unsure/bad | 279 | 141 | 321 |

Estimates of a “good” versus “unsure/bad” pedestrian OSM layer are provided in Figure 2.1.

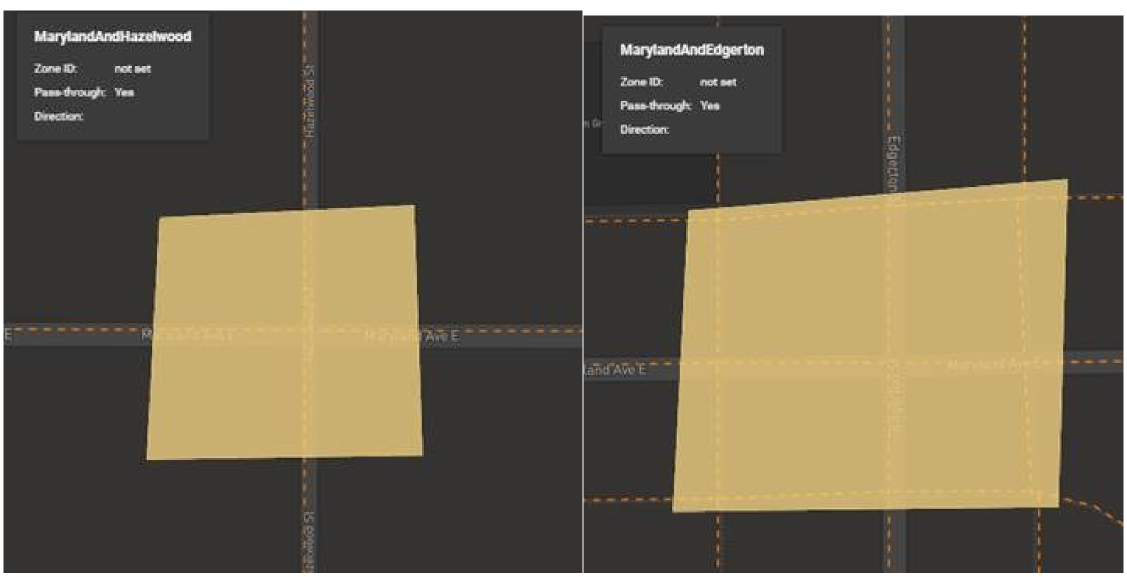


**Figure 2.1 Pedestrian Open Street Map (OSM) layers. A bad/unsure layer is on the left (Maryland & Hazelwood), and a good pedestrian OSM layer, suggesting better reliability of the estimated data is on the right (Maryland & Edgerton).**

### 2.1.1.2 Second Iteration List of Sites

Based on both quality of data (pedestrian OSM layer) and relative pedestrian volume estimation, the following sites were selected for final review (see Table 2.3 and Table 2.4), including sites from Saint Paul and Minneapolis (i.e., Cedar & Riverside). Other sites such as Lowry and Penn Avenue did not make the second iteration because the data quality extracted from the pedestrian OSM layer was low, or because their estimated pedestrian volume was low.

**Table 2.3 Second List of Dedicated Right-Turn-Only Lane Sites**

| Street 1 | Street 2 | # Lanes | Leg | City |
|---|---|---|---|---|
| Maryland | Payne | 3/2 | South Leg | Saint Paul |
| Marshall | Cretin | 2/4 | South Leg | Saint Paul |
| Marshall | Cleveland | 2/2 | South Leg | Saint Paul |
| Snelling | Ford | 4/3 | South Leg | Saint Paul |
| Wabasha | Plato | 3/2 | West Leg | Saint Paul |
| Riverside | Cedar | 2/2 | North Leg | Minneapolis |
| Marshall | Snelling | 2/4 | West Leg | Saint Paul |

**Table 2.4 Second List of Right-Turn Through Lane Sites**

| Street 1 | Street 2 | # Lanes | City |
|---|---|---|---|
| Maryland | Forest | 3/2 | Saint Paul |
| Marshall | Prior | 2/2 | Saint Paul |
| Larpenteur | White Bear Ave | 4/4 | Saint Paul |
| Wabasha | Fillmore/Water | 4/3 | Saint Paul |
| Riverside | 21st | 2/2 | Minneapolis |

### 2.1.1.3 Cross-sectional Final Site Selection Candidates

In total, nineteen right-turn-only intersections were initially reviewed, and seven were extracted for final consideration. Seventeen pairs of sites were selected as right-turn through lane sites for comparison, with five extracted for final consideration. Furthermore, an accounting of pedestrian crashes between 2015 and 2021 were retrieved from Minnesota Department of Transportation, to determine if any pedestrian crashes occurred at the sites of interest, or within a few blocks of the intersection of interest.

The review of RTL-Only sites was then considered on relatively higher volume estimations for pedestrian traffic, the basis of number of lanes on the leg, as well as general proximity to a transit stop. Review of risk toward pedestrians for right-turning vehicles found that proximity to transit stops lead to higher risk (Craig et al., 2019). Furthermore, the research team wanted to avoid selecting sites that were within the same corridor for RTL sites (e.g., all Snelling or Marshall). The site of Cedar and Riverside was rejected because its right turn lane was detachable from the street (e.g., channelized). Because the majority of right-turn lane only sites had bike lanes (presumably bike lanes suggest pedestrians are more likely to be present), the research team selected Marshall and Cretin as a final option despite the above rule of avoiding multiple sites on the same corridor because Marshall and Cretin does not have a clearly marked bike lane right at the intersection where the right turn is being made (north leg), although there is a bike lane present at the mid-block. Furthermore, Marshall and Prior was added to the list of non-RTL sites, because of the presence of bike turn lanes, to account for whether bike turn lanes influence turning behaviors across RTL-Only and non-RTL-Only sites. Images of the sites are provided in Appendix C. The final list of candidates is provided in Table 2.5 and Table 2.6. The location of the sites is in Figure 2.2.

**Table 2.5 Final List of Dedicated Right-Turn Lane Sites**

| Street 1 | Street 2 | # Lanes | Leg | City | At Intersection Crash | Near Intersection Crash |
|---|---|---|---|---|---|---|
| Maryland | Payne | 3/2 | South Leg | Saint Paul | 2 Ped Crash (nonfatal); 2018; 2019 | 1 Ped Crash (fatal); 2016; Maryland & Greenbrier |
| Wabasha | Plato | 3/2 | West Leg | Saint Paul | 1 Ped Crash (nonfatal); 2018 | - |
| Marshall | Cretin | 2/4 | North Leg | Saint Paul | 3 Ped Crash (nonfatal); 2017; 2019; 2020 | 1 Ped Crash (nonfatal); 2017; Cretin & Dayton |
| Marshall | Snelling | 2/4 | West Leg | Saint Paul | 1 Ped Crash (nonfatal); 2019 | 1 Ped Crash (nonfatal); 2018; Snelling & Selby |

**Table 2.6 Final List of Right-Turn Through Lane Sites**

| Street 1 | Street 2 | # Lanes | City | Site Specific Notes | At Intersection Crash | Near Intersection Crash |
|---|---|---|---|---|---|---|
| Maryland | Forest | 3/2 | Saint Paul | - | 1 Ped Crash (nonfatal); 2019 | - |
| Larpenteur | White Bear Ave | 4/4 | Saint Paul | - | - | 1 Ped Crash (fatal); 2015; White Bear & Idaho;<br>2 Ped Crash (nonfatal); 2015; 2019; White Bear & Idaho; White Bear & Montana |
| Wabasha | Fillmore/ Water | 4/3 | Saint Paul | Northwest Leg Preferred, Fillmore turning to Wabasha | - | 4 Ped Crash (nonfatal); 2017 (2); 2019 (2); Wabasha & Kellogg Blvd; Fillmore & Roberts |
| Marshall | Prior | 2/2 | Saint Paul | West Leg Preferred | 1 Ped Crash (nonfatal); 2018 | - |

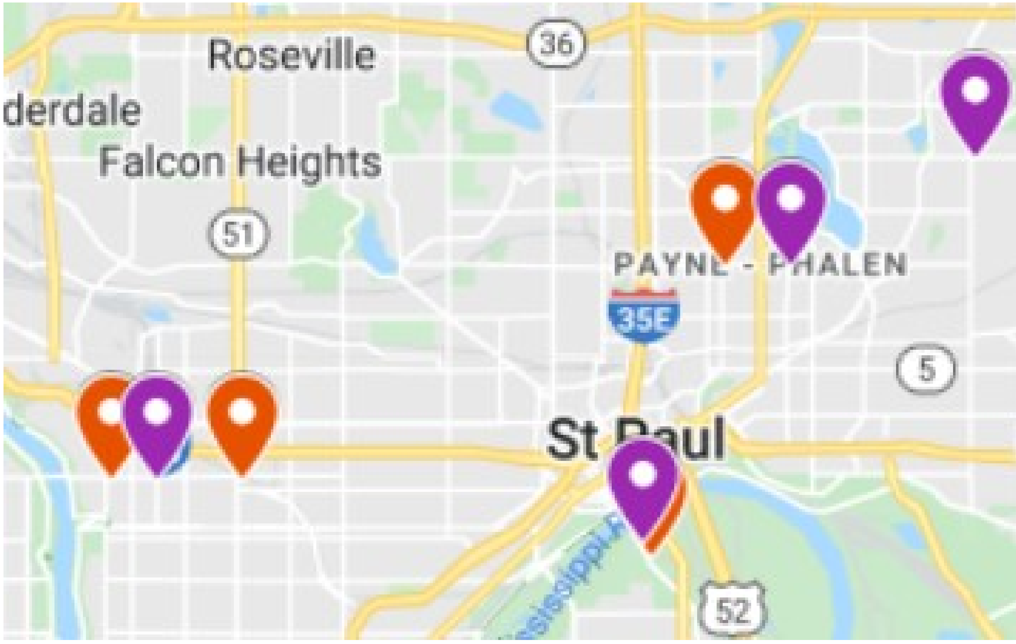


**Figure 2.2 Location of sites across Saint Paul, MN, USA. Dedicated right-turn only sites are in orange/red, and right-turn through sites are in violet/purple. (Google Maps image)**

### 2.1.2 Cross-sectional Camera Field Data Collection

The traffic data collection company Quality Counts LLC, specifically their Minnesota office, was contacted to provide a service to record camera footage from the sites. The data collection period was requested to be at least 14 days (2 weeks) for each site. Prior to data collection, Quality Counts contacted the research team at the Human Factors Safety Laboratory (HFSL) to confirm camera angles and locations for each site, which are provided in **Appendix E**. The HFSL team agreed to the indicated angles. For those sites pictured in **Appendix E** that had no angle specified for the camera, the team responded with the following:

**White Bear & Larpenteur:** "Any of the legs are good. I'm partial to the east and south legs because I think they'll get more turning traffic, but if there are technical camera placement issues that require focusing more on the other two legs, then they will work just fine."

**Maryland & Forest:** "I suspect the north and south legs will be the best for capturing turning traffic (Maryland turning to Forest). The other two legs (turning from Forest onto Maryland) have bike lanes, which make them less useful for our research question."

#### 2.1.2.1 Cross-sectional Camera Data Coding

Given that two weeks of camera data for 8 sites represent an estimated 2,688 hours of footage, it is not feasible to code all the data. Therefore, the research team selected a sampling of the video footage, specifically two-hour blocks from 7:00am to 9:00am, 11:00am to 1:00pm, and 4:00pm to 6:00pm. These times were chosen because they represented times of significant traffic volumes and pedestrian activity while still maintaining adequate visibility with environmental lighting for coding. One coder went through a subset of the video data for other times (e.g., 6:00pm to 12am) and verified that the selected time blocks represented a reasonable set of time windows for assessing vehicle and pedestrian interaction. The time of 7:00am to 9:00am was not coded on weekends, because this time block on weekends did not have enough traffic and pedestrian volume to be useful upon preliminary investigation of the data.

Video coding assessed two right turns, one per cycle on separate corners of an intersection, to measure direct and legal pedestrian conflicts, as the focus is on typical conflicts between right-turning vehicles and pedestrians who have the right of way on the walk cycle. The focus was on one right turn per cycle (e.g., green light / walk phase) to allow the coder to focus on one area of the video display, given that traffic can be busy and difficult to code during busy hours. Once a cycle ended (e.g., red light / flash don’t walk phase), coder attention alternated to the other turning option, and coding started on that cycle. If the turning lane was a dedicated right-turn only lane, this was coded afterwards in the dataset. Figure 2.3 presents an example of coding guidelines for Maryland and Payne, a dedicated right-turn only site, in which the coder would code any right turning vehicles following the orange path when the light to go straight on Maryland was green (circled in orange). Once the light changed to green on Payne (circled in purple) the coder directed attention to vehicles turning right following the path shown in purple.


**Figure 2.3 Video coding guidelines for Maryland and Payne, with alternating light/walk cycles. The turn from Maryland to Payne is a dedicated right-turn only lane, while the turn from Payne to Maryland is a right-through lane.**

The items that were coded for counting for each cycle include:

- Right turning vehicles (non-event)
- Right turning vehicles (high-speed)
- Right turning vehicles (wide turn)
- Right turning vehicles (high-speed + wide turn)

- Right turning vehicles (overtaking)
- Yield to Pedestrian (primary crosswalk)
- Yield to Pedestrian, Close Call (primary crosswalk)
- Not Yield to Pedestrian (primary crosswalk)
- Yield to Pedestrian (secondary crosswalk)
- Yield to Pedestrian, Close Call (secondary crosswalk)
- Not Yield to Pedestrian (secondary crosswalk)
- Pedestrian Crossing (primary crosswalk)
- Pedestrian Crossing (secondary crosswalk)
- Vehicle Goes Straight from Right Turn Only Lane (RTL Only)

Right turning non-events and pedestrians crossing were coded to provide an estimate for general vehicle and pedestrian volumes. The primary crosswalk was the first crosswalk a right-turning vehicle would cross, while the secondary crosswalk was the second crosswalk a right-turning vehicle would cross, see Figure 2.4. Overtaking right turns occurred when a vehicle turns from the far lane, passing a vehicle in the right-turn lane. Close call yields were when the vehicle hard brakes to stop at the last minute or otherwise endangers the pedestrian. Vehicles going straight from the right-turn lane was coded for when a vehicle in the right turn only lane goes straight.

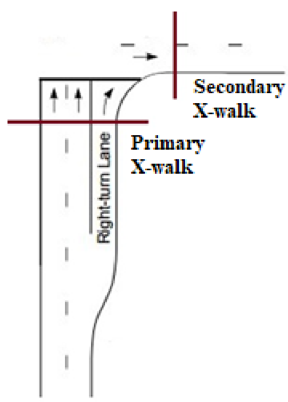


**Figure 2.4 Crosswalk specifications for right-turning vehicles. The horizontal line crossing the right-turn lane indicates the *primary* crosswalk. The vertical line that a vehicle would cross when turning right would be the *secondary* crosswalk.**

### 2.1.2.2 Cross-sectional Camera Data Collection Summary

The final analysis was conducted on 44,841 signal cycles, collapsed into two-hour time blocks, with alternating counts for each cycle/turn. After data cleaning, this was reduced to 584 two-hour blocks.

### 2.1.3 Cross-sectional Camera Data Descriptive Statistics

Averages are presented in the following descriptive statistics tables to provide an assessment of frequency that is not as biased by the degree of sampling. High speed and wide angle turns include those items coded as both high speed and wide angle at the same time (see Table 2.7).

**Table 2.7 Driver Behavior without Pedestrians Per Two Hours**

| Location | Direction | RT Vehicle *M (SD)* | High Speed *M (SD)* | Wide Angle *M (SD)* | Overtaking *M (SD)* |
|---|---|---|---|---|---|
| **Cretin & Marshall** | Cretin o Marshall | 206.7 (120.3) | .5 (1.6) | 128.0 (64.8) | 0 (0) |
| | Marshall to Cretin (*RTL*) | 47.9 (24.7) | .7 (1.2) | 62.1 (23.0) | .1 (.3) |
| **Forest & Maryland** | Forest to Maryland | 20.3 (13.1) | 1.5 (1.7) | 2.0 (1.9) | 0 (0) |
| | Maryland to Forest | 16.1 (9.2) | 1.0 (1.2) | 1.0 (1.1) | 0 (0) |
| **Payne & Maryland** | Maryland to Payne (*RTL*) | 104.7 (30.0) | .1 (.4) | .1 (.3) | .3 (.6) |
| | Payne to Maryland | 52.4 (16.4) | .1 (.4) | .1 (.3) | 0 (0) |
| **Plato & Wabasha** | Plato to Wabasha (*RTL*) | 33.5 (24.9) | .6 (.8) | 2.8 (3.8) | 0 (0) |
| | Wabasha to Plato (*RTL*) | 68.4 (33.8) | .8 (2.7) | 1.5 (6.2) | 0 (0) |
| **Prior & Marshall** | Prior to Marshall | 8.0 (5.3) | 0 (0) | 0.1 (0.3) | 0 (0) |
| | Marshall to Prior | 67.6 (22.0) | .5 (1.0) | 1.2 (1.4) | 0 (0) |
| **Snelling & Marshall** | Snelling to Marshall (*RTL*) | 164.2 (43.0) | 1.4 (1.4) | 1.9 (1.6) | .1 (.4) |
| | Marshall to Snelling (*RTL*) | 38.0 (17.4) | 1.0 (1.3) | 24.1 (14.3) | 0 (0) |
| **Water & Wabasha** | Water to Wabasha | 7.6 (4.3) | 0 (0) | 0 (0) | 0 (0) |
| | Wabasha to Water | 22.1 (7.7) | 0 (0) | 1.0 (1.1) | 0 (0) |
| **White Bear & Larpenteur** | White Bear to Larpenteur | 19.6 (10.5) | 1.0 (1.0) | 84.2(25.6) | .1 (.3) |
| | Larpenteur to White Bear | 9.0 (3.3) | .2 (0.6) | 14.7 (6.0) | 0 (0) |

*Note.* M stands for mean. SD stands for standard deviation.

Broadly speaking, the intersections of Cretin & Marshall, Marshall & Snelling, Payne & Maryland, and White Bear & Larpenteur were the busiest sites for turning vehicles, when considering right turns with no events and wide angle turns as a group. These are primarily sites with dedicated right-turn only lanes, suggesting that any inferential statistics need to account for vehicle volume. For vehicles that went straight from a dedicated right-turn only lane, this maneuver occurred at Marshall & Cretin 3.0 times ($SD$ = 2.4) on average every two hours, at Marshall turning to Snelling 0 times ($SD$ = 0), Snelling turning to Marshall 0.3 times ($SD$ = .7), at Maryland & Payne 1.9 times ($SD$ = 1.8), at Plato turning to Wabasha 0.1 times ($SD$ = 2.4), and at Wabasha turning to Plato .2 times ($SD$ = .5).

As Table 2.8 indicates, average number of pedestrians is higher for pedestrians at the secondary crosswalk, indicating that pedestrians are more likely to cross when the walk cycle is active. The exception to this relatively low rate of pedestrian crossing violations appears to be at crosswalks that have a relatively low rate of vehicle turning volumes (see Table 2.7), such as Prior turning to Marshall, and Water turning to Wabasha.

Table 2.8. Pedestrian Crossings (*No Conflict*) Per Two Hours

| Intersection | Direction | Primary Crosswalk *M (SD)* | Secondary Crosswalk *M (SD)* |
|---|---|---|---|
| **Cretin & Marshall** | Cretin to Marshall | .06 (.25) | 1.84 (1.53) |
| | Marshall to Cretin (*RTL*) | .10 (.40) | 5.58 (2.78) |
| **Forest & Maryland** | Forest to Maryland | .02 (.16) | .81 (1.89) |
| | Maryland to Forest | .20 (.60) | .63 (1.56) |
| **Payne & Maryland** | Maryland to Payne (*RTL*) | .09 (.28) | 2.00 (2.22) |
| | Payne to Maryland | .23 (.60) | 3.26 (2.47) |
| **Plato & Wabasha** | Plato to Wabasha (*RTL*) | .81 (1.14) | 3.26 (3.93) |
| | Wabasha to Plato (*RTL*) | .46 (.73) | 6.68 (5.23) |
| **Prior & Marshall** | Prior to Marshall | 0.95 (1.47) | 5.74 (4.51) |
| | Marshall to Prior | .90 (1.0) | 7.72 (5.48) |
| **Snelling & Marshall** | Snelling to Marshall (*RTL*) | .13 (.52) | 8.82 (4.21) |
| | Marshall to Snelling (*RTL*) | .21 (.47) | 4.84 (3.2) |
| **Water & Wabasha** | Water to Wabasha | 1.41 (1.66) | 3.05 (2.53) |
| | Wabasha to Water | .76 (.93) | 20.08 (9.29) |
| **White Bear & Larpenteur** | White Bear to Larpenteur | .55 (.79) | 2.12 (1.65) |
| | Larpenteur to White Bear | .30 (.53) | 3.85 (2.90) |

*Note.* M stands for mean. SD stands for standard deviation.

There is a relatively low rate of vehicle-pedestrian interactions at the primary crosswalk, as indicated in Table 2.9. This is likely due to the low rate of pedestrians crossing against the signal.

Table 2.9 Driver Behavior with Pedestrians on Primary Crosswalk Per Two Hours

| Intersection | Direction | Yield (Primary) *M (SD)* | Close Call (Primary) *M (SD)* | No Yield (Primary) *M (SD)* |
|---|---|---|---|---|
| **Cretin & Marshall** | Cretin to Marshall | 0 (0) | .03 (.18) | 0 (0) |
| | Marshall to Cretin (*RTL*) | 0 (0) | .10 (.40) | 0 (0) |
| **Forest & Maryland** | Forest to Maryland | .17 (1.09) | 0 (0) | 0 (0) |
| | Maryland to Forest | 0 (0) | .34 (1.39) | .02 (.15) |
| **Payne & Maryland** | Maryland to Payne (*RTL*) | .14 (.43) | 0 (0) | .09 (.51) |
| | Payne to Maryland | .06 (.24) | .03 (.17) | 0 (0) |
| **Plato & Wabasha** | Plato to Wabasha (*RTL*) | .03 (.16) | 0 (0) | .03 (.16) |
| | Wabasha to Plato (*RTL*) | 0 (0) | .03 (.16) | .11 (.51) |
| **Prior & Marshall** | Prior to Marshall | .10 (.31) | 0 (0) | 0 (0) |
| | Marshall to Prior | 0.03 (.16) | 0 (0) | 0.05 (.32) |
| **Snelling & Marshall** | Snelling to Marshall (*RTL*) | .05 (.23) | .08 (.49) | 0 (0) |
| | Marshall to Snelling (*RTL*) | .03 (.16) | 0 (0) | .10 (.38) |

| Intersection | Direction | Yield (Primary) *M (SD)* | Close Call (Primary) *M (SD)* | No Yield (Primary) *M (SD)* |
|---|---|---|---|---|
| **Water & Wabasha** | Water to Wabasha | .03 (.16) | 0 (0) | 0 (0) |
| | Wabasha to Water | 0 (0) | 0 (0) | 0 (0) |
| **White Bear & Larpenteur** | White Bear to Larpenteur | .03 (.17) | .03 (.17) | .27 (1.57) |
| | Larpenteur to White Bear | .03 (.17) | 0 (0) | .03 (.17) |

*Note.* M stands for mean. SD stands for standard deviation.

As Table 2.10 indicates relative to Table 2.9, there is a higher rate of vehicle-pedestrian interactions at the secondary crosswalk compared to the primary crosswalk. This can be primarily attributed to the higher pedestrian volumes at the secondary crosswalk during the walk cycle.

**Table 2.10 Driver Behavior with Pedestrians on Secondary Crosswalk Per Two Hours**

| Intersection | Direction | Yield (Secondary) *M (SD)* | Close Call (Secondary) *M (SD)* | No Yield (Secondary) *M (SD)* |
|---|---|---|---|---|
| **Cretin & Marshall** | Cretin to Marshall | 3.16 (2.40) | .06 (.25) | .77 (.96) |
| | Marshall to Cretin (*RTL*) | 1.77 (1.93) | .10 (.30) | .71 (1.01) |
| **Forest & Maryland** | Forest to Maryland | .14 (.417) | .02 (.154) | 0 (0) |
| | Maryland to Forest | .07 (.26) | 0 (0) | 0 (0) |
| **Payne & Maryland** | Maryland to Payne (*RTL*) | .46 (.70) | .06 (.24) | .14 (.43) |
| | Payne to Maryland | .63 (.94) | .09 (.37) | .20 (.58) |
| **Plato & Wabasha** | Plato to Wabasha (*RTL*) | .61 (.78) | .06 (.24) | .06 (.24) |
| | Wabasha to Plato (*RTL*) | .97 (1.15) | .03 (.16) | .21 (.47) |
| **Prior & Marshall** | Prior to Marshall | .59 (.85) | .05 (.22) | 0 (0) |
| | Marshall to Prior | .64 (.84) | .05 (.22) | .05 (.22) |
| **Snelling & Marshall** | Snelling to Marshall (*RTL*) | 3.71 (3.01) | .13 (.41) | .82 (1.14) |
| | Marshall to Snelling (*RTL*) | 1.66 (1.62) | .05 (.32) | .40 (.72) |
| **Water & Wabasha** | Water to Wabasha | .08 (.28) | 0 (0) | 0 (0) |
| | Wabasha to Water | .40 (.76) | 0 (0) | .14 (.35) |
| **White Bear & Larpenteur** | White Bear to Larpenteur | .67 (.89) | .03 (.17) | .15 (.44) |
| | Larpenteur to White Bear | .55 (.75) | 0 (0) | .30 (.59) |

*Note.* M stands for mean. SD stands for standard deviation.

### 2.1.4 Cross-sectional Camera Data Inferential Statistics

The following analyses on the rest of the field data use the following organization for the independent measure: *Site characteristics*, and *lane characteristics*. The site characteristics distinguish between sites that have only right-through lanes present, sites that have one or two dedicated right-turn lanes present, and sites that have three or more dedicated right-turn lanes present. The lane characteristics are specifically whether the lane in question is a right-through turn lane or a dedicated right-turn lane. The distinction between sites and lanes in the measurements are made to capture effects of traffic volume, density, and complexity that are not adequately captured by other measures of volume (e.g., turning vehicle count), given that we anticipate sites at which engineers install dedicated right-turn lanes will have greater traffic density, complexity, and volume than those sites without this lane type present. There are four general categories analyzed here for each measure, differing in lane and site characteristics:

- Right-through Lane at a site with only right-through lanes.
- Right-through Lane at a site with 1 or 2 dedicated right-turn lanes present.
- Dedicated right-turn lane at a site with 1 or 2 dedicated right-turn lanes present.
- Dedicated right-turn lane at a site with 3 dedicated right-turn lanes present.

In the following analyses, we establish the right-through lane at a site with only right-through lanes as the reference or standard category, to which the other categories are compared.

Unless otherwise stated, the reported analyses rely on generalized estimating equations (GEEs), which allow for assessment of variance in the data that is due to the participant/subject, possible because participants performed twice or more on most of the measures reported here. Furthermore, analysis can adjust for different distribution types (e.g., negative binomial) than those assessed in ANOVAs, when needed. For each GEE analysis, we will report: The dependent variable, the probability distribution used, the link function, goodness of fit measure (QIC), subject effects, model effect test (via Wald Chi-Square, df, and p-value), and finally the estimated marginal means of the primary factors of interest (e.g., Right-turn lane type) for the measured dependent variable. All analyses use right-turn lane and site type as the primary factor (independent variable) of interest, with any exceptions noted.

### 2.1.5 Cross-sectional Field Data Inferential Statistics Summary

The summary of the results from the analyses are presented in the following Table 2.11, Table 2.12, Table 2.13, and Table 2.14.

**Table 2.11 Summary of Field Study 1 Results for Camera Data**

| Camera Data Variable | Crosswalk | Description of Results |
|---|---|---|
| High Turning Speeds | N/A | Coders indicated higher turning speeds observed at dedicated right-turn lanes at sites with 3 dedicated right-turn lanes present, compared to the other lane/site combinations |
| Wide Turns | N/A | Coders observed a lower rate of wide turns at dedicated right-turn lanes compared to right-through lanes, irrespective of site type |
| Pedestrian/Vehicle Conflicts | Primary | A higher rate of conflicts was observed for sites with 1 or 2 dedicated right-turn lanes present |
| | Secondary | There was no association between right-turn lane type or site and conflicts at the secondary crosswalk |
| Not Yield Ratios | Primary | There was no association between right-turn lane type or site and not yielding at the secondary crosswalk |
| | Secondary | The worst yielding rates were observed at right-through lanes at sites with 1 to 2 dedicated right-turn lanes on other corners |

**Table 2.12 Summary of Field 1 Results for In-Person Data**

| In-Person Data Variable | Factor of Interest | Description of Results |
|---|---|---|
| Not Looking | Number of Dedicated Right-Turn Lanes | Higher rate of not looking at the pedestrian when there was one dedicated right turn lane present, compared to zero or multiple dedicated right-turn lanes |

**Table 2.13 Field cross-sectional camera data analysis statistical models**

| Observation | Model Details | Model Fit with QIC | Variables | Wald $\chi^2$ |
|---|---|---|---|---|
| High Turning Speeds (natural log transformed) | Normal distribution, Identity Link | 126.66 | Site (subject), RTL Site/Lane, Time Block, Estimated ADT, RT Vehicle Count, Lane Count, Pedestrian Crossing Count | $\chi^2$ = 24.243, df = 3, $p$ < .001. |
| Wide Turns | Normal distribution, Identity Link | 428.43 | Site (subject), RTL Site/Lane, Time Block, Estimated ADT, RT Vehicle Count, Lane Count, Pedestrian Crossing Count | $\chi^2$ = 6.6.63, df = 3, $p$ < .085. |

| Observation | Model Details | Model Fit with QIC | Variables | Wald $\chi^2$ |
|---|---|---|---|---|
| Primary Crosswalk Pedestrian/Vehicle Conflicts | Binomial distribution, Probit link (Offset: Total Count of Primary Pedestrian Crossings) | 252.66 | Site (subject), RTL Site/Lane, Time Block, Estimated ADT, RT Vehicle Count, Lane Count, Pedestrian Crossing Count | $\chi^2 = 35.151$, df = 3, $p < .001$. |
| Secondary Crosswalk Pedestrian/Vehicle Conflicts | Binomial distribution, Logit link (Offset: Total Count of Secondary Pedestrian Crossings) | 443.195 | Site (subject), RTL Site/Lane, Time Block, Estimated ADT, RT Vehicle Count, Lane Count, Pedestrian Crossing Count | $\chi^2 = 4.398$, df = 3, $p = .222$. |
| Primary Crosswalk Not Yield Ratios | Normal distribution, Identity Link | 15.03 | Site (subject), RTL Site/Lane, Time Block, Estimated ADT, RT Vehicle Count, Lane Count, Pedestrian Crossing Count | $\chi^2 = 2.297$, df = 3, $p = .513$. |
| Secondary Crosswalk Not Yield Ratios | Normal distribution, Identity Link | 25.06 | Site (subject), RTL Site/Lane, Time Block, Estimated ADT, RT Vehicle Count, Lane Count, Pedestrian Crossing Count | $\chi^2 = 464.616$, df = 3, $p < .001$. |

**Table 2.14 Field cross-sectional camera data estimated marginal means (emm)**

| Estimated marginal means | Right-Through Lane at Intersection with Right-Through Lanes | Right-Through Lane at Site with 1 or 2 Dedicated Right-Turn Lanes Nearby | Dedicated Right-Turn Lane at Intersection with 1 or 2 Dedicated Right-Turn Lanes | Dedicated Right-Turn Lane at Intersection with 3 Dedicated Right-Turn Lanes |
|---|---|---|---|---|
| High Turning Speeds (natural log transformed) | 0.017 (*SE* = .103) | -0.012 (*SE* = .096) | 0.005 (*SE* = .103) | 0.027 (*SE* = .102) |
| Wide Turns (natural log transformed) | .237 (*SE* = 491.98) | .272 (*SE* = 491.98) | .0907 (*SE* = 492.05) | -.064 (*SE* = 491.97) |
| Primary Crosswalk Pedestrian/Vehicle Conflicts | 0.0 (*SE* = .011) | 0.01 (*SE* = .102) | 0.05 (*SE* = .337) | 0.0 (*SE* = .013) |
| Secondary Crosswalk Pedestrian/Vehicle Conflicts | 0.0 (*SE* = .045) | 0.0 (*SE* = .025) | 0.0 (*SE* = .075) | 0.0 (*SE* = .047) |
| Secondary Crosswalk Not Yield Ratios | .20 (*SE* = .047) | .44 (*SE* = 1.24) | .237 (*SE* = 1.25) | -.011 (*SE* = 1.23) |

*Note*. SE stands for Standard Error.

The High-Turning Speed ratio variable is a ratio of high-speed turns to total right turn counts. This ratio was natural log transformed (with a constant of 1 added to account for zero values) to better fit a normal distribution. The values for the marginal means are not directly interpretable due to it being a natural log transformation. However, given the pattern of results, indications are that there's a statistically significant higher rate of high-speed turns at dedicated right-turn lanes with 3 dedicated right-turn lanes present at the site, compared to the other lane/site combinations.

A similar, marginal effect occurred for the wide-turns ratio variable, also natural log transformed. The indication is that there were more wide tuns at the right-turn through lanes across all sites. The calculated estimated marginal means must be considered with some skepticism, given the large standard errors provided by the analysis.

There appeared to be a higher likelihood of a pedestrian and right-turning vehicle conflict at the primary crosswalk, when the pedestrian does not have the right-of-way, at both lane types at the sites with 1 or 2 dedicated right-turn lanes present, compared to right-through lanes at a site that only has right-through lanes. There was a negative relationship between pedestrian crossing count with no conflicts at the site and the presence of a pedestrian and right-turning vehicle conflict at the primary crosswalk.

There appeared to be no effect of lane and site type on the presence of right-turn conflicts between turning drivers and pedestrians at the secondary crosswalk, when accounting for other factors, primarily turning vehicle counts and crossing pedestrian counts, as well as time of day.

The not-yield ratio variable is the ratio of the count of not yields at the crosswalk as the numerator, and total vehicle/pedestrian conflicts at the crosswalk on the denominator. No apparent effect of any of the variables were observed for this ratio at the primary crosswalk.

The analysis of the not-yield ratio variable for secondary crosswalks found that best yielding rate given the overall base rate of crossings was observed at dedicated right-turn lanes at dedicate right-turn (3 present) sites, and the worst yielding rates were seen at right-through lanes at dedicated right-turn (1-2 present) sites. The yielding rates at right-through lanes at right-through sites and dedicated right-turn lanes at dedicated right-turn (1-2 present) sites were statistically equivalent. For the other variables, more lanes in the direction of travel were associated with a higher ratio of not yields to conflicts at the secondary crosswalk. Time block was significant, in that there was a higher not yield ratio in the noon and afternoon blocks, compared to the morning block. The higher the estimated ADT, the lower the not yield ratio, whereas the higher the number of crossing pedestrians (count) the higher the not yield ratio. This analysis did not assess whether pedestrians crossed in packs.

### 2.1.6 In-Person Field Data Collection

To avoid overlapping with the data collected by the cameras, the in-person data collection focused primarily on whether approaching drivers that move into the right lane overtly look for any pedestrians as they anticipate making a turn. This driver behavior of looking is not effectively captured by the cameras given their angle of view and resolution, making the in-person study a reasonable complement to the camera work. Right-turning drivers must attend to other items of importance in the roadway (e.g., the vehicle in front of them, other vehicles that could unexpectedly merge into the turning lane, vehicles coming from the left or from a left turn in the opposite direction, or the radius of the turn, which is needed to smoothly perform the turning maneuver). Because of this competition for driver attention, there is limited attentional capacity to allocate toward the sidewalk or curb for a pedestrian, which is critical because observing a pedestrian allows the driver to anticipate any braking or stopping needed in case the pedestrian steps out into the secondary crosswalk once the driver initiates a turn. Without such anticipation, the driver will either not notice a pedestrian or notice in the last second, relying on rapid reaction time to avoid a pedestrian crash.

#### 2.1.6.1 Procedure

For each site, the coder would stand at the corner of intersection of interest, selecting a leg indicated in Table 2.5 and Table 2.6 and treating that leg as the secondary crosswalk to watch for vehicles right-turning onto said crosswalk. By standing near the corner, the coder is effectively acting as a staged potential pedestrian, for whom turning drivers should take note. The coder waited for ten full cycles of green and red signals, only coding turning vehicles on the red signal when they were not stopped by traffic in front of the vehicle. This is because drivers of waiting vehicles at a red light have sufficient opportunity to glance over and see the staged pedestrian (the coder) and this is difficult for a coder to catch over time, especially when multiple waiting vehicles are present. Otherwise, drivers of all turning vehicles were observed by the coder as they approached the intersection to turn right, and the coder marked whether the driver overtly looked over at them or other pedestrians at the crosswalk. If the coder was unable to determine (e.g., due to sunglasses or heavily tinted windows), the coder would mark the "Unsure" column, so that traffic volume is accounted for in the final analysis. If a natural pedestrian (i.e., not affiliated with the study) happened to be present on the crosswalk, the coder would mark whether the driver yielded. For turning or yielding vehicles, the coder could also mark "U" instead of a normal tally mark to indicate unsafe turning or yielding behavior (e.g., high speed turn, close yield, or hard brake, etc.). Finally, aggressive turning violations such as overtaking or turning from the wrong lane were noted in the far column. Please see **Appendix D** for a blank copy of the coding sheet used for in-person data collection.

#### 2.1.6.2 In-Person Data Collection Summary

Given the late spring weather, in-person data collection began on May 4th, 2022, and ended on June 22nd, 2022. The sites were intended to be measured at least once a week and optimally twice in a week, although sometimes this was not feasible due to weather conditions and staff availability. Coders were encouraged to visit sites during times of the day when there was busy traffic (e.g., lunch hour or afternoon rush hour) if possible. There was a total of 61 site visits over this period. The behavior of approximately 1074 turning vehicles was coded.

### 2.1.7 In-Person Data Descriptive Statistics

The average looking counts reported in Table 2.15 are generally consistent with the reported turning volumes in the camera data except for Marshall and Cretin. This may be due to different assessment periods during the day or the sampling nature of visiting for 10 cycles or approximately 20 minutes, instead of two-hour blocks.

**Table 2.15 Looking Behavior with Turning Drivers**

| | No Look | Look | Unsure |
|---|---|---|---|
| | *M (SD)* | *M (SD)* | *M (SD)* |
| **Cretin & Marshall** | 1.08 (1.00) | .74 (.90) | .69 (1.01) |
| **Forest & Maryland** | .19 (.32) | .11 (.32) | .10 (.30) |
| **Payne & Maryland** | .46 (.61) | .27 (.54) | .21 (.51) |
| **Plato & Wabasha** | .73 (.89) | .39 (.61) | .19 (.45) |
| **Prior & Marshall** | .23 (.54) | .30 (.55) | .11 (.36) |
| **Snelling & Marshall** | 2.71 (1.91) | 1.94 (1.60) | .69 (.79) |
| **Water & Wabasha** | .20 (.43) | .06 (.29) | .06 (.24) |
| **White Bear & Larpenteur** | 1.17 (1.44) | .79 (1.13) | .36 (.70) |

*Note.* M stands for mean. SD stands for standard deviation. The average is on a per cycle basis.

The yielding data in Table 2.16 indicates a very low rate of pedestrian-vehicle interactions during these visits, consistent with the low frequencies reported in the camera data. When pedestrian-vehicle interactions occurred, they were primarily observed to be yields. Due to the low rate and fewer samples available via the in-person data, further analyses do not consider yielding data and focus exclusively on looking behavior.

**Table 2.16 Yielding Behavior with Turning Drivers during In-Person Data Collection**

| Intersection | No Yield *M (SD)* | Yield *M (SD)* | Car Count *M (SD)* |
|---|---|---|---|
| **Cretin & Marshall** | 0 (0) | .04 (.19) | 2.56 (1.85) |
| **Forest & Maryland** | 0 (0) | .04 (.27) | .44 (.75) |
| **Payne & Maryland** | .01 (.12) | .01 (.12) | 1.01 (1.00) |
| **Plato & Wabasha** | 0 (0) | .04 (.19) | 1.38 (1.17) |
| **Prior & Marshall** | 0 (0) | .01 (.12) | .67 (.86) |
| **Snelling & Marshall** | .04 (.25) | .04 (.25) | 5.43 (2.8) |
| **Water & Wabasha** | .01 (.11) | .02 (.16) | .36 (.16) |
| **White Bear & Larpenteur** | .01 (.12) | .06 (.23) | 2.39 (2.34) |

*Note.* SD stands for standard deviation. The average is on a per cycle basis.

*Note.* For the **inferential statistics** following this section, we do not analyze the data on a per cycle basis, because preliminary analyses found that model fit was particularly poor when analyzing on a per cycle basis. Instead, the **data was aggregated on a site visit basis, with counts added up across each data collection session**. The prior presentation of the per cycle data in Table 2.16 is provided for descriptive purposes.

## 2.1.8 In-Person Data Inferential Statistics

### 2.1.8.1 Looking Data

#### NOT LOOKING WHEN CONSIDERING NUMBER OF DEDICATED RIGHT-TURN LANES

The statistical model is presented in Table 2.17, and the estimated marginal means of the ratio of not looking is presented in Table 2.18.

**Table 2.17 Field cross-sectional in-person data analysis statistical model for not-looking ratio**

| Model Components | Description | Wald $\chi^2$ (df) | *p*-value |
|---|---|---|---|
| Measure | Ratio of not looking counts | -- | -- |
| Model Details | Normal distribution, identity link | -- | -- |
| Model Fit (QIC) | 6.619 | -- | -- |
| Variables | Site (subject), Dedicated RTL Count, Car Count, Number of lanes, Pedestrian Average from Camera Data | -- | -- |
| Key Variable | Dedicated RTL Count | 15.572 (3) | .001 |

*Note.* df is degrees of freedom.

**Table 2.18 Field cross-sectional in-person data estimated marginal means (emm)**

| Zero Dedicated Right-Turn Lanes | One Dedicated Right-Turn Lane | Two Dedicated Right-Turn Lanes | Three Dedicated Right-Turn Lanes |
|---|---|---|---|
| .625 (*SE* = .233) | .650 (*SE* = .259) | .625 (*SE* = .269) | .629 (*SE* = .255) |

Note. SE stands for Standard Error.

This variable was the ratio of not looking counts over the total looking and not looking counts. Unsure looking counts were included in the car count variable. There was a significant effect of car count, with a higher number of cars being associated with a slightly lower rate of not looking, and a significant effect of lanes, with more lanes being associated with a higher rate of not looking.  There was also an effect of dedicated right turn lane count, which indicates that there was a slightly higher rate of not looking at the pedestrian when there was one dedicated right turn lane present, compared to when there were no dedicated right-turn lanes present or multiple dedicated right-turn lanes present.

## 2.2 Field Study 2 – Longitudinal Field Case Study

### 2.2.1 Data Collection Review

In 2024, dedicated right-turn lanes were installed on Larpenteur for the intersection of White Bear & Larpenteur in Saint Paul and Maplewood, Minnesota. The research team contacted the data collection vendor, Quality Counts LLC to collect video footage at White Bear Ave & Larpenteur Ave E for two weeks in mid-Spring of 2025.

Cameras were installed on April 8th, 2025, at similar viewing angles as the previous field data collection periods for this site. See Figure 2.5 for a diagram of the placement and angle of the camera on site. Cameras remained on site, recording data for two weeks, whereupon the camera was removed on April 22nd, 2025. The files were then transferred off the camera and provided to the UMN Human Factors Safety Laboratory research team on April 25th, 2025.

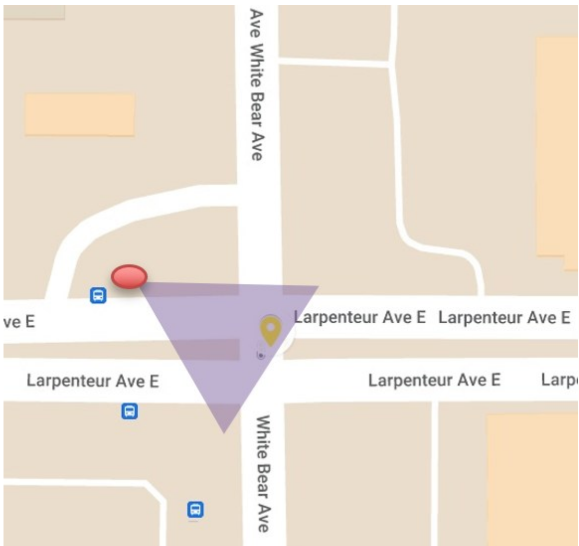


**Figure 2.5 Approximate camera placement at White Bear Ave & Larpenteur Ave E marked by a red dot, and a viewing angle indicate by a purple triangle**

An example of the video taken during the original field data collection (2022) at the site is provided in Figure 2.6. An example of the video taken during the second pre-installation task (2023) is provided in Figure 2.7. An example of the video taken during the current post-installation task (2025) is provided in Figure 2.8.


**Figure 2.6 Video still shot of White Bear Ave & Larpenteur Ave E in May 2022**


**Figure 2.7 Video still shot of White Bear Ave & Larpenteur Ave E in October 2023**


**Figure 2.8 Video still shot of White Bear Ave & Larpenteur Ave E in April 2025**

*Issue*. Crosswalk markings were removed from the south leg of the intersection post-installation, which includes a major “legal” conflict point between pedestrians and a driver turning right on the right turn lanes (see Figure 2.7 and Figure 2.8). Drivers may be less likely to be concerned about pedestrians crossing at this location, and this could change their behavior relative to when markings were present (e.g., turning speeds).

*Resolution*. By July 1st, 2025, the continental crosswalk markings were installed on the south leg. The research team installed their own cameras at this location on July 9th, 2025, at no cost to the project and captured a week of extra video footage at a similar angle. This week of video footage was the best source of comparative data in the following analyses.

This analysis examines the week of video data from July 9th, 2025, to July 16th, 2025. A screenshot of this footage is presented in Figure 2.9.


**Figure 2.9 Video still shot of White Bear Ave & Larpenteur Ave E in July 2025**

### 2.2.2 Video Scoring

The research team scored the week of July 2025, comprising two-hour blocks from 7:00am to 9:00am, 11:00am to 1:00pm, and 4:00pm to 6:00pm. These times were chosen because those were times of significant traffic volumes and pedestrian activity with adequate visibility with environmental lighting for coding. The time of 7:00am to 9:00am was not coded on weekends, because this time block on weekends did not have enough traffic and pedestrian volume to be useful upon preliminary investigation of the data.

Video coding assessed two right turns, one per cycle on separate corners of an intersection, to measure direct and legal pedestrian conflicts, as the focus is on typical conflicts between right-turning vehicles and pedestrians who have the right of way on the walk cycle. The focus was on one right turn per cycle (e.g., green light/walk phase) to allow the coder to focus on one area of the video display, given that traffic can be busy and difficult to code during busy hours. Once a cycle ended (e.g., red light/flash don't walk phase), coder's attention alternated to the other turning option, and coding started on that cycle. Figure 2.10 Video coding guidelines for White Bear & Larpenteur, with alternating light/walk cycles. This is for scoring the south and west sides of the intersection presents an example of coding guidelines for White Bear & Larpenteur, in which the coder would code any right-turning vehicles following the orange path when the light to go straight on White Bear was green (circled in orange). Once the light changed to green on Larpenteur (circled in purple) the coder directed attention to vehicles turning right following the path shown in purple.


**Figure 2.10 Video coding guidelines for White Bear & Larpenteur, with alternating light/walk cycles. This is for scoring the south and west sides of the intersection.**

The items that were coded for counting for each cycle include:

- Right turning vehicles (non-event)
- Right turning vehicles (high-speed)
- Right turning vehicles (wide turn)
- Right turning vehicles (high-speed + wide turn)
- Right turning vehicles (overtaking)
- Yield to Pedestrian (primary crosswalk)
- Not Yield to Pedestrian (primary crosswalk)
- Yield to Pedestrian (secondary crosswalk)
- Not Yield to Pedestrian (secondary crosswalk)
- Pedestrian Crossing (primary crosswalk)
- Pedestrian Crossing (secondary crosswalk)

Right-turning non-events and pedestrian crossings were coded to estimate vehicle and pedestrian volumes. The primary crosswalk was the first crosswalk a right-turning vehicle would cross, while the secondary crosswalk was the second crosswalk a right-turning vehicle would cross, see Figure 2.11. Overtaking right turns occur when a vehicle turns from the far lane, passing a vehicle in the right-turn lane, passing a vehicle in the right-turn lane.

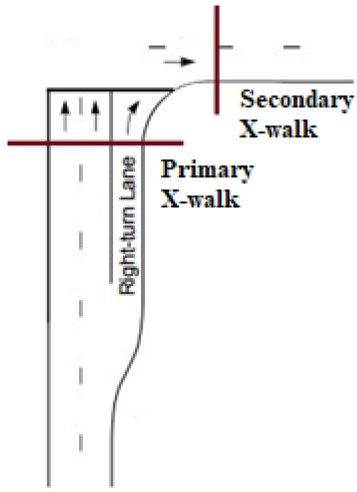


**Figure 2.11 Crosswalk specifications for right-turning vehicles. The horizontal line crossing the right-turn lane indicates the primary crosswalk. The vertical line that a vehicle would cross when turning right would be the secondary crosswalk.**

This analysis was conducted on two-hour time blocks. This analysis examines both sides of the intersection of White Bear & Larpenteur (see Figure 2.12). The east and west legs of the intersection (top and bottom of Figure 2.12 respectively) both have newly installed dedicated right-turn lanes, whereas the north and south legs of the intersection (left and right of Figure 2.12 respectively) have right-through lanes. Those scoring the video would focus on one side (color) for a given scoring session. For each side, there is a dedicated right-turn lane and a right-through lane. Both July 2025 and October 2023 assessment periods examined both sides of the intersection, while the May 2022 assessment period only scored the RED side (Figure 2.12).

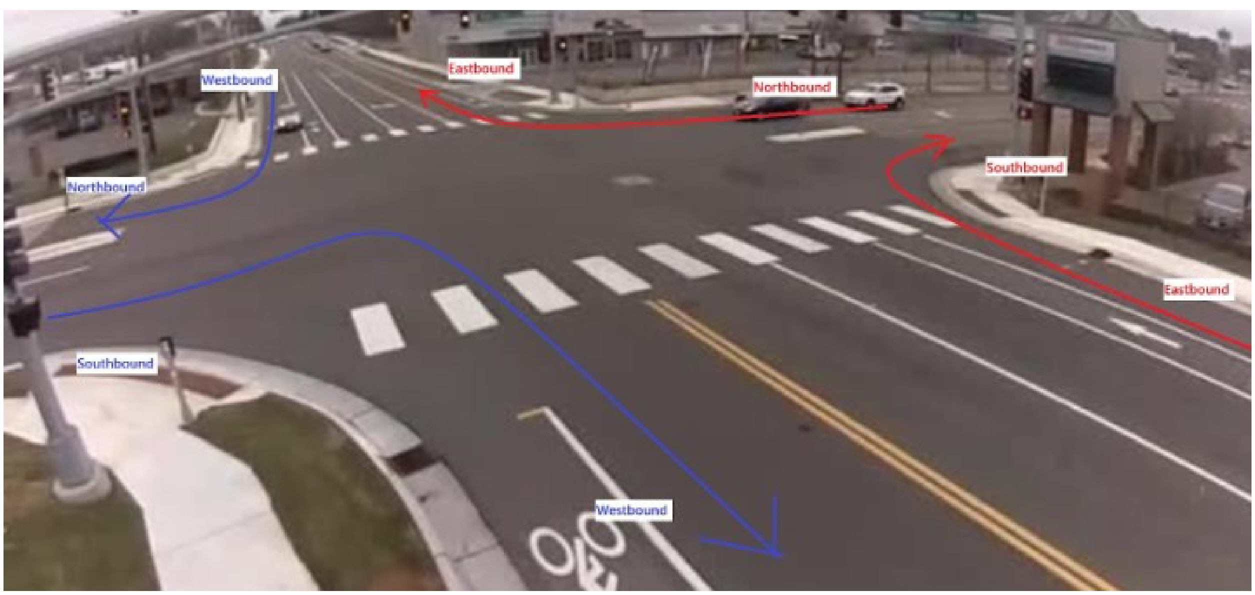


**Figure 2.12 Overlay of video scoring for both sides of the intersection (red and blue) of White Bear & Larpenteur, using an example screenshot from April 2025**

## 2.2.3 Analysis

### 2.2.3.1 Camera Data Descriptive Statistics

Averages are presented in the following descriptive statistics tables to provide an assessment of frequency that isn't as biased by the degree of sampling. The averages do not account for other factors, such as differences in sampling across the week, or seasonal differences (e.g., Spring vs. Autumn).

For Table 2.19, there appears to be a difference in the number of right-turning vehicles in 2023 and 2025 compared to 2022, perhaps reflecting both seasonal differences and changes in work-from-home rates. There also appears to be significant changes in vehicles scored as performing wide angle turns, which may be partially due to changes in lane striping, with lanes on Larpenteur converted to bicycle lanes, making wide angle turns less of a concern. See Figure 2.13. Vehicles were noted as turning wide if their wheels went over the white lane line in the left image of Figure 2.13, whereas the vehicle wheels would need to cross over the double yellow stripes to count as a wide angle turn in the right image of Figure 2.13.

**Table 2.19 Driver behavior without pedestrians per two hours**

| Side | Date | Intersection | RT Vehicle *M (SD)* | Speed + Wide Angle *M (SD)* | Speed *M (SD)* | Wide Angle *M (SD)* | Overtaking *M (SD)* |
|---|---|---|---|---|---|---|---|
| **Red** | **May 2022** | White Bear to Larpenteur | 20.0 (10.5) | .8 (.8) | .2 (.6) | 83.4 (25.6) | .1 (.4) |
| | | Larpenteur to White Bear | 9.0 (3.3) | .2 (.4) | .1 (.3) | 14.6 (6.0) | 0 (0) |
| | **October 2023** | White Bear to Larpenteur | 60.1 (37.1) | 2.8 (3.6) | 1.5 (3.0) | 39.4 (31.3) | 0 (0) |
| | | Larpenteur to White Bear | 12.7 (8.1) | 1.2 (1.3) | .5 (.9) | 5.5 (5.2) | 0 (0) |
| | **July 2025** | White Bear to Larpenteur | 69.1 (27.4) | 1.9 (2.0) | 4.0 (3.4) | 14.9 (7.9) | 0 (0) |
| | | Larpenteur to White Bear | 8.9 (5.0) | 1.2 (1.1) | 1.5 (1.8) | 2.4 (1.7) | .8 (1.0) |
| **Blue** | **October 2023** | White Bear to Larpenteur | 68.6 (35.4) | 3.7 (6.1) | 2.0 (3.3) | 52.4 (44.9) | 0 (0) |
| | | Larpenteur to White Bear | 59.0 (28.6) | 1.1 (1.7) | 2.5 (5.1) | 20.1 (24.0) | 0 (0) |
| | **July 2025** | White Bear to Larpenteur | 128.8 (41.5) | 5.8 (16.9) | 4.2 (3.7) | 4.7 (3.5) | 0 (0) |
| | | Larpenteur to White Bear | 44.4 (16.8) | 2.2 (5.4) | 1.4 (1.7) | 1.1 (1.9) | 0 (0) |

*Note. M* stands for mean. *SD* stands for standard deviation. **Bold** font means dedicated right-turn lane**.**

**Figure 2.13 Image of Larpenteur from 2023 (left) and 2025 (right) with the car lane converted into a bicycle lane at the bottom of the image**

Considering Table 2.20, the number of crossing pedestrians seemed relatively similar between 2022 and 2023, but the number of crossing pedestrians appeared to be increased on the south and west sides of the intersection in 2025.

**Table 2.20 Pedestrian crossings (no conflict) per two hours**

| Side | Date | Intersection | Primary Crosswalk *M* (*SD*) | Secondary Crosswalk *M* (*SD*) |
|---|---|---|---|---|
| **Red** | **May 2022** | White Bear to Larpenteur | .55 (.79) | 2.12 (1.65) |
| | | Larpenteur to White Bear | .30 (.53) | 3.85 (2.90) |
| | **October 2023** | White Bear to Larpenteur | .51 (.60) | 3.26 (2.76) |
| | | Larpenteur to White Bear | .36 (.49) | 3.56 (2.69) |
| | **July 2025** | White Bear to Larpenteur | .52 (.81) | 4.29 (2.39) |
| | | *Larpenteur to White Bear | .29 (.56) | 5.57 (2.93) |
| **Blue** | **October 2023** | White Bear to Larpenteur | .18 (.45) | 1.80 (1.44) |
| | | Larpenteur to White Bear | .68 (1.02) | 1.83 (1.88) |
| | **July 2025** | White Bear to Larpenteur | .10 (.31) | 2.25 (2.99) |
| | | *Larpenteur to White Bear | .85 (1.04) | 1.05 (1.40) |

*Note. M* stands for mean. *SD* stands for standard deviation. *indicates dedicated right-turn lane.

There is a relatively low rate of vehicle-pedestrian interactions at the primary crosswalk, as indicated in Table 2.21. This is likely due to the low rate of pedestrians crossing against the signal.

**Table 2.21 Driver behavior with pedestrians on primary crosswalk per two hours**

| Side | Date | Intersection | Yield *M (SD)* | No Yield *M (SD)* |
|---|---|---|---|---|
| **Red** | **May 2022** | White Bear to Larpenteur | .06 (.24) | .27 (1.57) |
| | | Larpenteur to White Bear | .03 (.17) | .03 (.17) |
| | **October 2023** | White Bear to Larpenteur | 0 (0) | .23 (1.01) |
| | | Larpenteur to White Bear | 0 (0) | 0 (0) |
| | **July 2025** | White Bear to Larpenteur | .05 (.22) | 0 (0) |
| | | *Larpenteur to White Bear | .05 (.22) | 0 (0) |
| **Blue** | **October 2023** | White Bear to Larpenteur | .03 (.16) | .03 (.16) |
| | | Larpenteur to White Bear | .10 (.30) | .33 (1.44) |
| | **July 2025** | White Bear to Larpenteur | 0 (0) | 0 (0) |
| | | *Larpenteur to White Bear | .15 (.37) | 0 (0) |

*Note. M* stands for mean. *SD* stands for standard deviation. *indicates dedicated right-turn lane.

**Table 2.22 Driver behavior with pedestrians on secondary crosswalk per two hours**

| Side | Date | Intersection | Yield *M (SD)* | No Yield *M (SD)* |
|---|---|---|---|---|
| **Red** | **May 2022** | White Bear to Larpenteur | .70 (.88) | .15 (.44) |
| | | Larpenteur to White Bear | .55 (.75) | .30 (.59) |
| | **October 2023** | White Bear to Larpenteur | .72 (1.3) | .15 (.37) |
| | | Larpenteur to White Bear | .31 (.69) | .18 (.45) |
| | **July 2025** | White Bear to Larpenteur | .81 (1.08) | .24 (.44) |
| | | *Larpenteur to White Bear | .71 (1.06) | .29 (.46) |
| **Blue** | **October 2023** | White Bear to Larpenteur | .23 (.53) | .05 (.32) |
| | | Larpenteur to White Bear | .88 (1.22) | .28 (.55) |
| | **July 2025** | White Bear to Larpenteur | .35 (.59) | 0 (0) |
| | | *Larpenteur to White Bear | .25 (.55) | .05 (.22) |

*Note. M* stands for mean. *SD* stands for standard deviation. *Indicates dedicated right-turn lane.

As Table 2.22 indicates relative to Table 2.21, there is a higher rate of vehicle-pedestrian interactions at the secondary crosswalk compared to the primary crosswalk. This can be primarily attributed to the higher pedestrian volumes at the secondary crosswalk during the walk cycle. The pedestrian conflict rate for both Table 2.21 and Table 2.22 appears relatively consistent between 2022, 2023, and 2025.

### 2.2.3.2 Preliminary Stopping Count Analysis for Secondary Crosswalk

The following is a preliminary analysis to examine stopping counts, which may be more appropriate for low incidence data with many zeroes instead of using rates or percentages. The count of drivers stopping for pedestrians crossing at the secondary crosswalk is considered here as the dependent variable due to the likelihood of driver/pedestrian conflicts on this crosswalk. A generalized linear model (GLM) with a negative binomial distribution and loglink function was conducted with total crossings at the secondary crosswalk per two-hour block used as the offset variable to account for exposure. The following variables were entered into the model:

1. Year (2023 vs. 2025) (2 levels)
2. Weekday (Mon-Thurs) vs. Weekend (Fri-Sun) (2 levels)
3. Street with Green Light (Larpenteur vs. White Bear) (2 levels)
4. Estimated right-turning vehicle volume.

The general results are found in Table 2.23. The estimated marginal means of the analysis are presented in Table 2.24.

The post-hoc breakdown of the significant interaction of Year by Street w/ Green Light is presented in Table 2.25.

**Table 2.23 GLM of secondary crosswalk stopping count for pedestrians**

| **Model Components** | **AIC / BIC** | **Omnibus Test, $\chi^2$ (df)** | ***p*-value** | **Significance** |
|---|---|---|---|---|
| Model | 607.82 / 628.70 | | | |
| Intercept | | 358.80 (1) | < .001 | |
| Year | | 14.59 (1) | < .001 | Stopping count is higher in 2023 (*M* = 0.005) than for 2025 (*M* = 0.001) |
| Weekday/Weekend | | .29 (1) | .589 | |
| Street with Green Light | | 3.45 (1) | .357 | More likely to stop when turning from White Bear to Larpenteur, than from Larpenteur to White Bear |
| Year x Street w/ Green Light Interaction | | 14.77 (1) | < .001 | See **Table 2.20** and **Table 2.21**. |
| Right-Turning Vehicle Volume | | 3.45 (1) | .063 | |

**Table 2.24 Estimated marginal means from Generalized Linear Model (GLM).**

| Year | Street with Green Light | Mean | Std. Error |
|---|---|---|---|
| 2023 | Larpenteur | 0.0077 | .0022 |
| | White Bear | 0.0027 | .0011 |
| 2025 | Larpenteur (Dedicated RTL) | 0.0004 | .0002 |
| | White Bear | 0.0025 | .0010 |

**Table 2.25 Comparisons between marginal means of stopping count on secondary crosswalk for time periods.**

| Location and Time | 2023 Larpenteur | 2023 White Bear | 2025 Larpenteur (Dedicated RTL) | 2025 White Bear |
|---|---|---|---|---|
| 2023 Larpenteur | | *p* = .294 | *p* = .004* | *p* = .187 |
| 2023 White Bear | | | *p* = .195 | *p* = 1.00 |
| ***2025 Larpenteur (Dedicated RTL)*** | | | | *p* = .287 |
| 2025 White Bear | | | | |

*Notes*. All comparisons use the Bonferroni correction to control for Type I errors (false positives). *means statistically significant, $p < .01$.

A second analysis is similar but focuses on the count of non-stopping vehicles to pedestrians on the secondary crosswalk. The results are shown in Table 2.26. There is no interaction between the Street with the Green Light and Year (p = .357).

**Table 2.26 GLM of secondary crosswalk not stopping count for pedestrians.**

| Model Components | AIC / BIC | Omnibus Test, $\chi^2$ (df) | *p*-value | Significance |
|---|---|---|---|---|
| **Model** | 346.86 / 367.75 | | | |
| Intercept | | 186.84 (1) | < .001 | |
| Year | | 10.30 (1) | .001 | The “not stopping” count is slightly higher in 2023 (*M* = 0.0008) than for 2025 (*M* = 0.0001) |
| Weekday/Weekend | | 8.67 (1) | .003 | The not stopping count is slightly higher in Weekend (*M* = 0.0006) than for Weekday (*M* = 0.0001) |
| Street with Green Light | | 1.55 (1) | .214 | |
| Year x Street w/ Green Light Interaction | | .85 (1) | .357 | |
| Right-Turning Vehicle Volume | | .21 (1) | .649 | |

The third GLM analysis is like the first two analyses but focuses on the count of pedestrian-vehicle conflicts on the secondary crosswalk. The general results are found Table 2.27. The estimated marginal means of the analysis are presented in

Table 2.28 2.28. The post-hoc breakdown of the significant interaction of Year by Street w/ Green Light is presented in Table 2.29.

**Table 2.27 GLM of secondary crosswalk conflict count**

| Model Components | AIC / BIC | Omnibus Test, $\chi^2$ (df) | *p*-value | Significance |
|---|---|---|---|---|
| **Model** | 697.67 / 718.56 | | | |
| Intercept | | 317.35 | < .001 | |
| Year | | 15.38 (1) | < .001 | Conflict count is higher in 2023 (*M* = 0.005) than for 2025 (*M* = 0.001) |
| Weekday/Weekend | | .14 (1) | .708 | |
| Street with Green Light | | .01 (1) | .930 | |
| Year x Street w/ Green Light Interaction | | 4.67 (1) | .001 | See **Table 2.24** and **Table 2.25**. |
| Right-Turning Vehicle Volume | | 11.86 (1) | .030 | |

**Table 2.28 Estimated marginal means from GLM.**

| Year | Street with green light | Mean | Std. Error |
|---|---|---|---|
| 2023 | Larpenteur Green | .0148 | .0037 |
| | White Bear Green | .0042 | .0015 |
| 2025 | Larpenteur Green (RTL) | .0010 | .0005 |
| | White Bear Green | .0033 | .0013 |

*Notes*. Covariates appearing in the model are fixed at the following values: Right-Turning Vehicle Volume (Non-Event) = 80.1542

**Table 2.29 Comparisons between marginal means of conflict count on secondary crosswalk.**

| **Location and Time** | 2023 Larpenteur | 2023 White Bear | ***2025 Larpenteur (Dedicated RTL)*** | 2025 White Bear |
|---|---|---|---|---|
| 2023 Larpenteur | | *p* = .074 | *p* = .001* | *p* = .024* |
| 2023 White Bear | | | *p* = .351 | *p* = 1.00 |
| ***2025 Larpenteur (Dedicated RTL)*** | | | | *p* = .669 |
| 2025 White Bear | | | | |

*Notes*. All comparisons use the Bonferroni correction to control for Type I errors (false positives). *Means statistically significant, *p* < .05.

## 2.2.4 Field Longitudinal Case Study Analysis Summary

This analysis provides descriptive statistics of scored vehicle maneuvers and pedestrian/driver interactions from 2022, 2023, and 2025, with 2025 comprising of the new dedicated right-turn lanes on Larpenteur. The focus of the analysis was on comparing the 2023 pre-installation video footage with the 2025 post-installation video footage.

There appeared to be no major statistically significant differences in vehicle and pedestrian crossing volumes There appeared to be a statistically significant increase in the rate of high-speed turns from 2023 to 2025. This increase was the same for turns from Larpenteur to White Bear, and White Bear to Larpenteur across the two years, suggesting that the addition of the dedicated right-turn lane may either play a minor role or no role on this increase in the high-speed turn rate.

Not stopping rates for pedestrians on the primary crosswalk appear to have decreased from 2023 to 2025, with no difference between the Larpenteur or White Bear turns. There was no statistically significant effect of the year (2023/2025) on the not stopping rate for pedestrians on the secondary crosswalk.

To carefully examine these conclusions on the secondary crosswalk, the research team conducted a preliminary analysis of the count data instead of the incidence rate data, with generalized linear models (GLMs). These analyses found that the stopping count for pedestrians on the secondary crosswalk declined from 2023 to 2025 on the Larpenteur to White Bear turns when controlling for exposure, but that there was no statistically significant corresponding increase in the not stopping count for that same turn. A third GLM analysis examined whether this change in the stopping count can be partially attributed to a change in the rate of conflict between pedestrians and drivers on the secondary crosswalk, which was found to be the case, with a decline in conflict count from 2023 to 2025 on the Larpenteur to White Bear turns.

For dedicated right-turn lanes, field observation takeaways from the longitudinal case study are:

1. There may be a contributing role of the dedicated right-turn lane on the rate of high-speed turns, but the increase of the rate of high-speed turns did not appear to differ between the turns with the added dedicated right-turn lane and the turns with right-turn through lanes.
2. There is a decline in the stopping count for turns made after the dedicated right-turn lane is installed, but the primary culprit appears to be a decline in the conflict count between pedestrians and drivers.
    a. Given that there are no major differences in pedestrian volume between years, a plausible explanation may be that the addition of a dedicated right-turn lane on a right-on-red permitted location allows for more throughput of turning traffic, resulting in fewer opportunities for conflict between pedestrians and right-turning drivers at the secondary crosswalk during the WALK cycle.

## 2.3 Integrated Analysis of Field Studies

The cross-sectional field data taken from the traffic cameras in 2022 and the longitudinal case study data taken from the traffic cameras from the single site in 2023 and 2025 were considered together in a single set of analyses.

### 2.3.1 Annual Average Daily Traffic Segregation

The sites across the field studies varied widely in their estimated annual average daily traffic (AADT). These AADT numbers were updated from the original analyses provided earlier to match the corresponding year of camera data measurement (2022, 2023, or 2025), except for Marshall Avenue at the Marshall and Prior intersection, as updated numbers were not available for that segment. The updated AADT numbers were taken from the Traffic Count Database System (TCDS) as part of MnDOT Transportation Data Management System. Estimates for Wabasha at Wabasha & Plato took the average of the Wabasha north of the intersection (near Water) at 11,052 in 2022 and south of the intersection at 9,522 in 2022. Similar averages are taken using the east (15361) and west (25,160) of the Maryland section of the Maryland & Payne intersection in 2022.

To understand the effects of dedicated right-turn lanes better in the context of traffic volume, the following analyses segment the analyses according to the estimated AADT for the given road segment (both directions). This resulted in the following categories:

1. Lower vehicle volume urban roadways (662 – 11052 AADT, both directions)
2. Higher vehicle volume urban roadways (16062 – 35393 AADT, both directions)

### 2.3.2 Integrated Analysis Results

All analyses were generalized estimating equations (GEEs), using the site as the subject variable, and the following as control variables: Number of lanes in the direction of travel, time block coded (morning, lunch, or afternoon), count of right-turning vehicles, count of pedestrians for the specific interaction of interest (primary crosswalk, secondary crosswalk, or total), and estimated AADT. The key variable was whether the turning assessment was being made on a Dedicated Right-Turn Lane (Yes/No). All models used normal distributions with identity link functions. The results for lower vehicle volume urban roadways (662 – 11052 AADT, both directions) are summarized in Table 2.30. The results for higher vehicle volume urban roadways (16062 – 35393 AADT, both directions) are summarized in Table 2.31.

**Table 2.30 GEE Analysis for lower vehicle volume urban roadways focusing on dedicated right-turn lanes.**

| Measure | Model Fit (QIC) | Wald $\chi^2$ (df) | *b* (SE) | *p*-value | Estimated Marginal Means | | Odds Ratio |
|---|---|---|---|---|---|---|---|
| | | | | | Right-Turn Through Lane | Dedicated Right-Turn Lane | |
| High-Speed Turn Ratio | 58.68 | .025 (1) | -.003 (.021) | .875 | .027 | .024 | .997 |
| Primary Crosswalk Conflict Rate | 48.61 | .981 (1) | .001 (.001) | .332 | .003 | .004 | 1.001 |
| Primary Crosswalk Not Yield Rate | 15.56 | 3.33 (1) | .214 (.117) | .068 | .579 | .794 | .807 |
| Secondary Crosswalk Conflict Rate | 54.89 | 4.94 (1) | .009 (.004) | **.026** | .013 | .023 | 1.009 |
| Secondary Crosswalk Not Yield Rate | 30.92 | 23.53(1) | -.133 (.028) | **<.001** | .168 | .035 | .875 |

Table 2.31 GEE Analysis for higher vehicle volume urban roadways focusing on dedicated right-turn lanes.

| Measure | Model Fit (QIC) | Wald $\chi^2$(df) | *b* (SE) | *p*-value | Estimated Marginal Means | | Odds Ratio |
|---|---|---|---|---|---|---|---|
| | | | | | Right-Turn Through Lane | Dedicated Right-Turn Lane | |
| High-Speed Turn Ratio | 11.80 | 118.47 | -.048 (.004) | **<.001** | .063 | .015 | .953 |
| Primary Crosswalk Conflict Rate | 127.31 | .04 (1) | .000 (.002) | .850 | .008 | .008 | 1.000 |
| Primary Crosswalk Not Yield Rate | 14.58 | 3.41 (1) | .119 | .065 | .692 | .811 | .888 |
| Secondary Crosswalk Conflict Rate | 45.82 | 4.44 (1) | .004 | **.035** | .009 | .012 | 1.004 |
| Secondary Crosswalk Not Yield Rate | 17.94 | 6.96 (1) | .048 (.018) | **.008** | .147 | .195 | 1.049 |

The exact values shown in the estimated marginal means should be taken with skepticism due to the high standard errors associated with those values.

The results can be summarized as follows.

- Lower-volume AADT urban roadways
  - Dedicated right-turn lanes are not associated with the rate of high-speed turns.
  - Dedicated right-turn lanes are significantly associated with a slightly higher rate of conflicts with pedestrians on the secondary crosswalk.
  - Dedicated right-turn lanes are not associated with the rate of conflicts on the primary crosswalk.

    - Dedicated right turn lanes are associated with a higher likelihood of drivers **stopping** for pedestrians on the secondary crosswalk.
    - Dedicated right turn lane is possibly associated with a higher likelihood of drivers stopping for pedestrians on the primary crosswalk, although this effect is marginal ($p$ = .068).
- Higher-volume AADT urban roadways
    - Dedicated right-turn lanes are associated with a slight reduction in the rate of high-speed tuns.
    - Dedicated right-turn lanes are associated with a slightly higher rate of conflicts with pedestrians on the secondary crosswalk.
    - Dedicated right-turn lanes are not associated with the rate of conflicts on the primary crosswalk.
    - Dedicated right turn lanes are associated with a higher likelihood of drivers **not stopping** for pedestrians on the secondary crosswalk.
    - Dedicated right turn lanes are possibly associated with a higher likelihood of drivers stopping for pedestrians on the primary crosswalk, although this effect is marginal ($p$ = .065).

The general difference in safety outcomes between lower and higher-volume urban roadways are (1) that dedicated right-turn lanes tend to reduce the likelihood of high speed turns on higher volume roadways, but does not have a similar effect for lower volume roadways, and (2) dedicated right-turn lanes appear to be associated with a higher likelihood of right-turning drivers stopping for pedestrians on lower-volume roadways and a lower likelihood of right-turning drivers stopping for pedestrians on higher-volume roadways.

# Chapter 3: Driving Simulation Study

## 3.1 Simulation Development

### 3.1.1 Simulation World

The simulation comprised an urban road environment with wide two-lane roads (one road in each direction). See Figure 3.1 for an overview of the route. These roads had local traffic in the intersecting lanes and pedestrians walking on the sidewalks to ensure that the presence of pedestrians at crosswalks was not unusual or particularly novel, which would trigger particularly attentive behavior from participants.

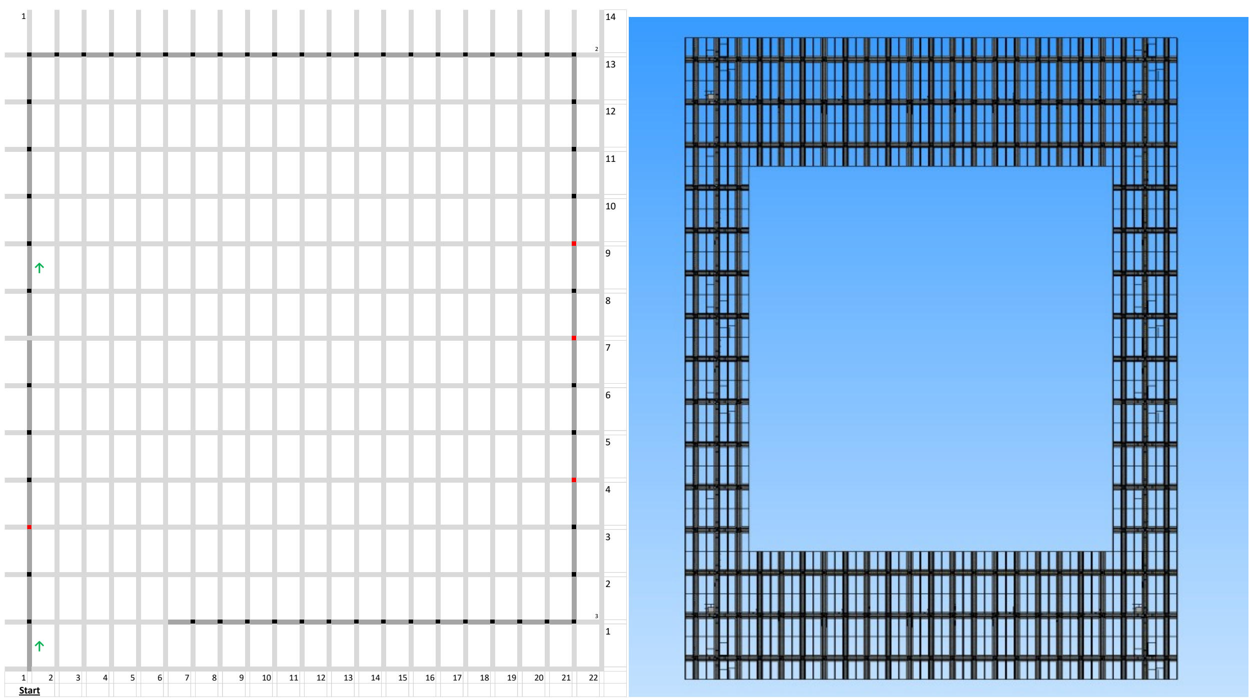


**Figure 3.1 Route overview for simulation study. Left is top-down view of one block of trials, comprising primarily of straight paths through stoplights, along with three right-turns to be taken by the participant. Right is 3D top-down overview.**

The presentation of intersections was varied to allow for straight and turning movements. See Figure 3.2 for an example of a dedicated right-turn lane where turning is not required, and the participant should drive through. See Figure 3.3 for examples of a dedicated right-turn only intersection where turning is required. Figure 3.4 presents an example of a non-right turn lane intersection (right-through lane), where turning is required.

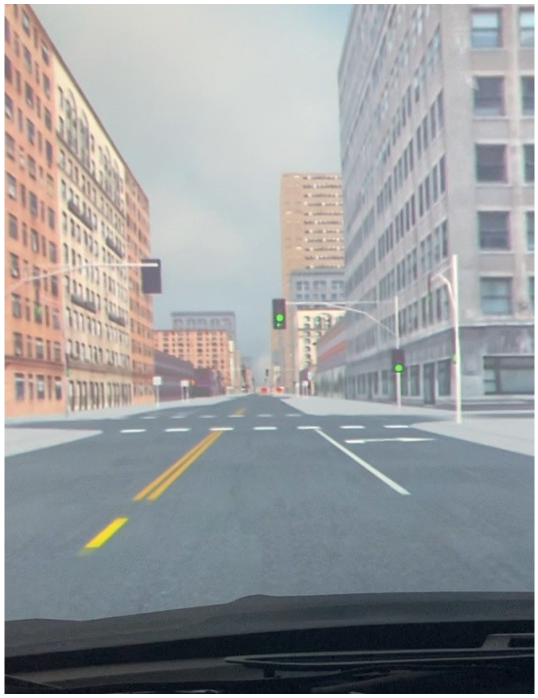

**Figure 3.2 An intersection that the vehicle does not turn (goes straight through).**

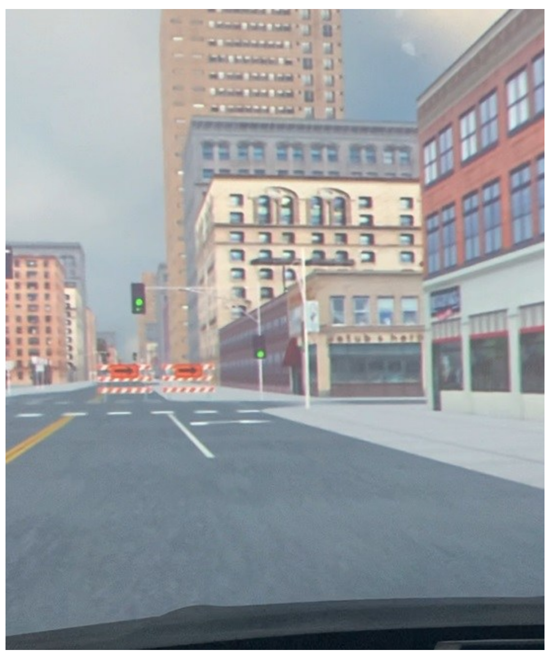

**Figure 3.3 A dedicated right-turn intersection where the participant vehicle must turn right.**

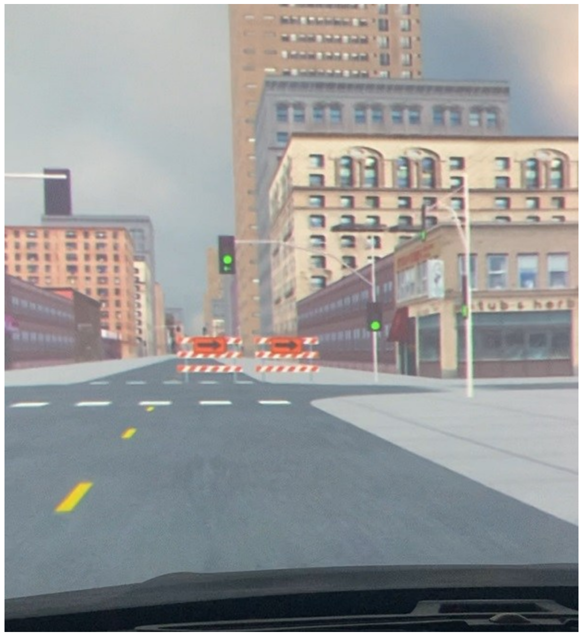

**Figure 3.4 A right-turn through lane intersection requiring a turn by the participant, which comprised one block of trials.**

For actual pedestrian behavior, if a pedestrian is present but is not part of the crossing condition, they remained in place for approximately 7 seconds, before turning and moving away, allowing participants who are yielding to the pedestrian to proceed. See Figure 3.5 for an example.

**Figure 3.5 Picture of a pedestrian in the non-crossing condition. The left is the pedestrian waiting at the intersection, the right is the pedestrian moving away from the intersection after 7 seconds.**

For the crossing condition, the pedestrian is designed to begin crossing the intersection when the participant vehicle is 30 ft from the intersection. Please see Figure 3.6 for an example.

**Figure 3.6 A pedestrian crossing during the crossing condition.**

Figure 3.7 and Figure 3.8 provide images of the 3D world outside of the experimental conditions, with Figure 3.7 presenting a dedicated right-turn intersection, and Figure 3.8 presenting a right-turn through lane intersection.

**Figure 3.7 Dedicated Right-Turn Lane 3D model.**

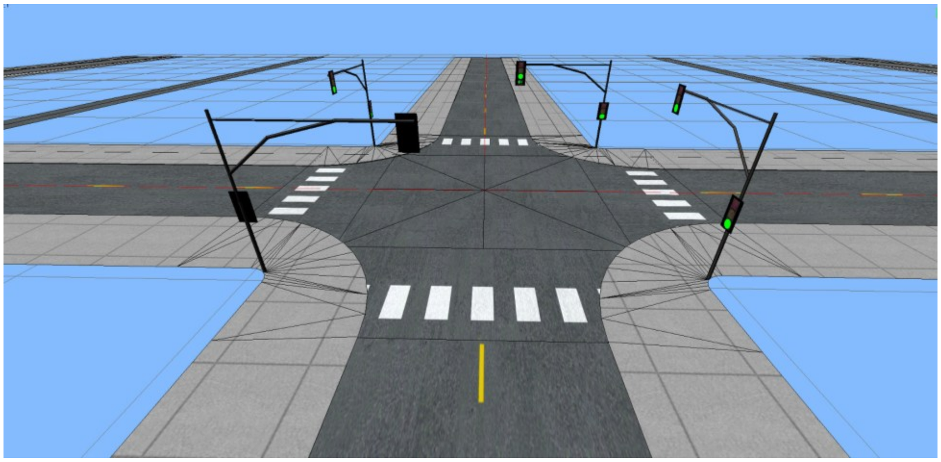

Figure 3.8. Right Turn Through Lane 3D Model.

## 3.2 Simulation Study Method

### 3.2.1 Participants

Forty (40) people participated in the study, with a mean age of 40.95 years (*SD* = 16.86). The participant demographics are provided in Table 3.1**.**

**Table 3.1 Participant Demographics**

| Attribute | Options | Count |
|---|---|---|
| **Gender** | Female | 16 |
| | Male | 24 |
| **Highest Education** | High School Diploma or GED | 4 |
| | Some College | 3 |
| | Associate's Degree | 2 |
| | Bachelor's Degree | 20 |
| | Graduate Degree | 11 |
| **Race** | White | 34 |
| | Black or African American | 1 |
| | American Indian or Alaska Native | 1 |
| | Asian | 3 |
| | Multiracial | 1 |
| **Living Location** | Urban | 25 |
| | Suburban | 11 |
| | Rural | 4 |
| **Primary Driving Location** | Urban | 24 |
| | Suburban | 12 |
| | Rural | 4 |

*Note.* There were *n* = 40 participants.

### 3.2.2 Experimental Task

Participants drove a simulated vehicle through an urban route, comprising 3 right turns in the experiment drives. The route was one practice drive with one right turn, and 2 experiment drives with 6 right turns. For some of these right turns, a pedestrian was present at the intersection, positioned near the secondary crosswalk. Sometimes the pedestrian did not cross, and other times the pedestrian crossed after a brief pause. The correct response for the participant was to stop for the stimulated pedestrian. For other turns, there was no pedestrian present. For one block of right turns, there was a dedicated right-turn only lane present. For the other block of right turns, there was a right-through lane present. The design of the lanes was consistent, besides the difference of lane type.

### 3.2.3 Experimental Design

The order of pedestrian presence and pedestrian action was counterbalanced. The presentation of right-turn lane types (dedicated right-only lane or right-through lane) were counterbalanced and blocked. See Table 3.2.

**Table 3.2. Count of turning trials with blocked within-subjects design (Ped Action x RTL Type).**

| Pedestrian | Block 1<br>Right Turn Through Lane | Block 2<br>Dedicated Right Turn Lane |
|---|---|---|
| **No Ped Present** | 1 | 4 |
| **Ped Present** | 2 | 5 |
| **Ped Step in crosswalk** | 3 | 6 |

### 3.2.4 General Procedure

After providing informed consent, the participants drove through a test drive with one right turn. After the test drive, participants filled out a simulation sickness questionnaire to ensure that they were not prone to simulation sickness. Afterwards, participants performed the first block of trials. They then filled out a questionnaire on mental demand (RSME) as well as another assessment of simulation sickness. Participants then completed a second block of trials and filled out the same set of subjective questionnaires. They then received their compensation ($50).

## 3.3 Simulation Study Results

Unless otherwise stated, the reported analyses relied on generalized estimating equations (GEEs), which allow for assessment of variance in the data that is due to the participant/subject, possible because participants performed twice or more on most of the measures reported here. Furthermore, analysis can adjust for different distribution types than those assessed in ANOVAs. For each GEE analysis, we reported: The dependent variable, the probability distribution used, the link function, goodness of fit measure (QIC), subject effects, model effect test (via Wald Chi-Square, df, and p-value), and finally the estimated marginal means of the primary factors of interest (e.g., Right-turn lane type) for the measured dependent variable. All analyses used right-turn lane type as the primary factor (independent variable) of interest, with any exceptions noted.

Some of the distinctions made in the results distinguish between the primary and secondary crosswalks at the turn. The primary crosswalk represents the first crosswalk crossed by a turning vehicle, and the secondary crosswalk represents the second crosswalk crossed by a turning vehicle. See Figure 3.9.

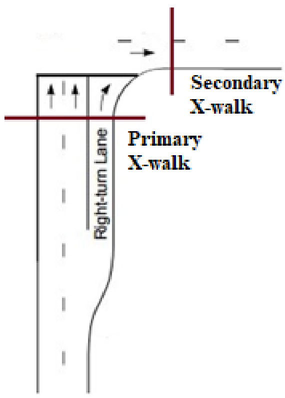


**Figure 3.9 Primary and secondary crosswalks for right-turning vehicles.**

### 3.3.1 Mental Workload (RSME)

The mental workload measure Rating Scale Mental Effort (RSME) is a self-report scale with scores ranging from 0-150. The results of the GEE analysis are presented with the estimated marginal means in Table 3.3.

**Table 3.3. Mental workload scores (RSME) estimated marginal means.**

| Average Dedicated Right-Turn Lane | Average Right-Turn Through Lane | Statistical Result (*p*-value) |
|---|---|---|
| 39.15 (2.31) | 42.41 (2.50) | Significant difference, participants report lower mental workload on dedicated right-turn lane ($p$ = .018). |

*Note*. Standard Error show in in parentheses

This indicates that there is a small but statistically significant effect of greater mental demand required for right turn through lane turns relative to right turn only lane turns, as presented in this study.

### 3.3.2 Driving/Turning Performance When No Pedestrian is Present

The dedicated right-turn lane condition resulted in drivers turning closer to the curb, while the right-turn through lane condition had drivers turning closer to the center of the road. See Figure 3.10. The point measured for offset is the left or initial part of the secondary crosswalk, from the turning participant's perspective. See Figure 3.11.

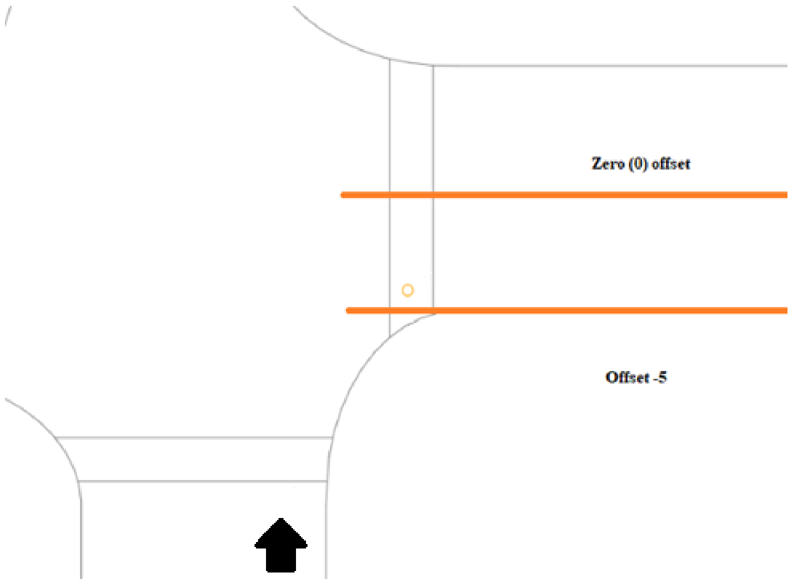


**Figure 3.10 Turning offset from center of road, with vehicles turning from the right-turn lane to the adjoining street. Offset is measured from the center of the street (0 offset) to the curb (-5 offset).**

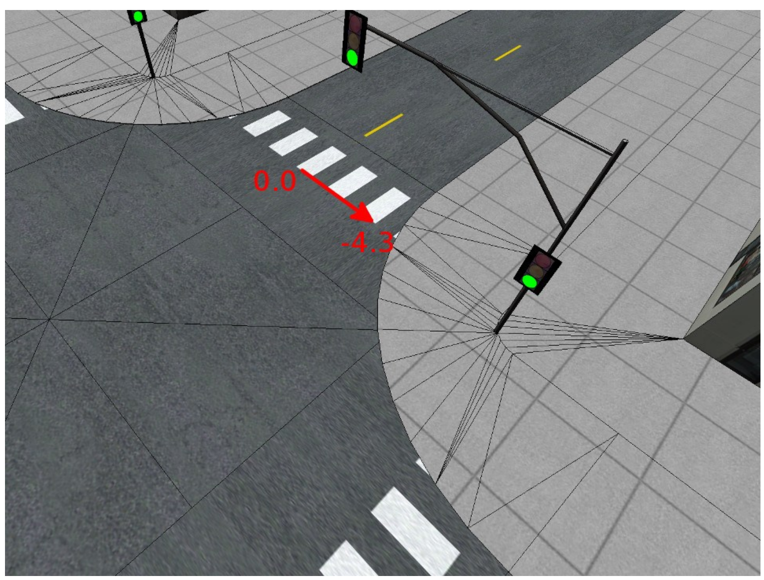


**Figure 3.11 Turning measurement in simulation study. The point at which turning offset and normalized subject heading was measured, the left or initial part of the secondary crosswalk from the turning driver/participant's perspective.**

The variable of the normalized subject heading at that the crosswalk indicated in Figure 3.11. The original heading (before turning) is zero degrees (going straight). The subject is making a turn toward 90 degrees. Without a pedestrian present, participants in the right-through lane are turning more perpendicular to their original heading relative to the individuals turning from the dedicated right-turn lane. See the summary results in Table 3.4.

**Table 3.4 Results Summary Table for Turning Without Pedestrians**

| Variable | Average Dedicated Right-Turn Lane Only | Average Right-Turn Through Lane | Statistical Result (*p*-value) |
|---|---|---|---|
| Entry Speed | 27.7 mph | 28.4 mph | No difference (p > .10) |
| Delta Speed | 16.7 mph | 16.8 mph | No difference (p > .10) |
| Maximum Speed | 28.0 mph | 28.8 mph | No difference (p > .10) |
| Turn Offset | -4.4 | -3.6 | Difference ($p < .001$) |
| Heading at Turn | 55.418 degrees | 67.91 degrees | Difference ($p < .001$) |

## 3.3.3 Driving/Turning Performance When Pedestrian is Present

When drivers yielded to a pedestrian present on the crosswalk, there was no difference between the right-turn lane types in the likelihood of drivers passing the primary crosswalk and yielding closer to the secondary crosswalk (closer to the pedestrian). There was no difference between the right-turn lane types in the likelihood of drivers yielding when a pedestrian was present, and yielding rates were very high. There was a marginal difference between the right-turn lane types on likelihood of committing a full stop when a pedestrian was present. See Table 3.5.

**Table 3.5 Results Summary Table for Turning with Pedestrians Present**

| Variable | Average Dedicated Right-Turn Lane Only | Average Right-Turn Through Lane | Statistical Result |
|---|---|---|---|
| Passed Primary Crosswalk (Y/N) | .38 | .41 | No difference ($p = .751$) |
| Yield (Y/N) | .95 | .96 | No difference ($p = .626$) |
| Full Stop (Y/N) | .60 | .49 | Marginal difference ($p = .06$) |

## 3.3.4 Driving/Turning Performance When Pedestrian Enters Crosswalk

No clear difference observed between lane types for entry speed into the turn on conditions when the pedestrian is entering the crosswalk, although there is potentially a marginal effect ($p = .082$). A significant difference was observed between lane types for changes in turning speed when a pedestrian is entering, with a higher change in speed for the right-turn through lane. A follow-up analysis was then conducted on the same variable to determine if this is due to the marginal effects observed of right-turn lane type on entry speed. The significant effect of right-turn lane type on change in turning speed disappears when adding entry speed to the model, suggesting that the effect of right-turn lane type on change in speed is partially attributable to marginal differences in entry speed. There was no difference observed between lane types for maximum turning speed. The dedicated right-turn only lane condition resulted in drivers turning closer to the curb, while the right-turn through lane condition had drivers turning closer to the center of the road. There was a significant difference in max deceleration speed at pedestrian walk onset for the pedestrian entering condition. There was a significant difference for right-turn lane type for stopping distance to the secondary crosswalk for the pedestrian entering condition, with a smaller average crossing distance for the dedicated right-turn only lane. See Figure 3.12. To test for any consequences, we conduct a follow-up analysis on minimum stopping distance to the crossing pedestrian. For a summary of these results, see Table 3.6.

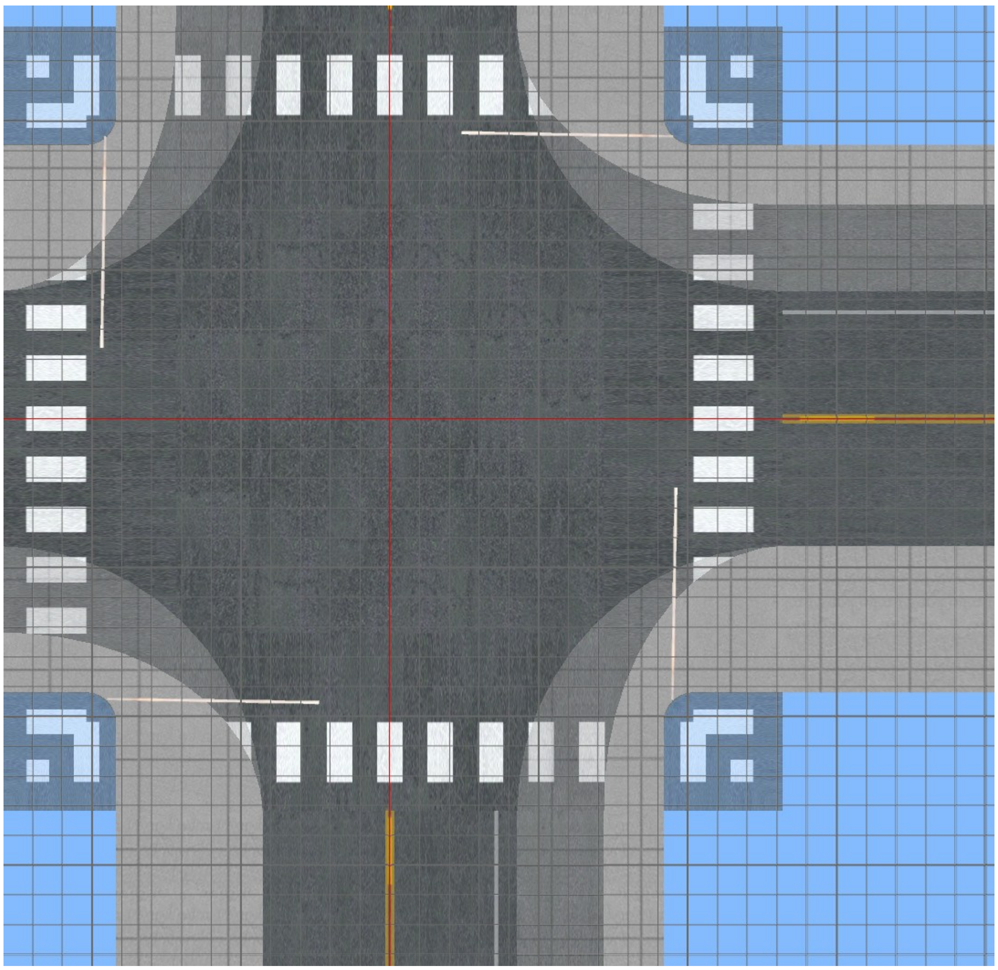

**Figure 3.12. An overhead comparison of road geometries for the dedicated right-turn only and right-turn through lanes. There is a shorter distance to the secondary crosswalk present for the dedicated right-turn only condition.**

**Table 3.6 Results Summary Table for Turning with Pedestrian Entering Crosswalk**

| Variable | Average Dedicated Right-Turn Lane Only | Average Right-Turn Through Lane | Statistical Result (*p*-value) |
|---|---|---|---|
| Entry Speed | 27.8 mph | 29.4 mph | Marginal difference ($p = .082$) |
| Delta Speed | 26.3 mph | 28.4 mph | Significant difference, partly explained by minor differences in entry speed ($p = .046$) |
| Maximum Speed | 28.1 mph | 29.5 | No difference ($p > .10$) |
| Turn Offset | -4.0 | -3.4 | Significant difference, possibly due to the differences in the curb radius ($p = .129$) |
| Normalized Heading | 38.75 degrees | 55.21 degrees | Significant difference, possibly due to the differences in the curb radius ($p = .001$) |
| Deceleration Speed | 3.7 mph | 3.7 mph | No difference ($p = .993$) |
| Distance to Secondary Crosswalk | 7.4 m | 9.1 m | Significant difference ($p < .001$) |
| Minimum Distance to Crossing Pedestrian | 6.7 m | 6.8 m | No difference (p = .693). |

## 3.4 Simulation Study Discussion

The simulation data analysis considered the effects of right-turn lane type on (1) subjective reporting of mental demand, (2) driving performance when a pedestrian was not present (in order to assess what behavior would be like if a driver did not notice a pedestrian present), (3) driving performance when a pedestrian was present irrespective of crossing behavior, and (4) driving performance when a pedestrian crossed. When considering the parameters of driving in this simulated environment, with no traffic present, the right-turn through lane appears to present a slightly higher risk profile based on the results presented here.

Our conclusion of a slightly higher risk profile for right-turn through lanes in this scenario is based on a small but statistically significant difference in reported mental workload for the right-turn through lane, a marginal difference in the likelihood of fully stopping for right-turn through lanes, marginal difference in the entry speed for right-turn through lanes, and a significant difference in speed change for right-turn through lanes. The only indication of greater risk for dedicated right-turn only lanes in this scenario is the shorter stopping distance to the secondary crosswalk, which may be explained by the differences in road geometries in the two conditions (see Figure 3.12).

An interesting contributing factor to some of the results are the persistent effects of turning offset, in which drivers tended to cross the secondary crosswalk closer to the curb in the dedicated right-turn only lane condition and cross closer to the center of the median in the right-turn through lane condition. This appears to affect the likelihood of fully stopping for pedestrians for the two considered lane types and may have other effects on pedestrian safety considering if the pedestrian is crossing from the near or far side of the intersection on the secondary crosswalk. Furthermore, the turning offset value is associated with the likelihood of yielding to a pedestrian, Wald Chi-Square = 8.529, df = 1, $p$ = .003, with drivers turning more widely being less likely to yield to a pedestrian crossing from the near side as presented in this study. This analysis was not investigated in detail because of the high yielding compliance and the lack of effect of right-turn lane type on yielding rate. Related to this was the observation that in both pedestrians not being present and pedestrians entering, turning drivers were more likely to be more oriented toward the adjacent street when they reach the secondary crosswalk in the right-through lane condition. A preliminary analysis observed a significant interaction with pedestrian present type and lane type, indicating that the tendency to turn more into the crosswalk was significantly greater in the condition when the pedestrian was present (see Figure 3.13). This implies that with right-through lanes, there's a greater risk of a head-on collision compared to dedicated right-turn lanes, at least for the road geometries as currently constructed.

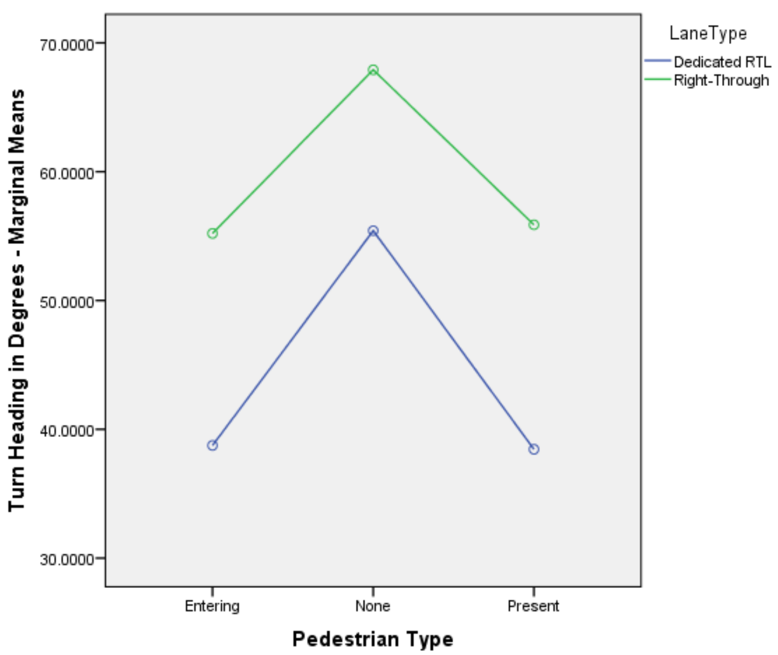


**Figure 3.13. Marginal means of normalized turn heading in degrees across pedestrian type and lane type.**

# Chapter 4: Conclusions & Recommendations

This chapter considers the costs and benefits of installing a dedicated right-turn lane and recommendations for implementation. The first element to consider is the general non-pedestrian-related criterion for the installation of a dedicated right-turn lane. In the *Road Design Manual*, for urban areas, right-turn lanes should be an option whenever the economics are feasible (5-3.01.01) and they should be no longer than a quarter of a mile and on roads with speeds greater than 30 mph with high volumes and turning demands (5-3.01.07). In the MnDOT *Access Management Manual*, right-turn lanes are recommended for high-volume (>1500 AADT for 2-lane highways, >3000 AADT for 4-lane highways, and >100 trips/day for cross streets ADT) undivided roads and signalized intersections, especially with sites prone to crashes (sideswipe, rear end) that would be mitigated with a dedicated turn lane. A Transportation Research Synthesis (TRS 1406) found that a right-turn lane that cost $20,000 to install would be feasible with traffic volumes of 200 through vehicles and 60 turning vehicles per hour, a lane that cost $50,000 to install would be warranted at traffic volumes in excess of 600 through vehicles per hour, and savings would start to accrue at ADTs greater than 5,000 per day, with right-turning vehicle traffic volumes going beyond 25% of through traffic (CH2M HILL, 2014).

## 4.1 Costs and Benefits

The primary factor is the estimated cost of a pedestrian fatality, and a secondary factor is the estimated cost of a pedestrian injury crash. Furthermore, because yielding is used as a proxy measure for crashes, the known relative relationship between yielding rates and pedestrian crashes was investigated. The analysis of costs cited established literature estimating these costs.

The primary goal of this research was to determine whether drivers yield to pedestrians when making right turns. The key was to identify relative levels of risk of dedicated lanes and right-through lanes. Moreover, since speed was a strong factor in determining the severity of injury with pedestrian-involved crashes (Rosen & Sander, 2009), observing speed changes at intersections with or without dedicated right-turn lanes was important.

### 4.1.1 Costs

#### 4.1.1.1 Crashes

From 2009 to 2018, there was an average of 39.4 pedestrian fatalities per year for the entire state of Minnesota. The Center for Disease control lists 2018 Minnesota pedestrian deaths as resulting in $68 million in medical costs and work loss costs (CDC, 2020). More generally, fatalities are estimated to cost society $4,538,000 per death (Xie, Ozbay, Kurkcu, & Yang, 2017), meaning the past decade's fatal pedestrian crashes will cumulatively cost Minnesotans approximately $1.8 billion. For pedestrian injury crashes, one estimate indicated that serious injuries from pedestrian-vehicle crashes will result in lifetime financial losses of $135,558 per case (Miller et al., 2004). An occasionally cited set of numbers for the comprehensive costs of pedestrian non-fatality crashes was $230,000 for incapacitating injury crashes and $58,700 for non-incapacitating evident injury crashes (Michigan Crash Facts, 2012), based on a 2012 analysis by the National Safety Council.

#### 4.1.1.2 Yielding rates and crashes

The strength of the relationship between the rates of drivers yielding the right of way to pedestrians and crash rates has not been the topic of significant study. However, one investigation measuring performance at 20 sites in Milwaukee, WI, found that for uncontrolled intersections with low initial yielding rates, sites that had two or more pedestrian crashes were associated with a change in rate of driver yielding of 6.4% (Schneider et al., 2017; Schneider et al., 2018). Analyses at signalized, high-speed intersections (i.e., 45 mph posted speed limit) in Louisiana found that yielding on right turns is associated with a reduction in crashes (Hossain et al., 2024). Although this model won't directly transfer to signalized intersections with high yielding rates, we can expect a relationship between higher driver yielding and a reduced likelihood for at least 2 pedestrian crashes at a given location.

#### 4.1.1.3 Walkability

Examinations of travel patterns in large cities have found that improving traffic safety through investment in pedestrian infrastructure will increase the likelihood that people choose to travel via active modes of transportation, such as walking and biking (Aziz et al, 2017). This is critical for public health, as the World Health Organization lists physical inactivity among one of the leading global risks for mortality (WHO, 2009), although this is difficult to quantitatively calculate.

### 4.1.2 Benefits

#### 4.1.2.1 Crashes

There were no crashes reported in our data, so direct calculations were not possible. However, we can provide an assessment of the impact of yielding rates and other contributing factors to crashes. Furthermore, the research team reviewed public data that was analyzed by Toole Design on MnDOT pedestrian crash data over four years (2016-2019), highlighting the subset of the analyzed data on right-turn crashes in urban and suburban centers. While lane-type information was not defined in the dataset, other relevant characteristics that contribute to risk of crashes at signalized intersections were clarified.

For urban centers, the highest risks of pedestrian crashes with right-turning vehicles all predominantly occurred at high-volume intersections (7000+ ADT) and lower-posted speeds (30 MPH or less), with varying degrees of risk based on the number of lanes at the intersection and the presence of a transit stop. In general, with more lanes and a transit stop, the crash risk increased, suggesting a role of greater complexity and conflict points. For suburban communities, the risk was elevated with similar characteristics to the urban centers, but with higher posted speeds (35-50 MPH), although overall the risk of pedestrian-vehicle crashes was reduced compared to urban centers. The types of suburban signalized intersections that had comparative risk to urban centers were high-volume intersections with posted speeds between 35 and 50 MPH, 4 or more lanes at the intersection and at least 1 transit stop near the intersection. Given the higher posted speeds, it is possible that fatality risks are higher as well for these crashes.

The general takeaway for urban signalized intersections and right-turn crashes with pedestrians is highlighting the risk of high-volume traffic, number of lanes, and other factors that lead to dense, complex traffic interactions with multiple conflict points. Presumably, these environments lead drivers to attend to multiple events and stimuli on the roadway, which reduces the attention available to allocate to pedestrians. The most complex of these intersections present a similar level of risk in suburban communities, except with even greater posted speeds. Finally, as prior research literature indicates, the pedestrian crash-risk may be particularly salient at the secondary crosswalk as drivers accelerate to complete the turn and because pedestrians may frequently interact with turning drivers at this part of the intersection.

#### 4.1.2.2 Changes in Rate of Conflicts between Pedestrians and Drivers

The occurrence of a conflict between a pedestrian and a driver leads to the risk of a crash. Increasing the rate of conflicts is more likely to increase the odds of a crash.

The field data presented two general conclusions. The first conclusion is that, in general, the presence of a dedicated right-turn lane is associated with more driver-pedestrian conflicts. This appears to be because with the mix of right-turning and straight maneuvers undertaken by drivers in the right-through lane, there's a lower likelihood that a pedestrian will encounter a right-turning driver while crossing. It is worth noting that these effects are very small, even if statistically significant.

The second conclusion from the longitudinal case study on White Bear and Larpenteur indicates that there is a specific set of circumstances for which a dedicated right-turn lane can lead to a lower rate of conflict between right-turning drivers and pedestrians. This appears to occur for relatively low vehicle-volume intersections with a right-on-red permitted and relatively low pedestrian volume. In this case, installing a dedicated right-turn lane could reduce the rate of driver-pedestrian conflicts on the secondary crosswalk by increasing the right-turning traffic flow during right-on-red before the pedestrian has the right of way.

#### 4.1.2.3 Changes in Crosswalk Failure to Yield in Field Data

For **failure to yield,** the following results focus on the integrated analysis of the field camera data presented at the end of Chapter 2, as these analyses use updated AADT values and distinguish between lower-volume and higher-volume roadways.

1. Lower vehicle volume urban roadways (662 – 11052 AADT, both directions)
2. Higher vehicle volume urban roadways (16062 – 35393 AADT, both directions)

There's a slight tendency for improved yielding to pedestrians crossing on the **primary crosswalk** for both lower- and higher-volume roadways, although these effects are only marginally statistically significant.

For the **secondary crosswalk stopping rates**, there is increased likelihood of yielding to pedestrians when a dedicated right-turn lane is present for lower-volume roadways and a decreased likelihood of yielding to pedestrians on higher-volume roadways. This may be because for lower-volume roadways, drivers could be under less pressure to proceed through the turn because driving through a low-volume intersection is more efficient for that driver. Furthermore, these drivers may experience less mental effort to navigate the turn (see the driving simulation data), meaning they are more likely to notice and stop for an approaching pedestrian. However, for higher-volume intersections, the driver's efficiency goals may become more salient because it becomes more difficult to progress quickly through high-volume intersections, and the presence of a dedicated right-turn lane may lead these drivers to feel like they are "permitted" to turn despite a nearby pedestrian. There may also be something of a "follow-the-leader" effect going on at higher-volume roads with dedicated right-turn lanes.

#### 4.1.2.4 Field Data High Speed Turns

Given that high driver speed is associated with a higher likelihood of pedestrian fatality (Tefft, 2013), it is important to consider whether speeds are influenced by the right-turn lane.

For **the rate of high-speed turns,** the following results focus on the integrated analysis of the field camera data presented at the end of Chapter 2. With the updated AADT numbers in this analysis, the results indicate that for higher-volume roadways, the presence of a dedicated right-turn lane reduces the rate of high-speed turns, whereas the lane type does not appear to affect the high-speed turn rate for roadways with lower AADT. This may be because with the reduction in traffic flow and increased salience of efficiency goals, right-turning drivers may want to speed up if they have been slowed by drivers who have stopped at the right-turn through lane to proceed straight (e.g., kangaroo jumps, De Pauw et al., 2014), which is less of an issue for dedicated right-turn lanes.

#### 4.1.2.5 Looking Data

The analysis of the looking data, controlling for lane count, site, car-count volume, and number of dedicated right-turn lanes present at the intersection, with total looks, no looks, and unsure if looking counts as the offset variable, indicates that there is a marginal effect ($p$ = .058) of number of right-turn lanes present at the site on the rate of not looking at the pedestrian at the corner ($OR$ = 1.451). This indicates a possible adverse effect of traffic density, and a significant effect of a dedicated right-turn lane on rate of not looking, meaning turning drivers were less likely to not look at a pedestrian ($OR$ = .452) when turning at a dedicated right-turn lane. This may suggest less vigilance by drivers for the presence of pedestrians while driving in a dedicated right-turn lane.

Considering the mental workload data in the simulation study and the looking data in the field study together, the presence of dedicated right-turn lanes may slightly reduce the attentiveness of drivers, because less is mentally required of drivers to safely traverse a dedicated turn lane. These results are relatively small in terms of magnitude but may play a role in specific situations. For instance, adequate viewing time may permit a better opportunity to notice a pedestrian and stop in lower-volume roadways, but there may be less time for this on higher-volume roadways, where a slightly higher level of inattentiveness could result in a greater likelihood of not stopping.

#### 4.1.2.6 Simulation Data Speed

The analysis of the simulation data comparing dedicated right-turn lanes to right-turn through lanes indicated that there was a propensity for higher average entry speeds and higher maximum speeds when entering the turn for the right-turn through lane, relative to the dedicated right-turn lanes when controlling for other factors, but the magnitude of differences were relatively constrained (e.g., 29.04 mph maximum average speed in right-turn through lane vs. 27.79 mph in dedicated right-turn lane).

The general takeaway for speed is that when the geometry of the lane itself is considered, the simulation data suggests that, all things being equal, you may see slightly greater speeds at right-turn through lanes because drivers may typically reduce their speed to enter the dedicated right-turn lane. This scenario assumes very little traffic.

#### 4.1.2.7 Turn Offset Analysis

Although the direct implications for pedestrian safety are not clear, a secondary consideration is the impact of lane type on turning curvature, which could change the likelihood of coming into closer proximity to pedestrians on the secondary crosswalk crossing from the near corner or far corner. Using a similar natural log conversion as for the high-speed turns in the field data, wide-angle turns were analyzed controlling for other factors. There was a significantly higher likelihood of wide-angle turns, where the turning vehicle did not turn directly into the appropriate lane but intruded over the lane line, for right-turn through lanes at sites both with and without dedicated right-turn lanes present, compared to dedicated right-turn lanes. There were no statistical differences between dedicated right-turn lanes for sites with a varying number of dedicated right-turn lanes present. This is consistent with the data from the simulation study, which demonstrated a clear propensity for turning drivers to turn wide or more offset at right-turn through lanes and turn closer to the near corner for dedicated right-through lanes. Engineers should **consider sight lines** and typical **pedestrian crossing behaviors and volume** for crossing the secondary crosswalk at the **near corner** and **far corner** to best consider what the relative pedestrian safety impact will be for having a dedicated right-turn lane or a right-turn through lane at the intersection.

## 4.2 Recommendations and Implementation Guidance

The general safety benefits of dedicated right-turn lanes are difficult to disentangle from the overall characteristics of the sites, in that intersections with dedicated right-turn lanes present are characterized by high traffic density and high vehicle volume, which are more dangerous to pedestrians. It is not clear whether installing the dedicated right-turn lane leads to this traffic density or whether the installation follows the increase in density. However, given the guidelines for installing dedicated right-turn lanes in that the benefits of dedicated right-turn lanes appear on roads with ADTs greater than 5,000 per day, with right-turning vehicle traffic volumes going beyond 25% of through traffic (CH2M HILL, 2014), it seems reasonable that dedicated right-turn lane installation usually follows increased traffic volume and traffic density.

Given this, we provide the following observations and recommendations based on the results of this research project.

1. Engineers should evaluate the rate of pedestrians crossing at the intersection (Feng et al., 2025).
    a. For lower pedestrian volumes (a maximum of 10 pedestrians per minute), a non-channelized dedicated right-turn lane tends to be safer than the right-turn through lane.
        i. Smaller turning radii (i.e., 10 to 20 meters) has better outcomes for safety measures such as pedestrian encroachment time and crossing speed.
    b. For higher pedestrian volumes (e.g., 20 pedestrians per minute), non-channelized or channelized right-turn lanes are safer than right-turn through lanes.
        i. Channelized dedicated right-turn lanes are best for connecting very large intersections connecting major roads, with a limit of 30 meters for the turning radius. Otherwise, non-channelized dedicated right-turn lanes with smaller turning radii are preferred, as channelized dedicated right-turn lanes can be problematic for pedestrian safety (Jiang et al., 2020).
2. Engineers should evaluate the average daily traffic of the roadway as well as the turning volume.
3. If high-speed turns are a concern, dedicated right-turn lanes as tested in this study (non-channelized) were associated with fewer high-speed turns in both the field and simulation data. This is also consistent with other research (Fitzpatrick et al., 2021).
    a. When following other vehicles, a driver tends to turn right faster if the vehicle ahead of them proceeds through instead of making a right turn (Fitzpatrick et al., 2021).
4. Extrapolating from the longitudinal case study data, if the following is true, then a dedicated right-turn lane could reduce the rate of driver-pedestrian conflicts for legal crossings on the secondary crosswalk.
    a. Right-on-red is permitted.

  b. The rate of pedestrians crossing is relatively low (e.g., up to about 4 to 5 crossings every two hours on average, based on the White Bear and Larpenteur data).
  c. The daily vehicle volume is relatively low (up to 7000 AADT when adding both directions, based on White Bear and Larpenteur data).

5. In all other situations in the current dataset, dedicated right-turn lanes were associated with a small increase in the rate of driver-pedestrian conflicts for both primary and secondary crosswalks.
  a. This is likely only a concern if pedestrian volume is very high and right-on-red is not permitted.
6. For lower-volume roadways (up to 11000 AADT based on the current dataset, both directions added together), dedicated right-turn lanes may be beneficial for pedestrian safety.
  a. Results indicate that dedicated right-turn lanes are associated with increased likelihood of drivers stopping for pedestrians for lower-volume roadways.
  b. Drivers stopping for pedestrians is generally associated with a lower likelihood of pedestrian crashes (Hossain et al., 2024; Schneider et al., 2018).
7. For higher-volume roadways (16000+ AADT based on the current dataset, both directions added together) dedicated right-turn lanes have mixed results for pedestrian safety.
  a. Benefits for pedestrian safety: dedicated turn lanes on higher-volume roadways are associated with lower high-speed turn rates. This is consistent with the speed data in the driving simulation.
  b. Costs for pedestrian safety: dedicated turn lanes on higher-volume roadways are associated with lower likelihood of right-turning drivers stopping for pedestrians, particularly on the secondary crosswalk.
    i. Unreported follow-up analyses indicated that the most problematic range of AADT for the rate of stopping for pedestrians at the secondary crosswalk for dedicated right-turn lanes was between 16,000 and 20,000 vehicles per day. Higher AADT roadways (i.e., more than 20,000 AADT) showed little to no effect of right-turn lane type on stopping rate.
8. For higher-volume roadways, the implementation of a dedicated turn lane should be considered in conjunction with pedestrian safety countermeasures, particularly for conflicts at the secondary crosswalk.

a. Traffic calming measures may be effective at reducing pedestrian fatalities and collisions. The most effective are speed humps/bumps (Batomen et al., 2023) and pedestrian islands (Kang, 2019).

b. Improve the visibility of the pedestrian through consideration of sightlines.

c. Remind drivers that pedestrians are present through signage. Consider leading pedestrian intervals.

d. Consider advance stop lines so that drivers may be more likely to stop farther back and attend to the roadway.

e. Consider other methods to slow down drivers through the turn of a dedicated right-turn lane to reduce the impact speed of any pedestrian collision at the secondary crosswalk. If possible, shortening the turning radii could be effective at reducing turning speeds (Fitzpatrick et al., 2021).

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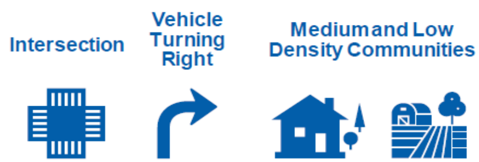
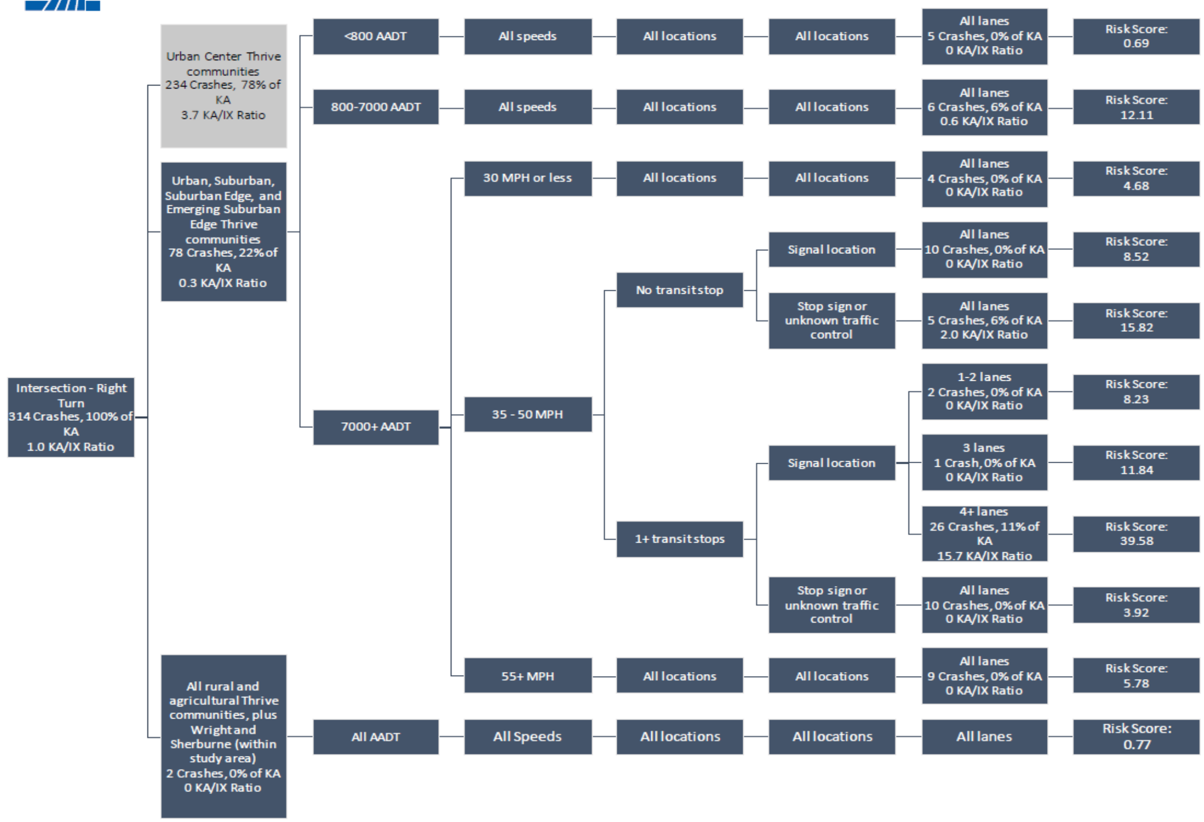
# Appendix A
# Suburban and Rural Communities Crash Tree



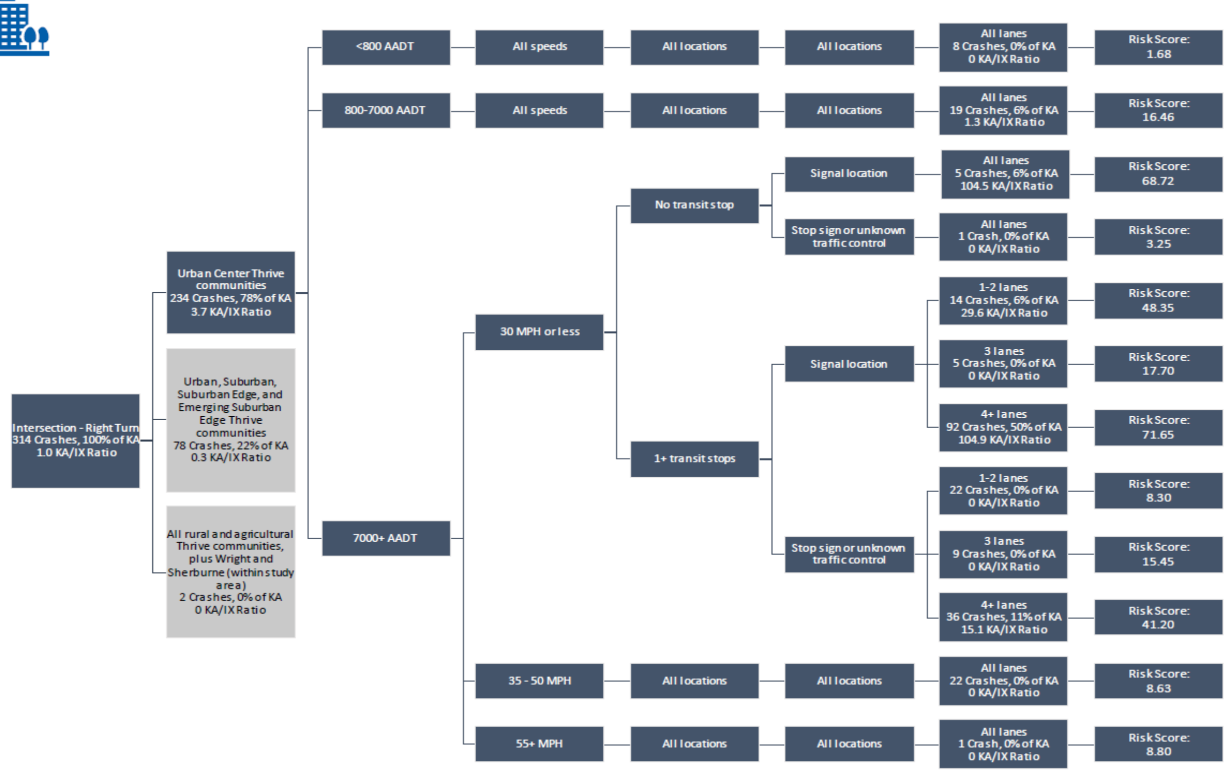

**COURTESY OF TOOLE DESIGN**

# Appendix B
# Urban Community Crash Tree

Intersection

Vehicle Turning Right

High Density Communities

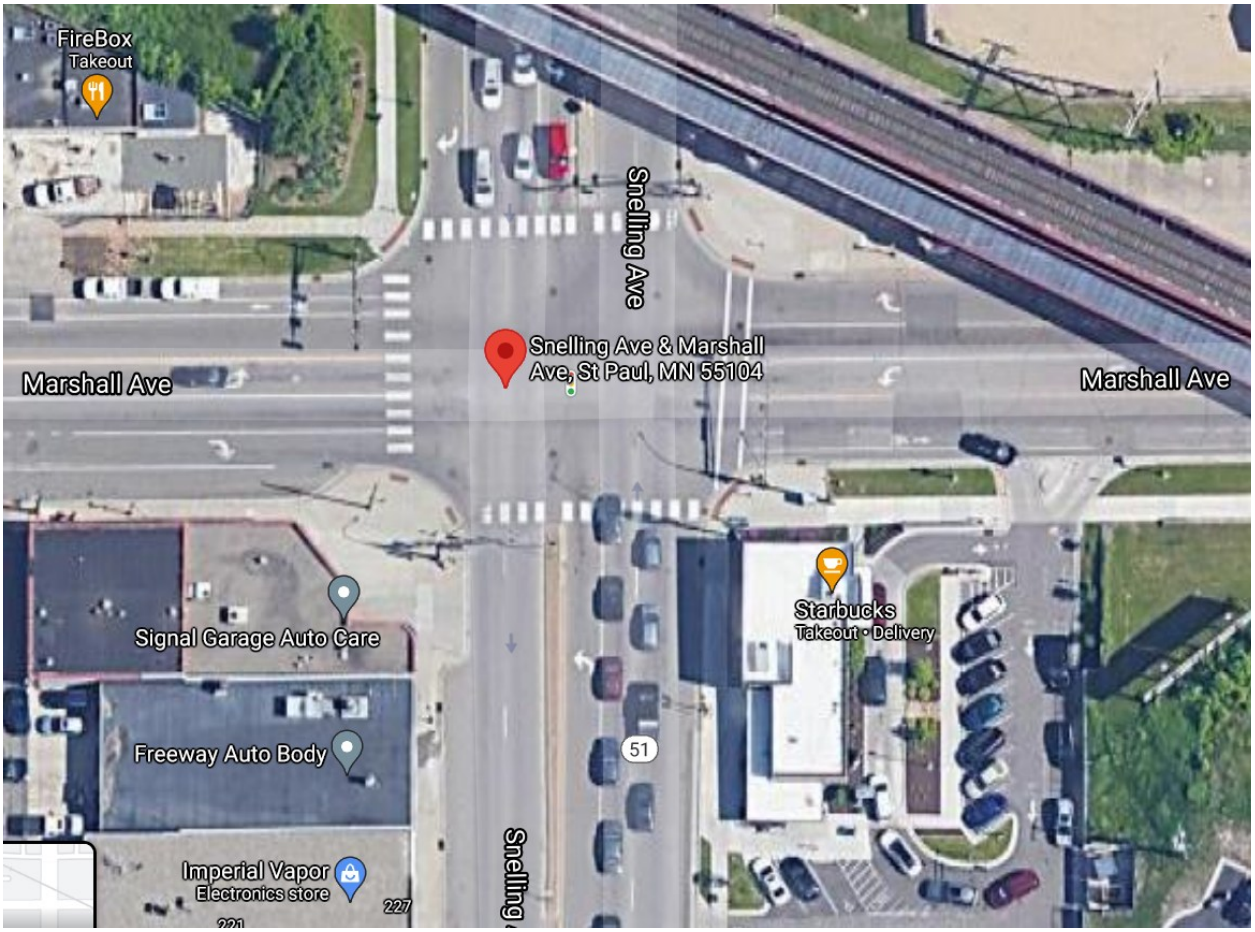



METROPOLITAN COUNCIL | TOOLE DESIGN

**COURTESY OF TOOLE DESIGN**

# Appendix C
# Site Selection Images

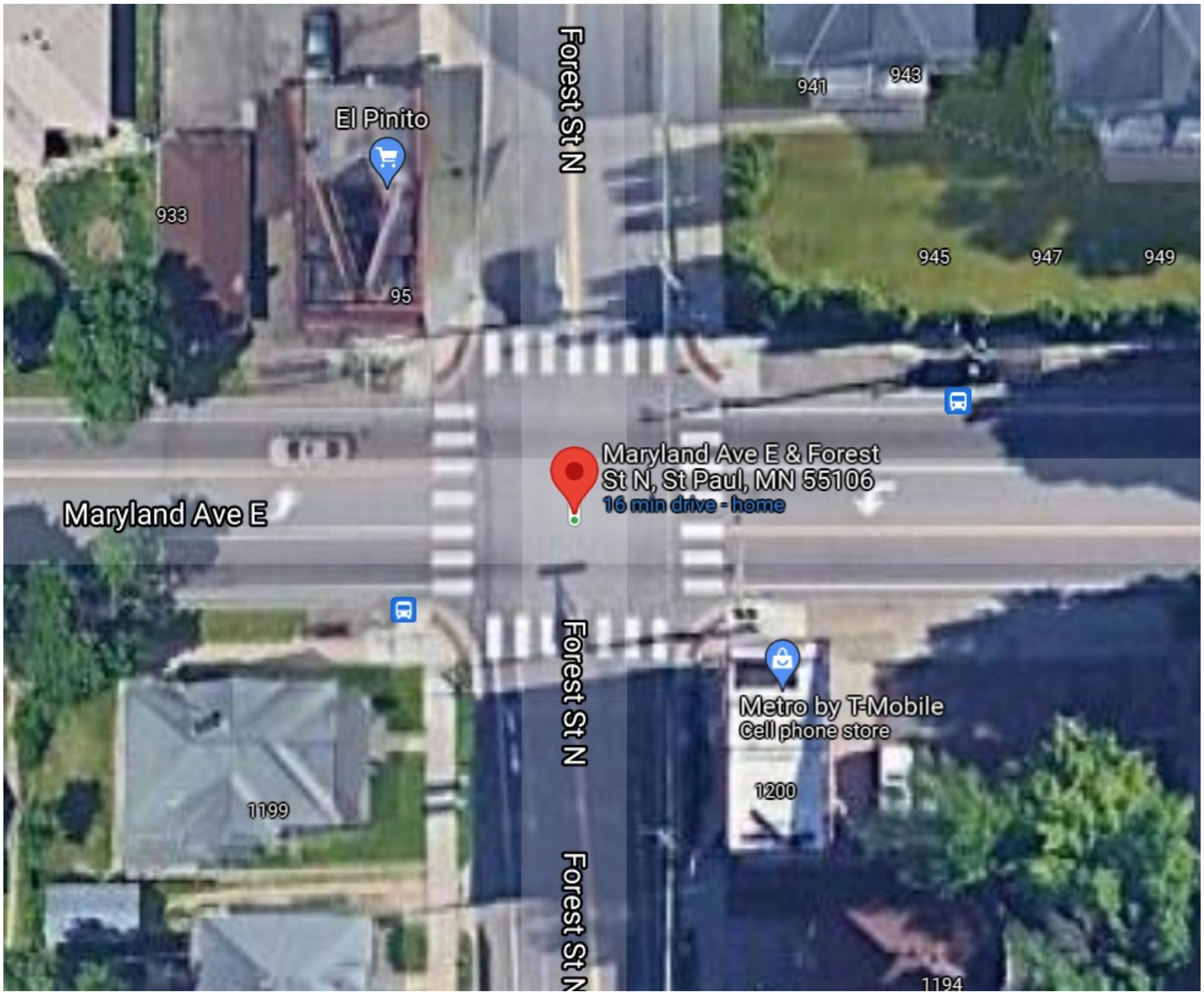

**Maryland Avenue and Payne Avenue (Dedicated Right-Turn Site).**




**Snelling Avenue & Marshall Avenue (Dedicated Right-Turn Site).**


**Wabasha Street & Plato Boulevard (Dedicated Right-Turn Site).**


**Marshall Avenue & Cretin Avenue (Dedicated Right-Turn Site).**



**Maryland Avenue & Forest Avenue (Right-Turn Through Site).**


**Wabasha Street & Fillmore Avenue / Water Street (Right-Turn Through Site).**


**Larpenteur Avenue & White Bear Avenue (Right-Turn Through Site).**


**Marshall Avenue & Prior Avenue (Right-Turn Through Site).**

# Appendix D

# In-Person Coding Sheet

Location: ______________________________________________________________

Describe condition: ________________________ Coder __________ Type: RT Only / RT Through

Date: ____________________ Start Time:______________ Stop Time:______________

| | Walk Cycle | Approach (/ or U) | | | R.Not Yield | R.Yield | Violation |
|---|---|---|---|---|---|---|---|
| | | Not Look | Look | Unsure | / or U | / or U | Overtake |
| Corner | 1 | | | | | | |
| | 2 | | | | | | |
| | 3 | | | | | | |
| | 4 | | | | | | |
| | 5 | | | | | | |
| | 6 | | | | | | |
| | 7 | | | | | | |
| | 8 | | | | | | |
| | 9 | | | | | | |
| | 10 | | | | | | |
| TOTAL | | | | | | | |
| MISC | | | | | | | |

Location: ______________________________________________________________

Describe condition: ________________________ Coder __________ Type: RT Only / RT Through

Date: ____________________ Start Time:______________ Stop Time:______________

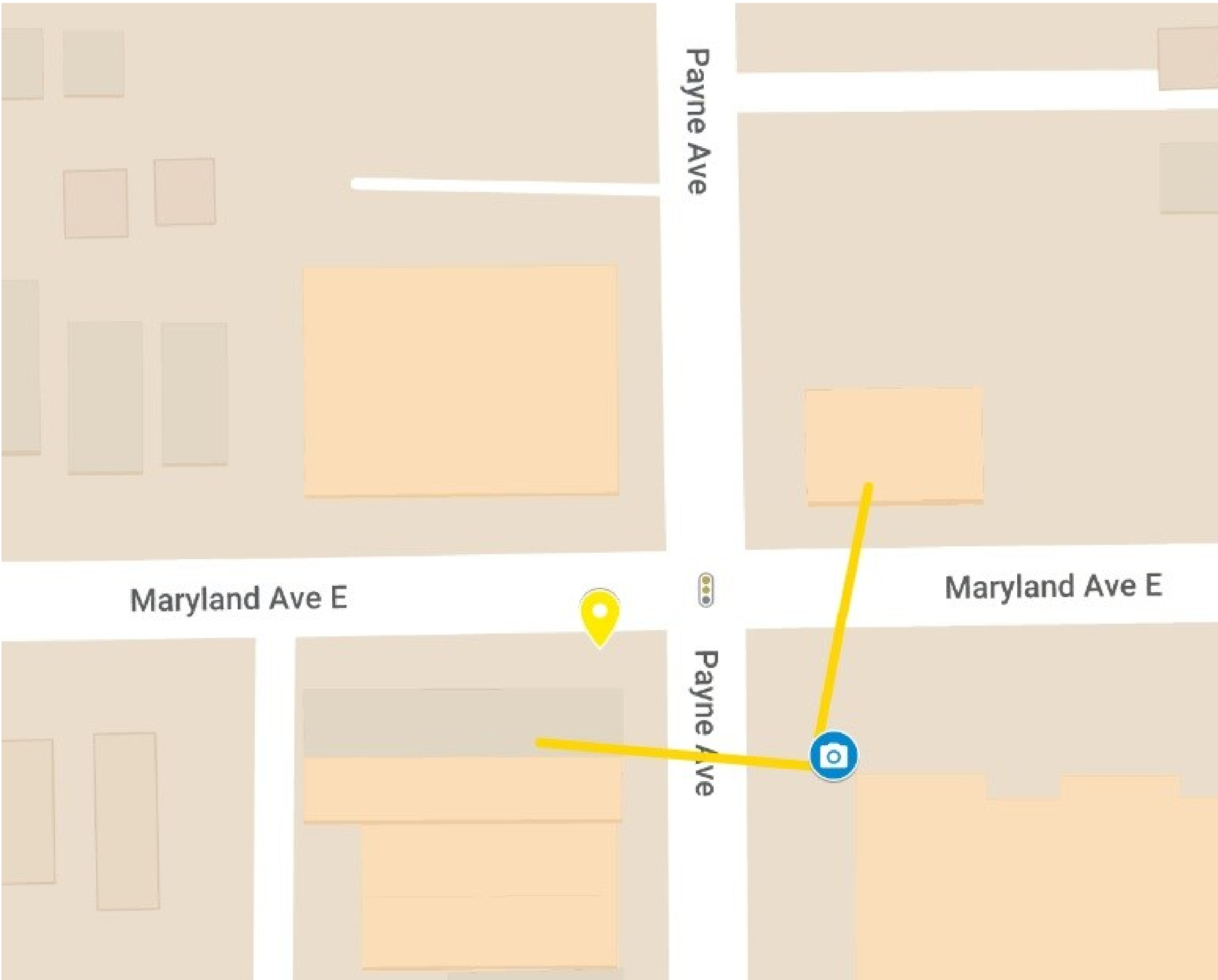
| | Walk Cycle | Approach (/ or U) | | | R.Not Yield | R.Yield | Violation |
|---|---|---|---|---|---|---|---|
| | | Not Look | Look | Unsure | / or U | / or U | Overtake |
| Corner | 1 | | | | | | |
| | 2 | | | | | | |
| | 3 | | | | | | |
| | 4 | | | | | | |
| | 5 | | | | | | |
| | 6 | | | | | | |
| | 7 | | | | | | |
| | 8 | | | | | | |
| | 9 | | | | | | |
| | 10 | | | | | | |
| TOTAL | | | | | | | |
| MISC | | | | | | | |

| **Legend** | / | Basic count, safe turn or yield |
|---|---|---|
| | U | Unsafe turn (speed) or yield (aggressive) |

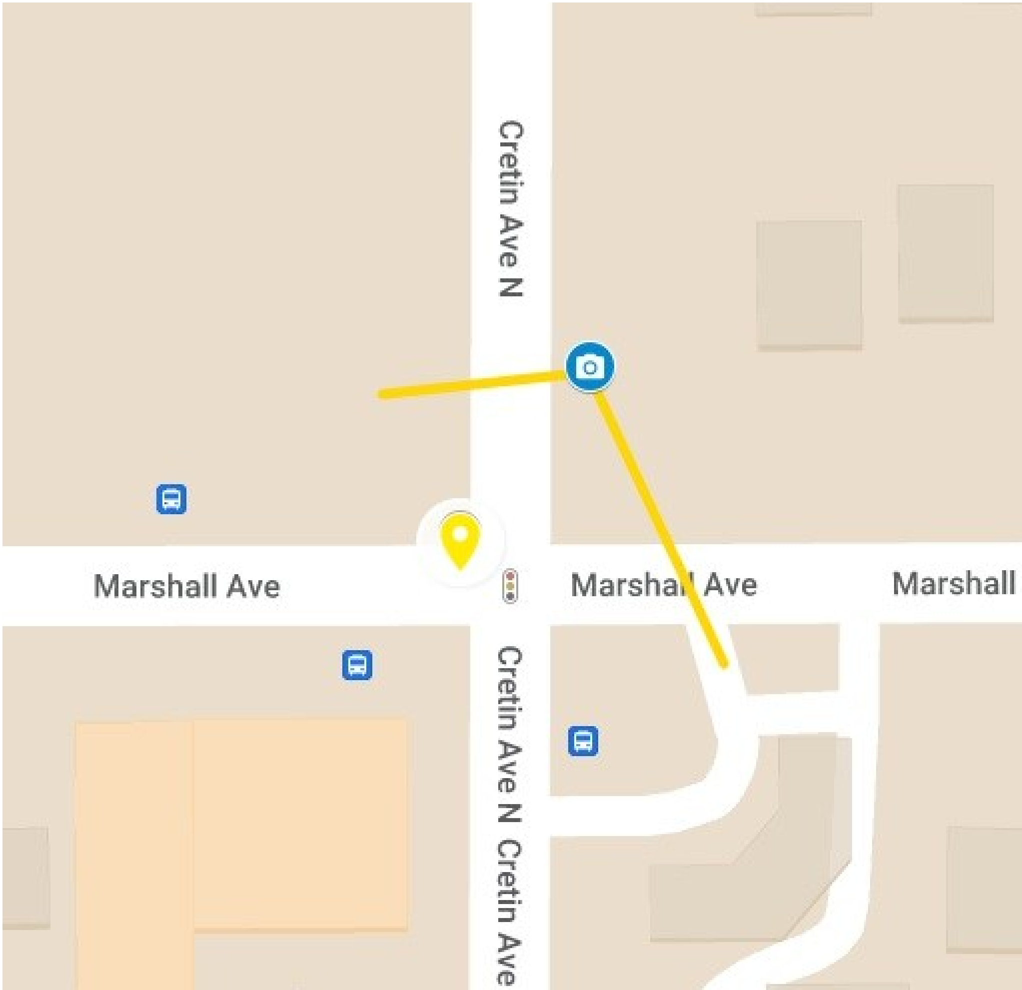
Code Approach for approaching vehicles, or first vehicle approaching red light, not vehicles in a queue.

Code Overtake if vehicle turns from far lane.

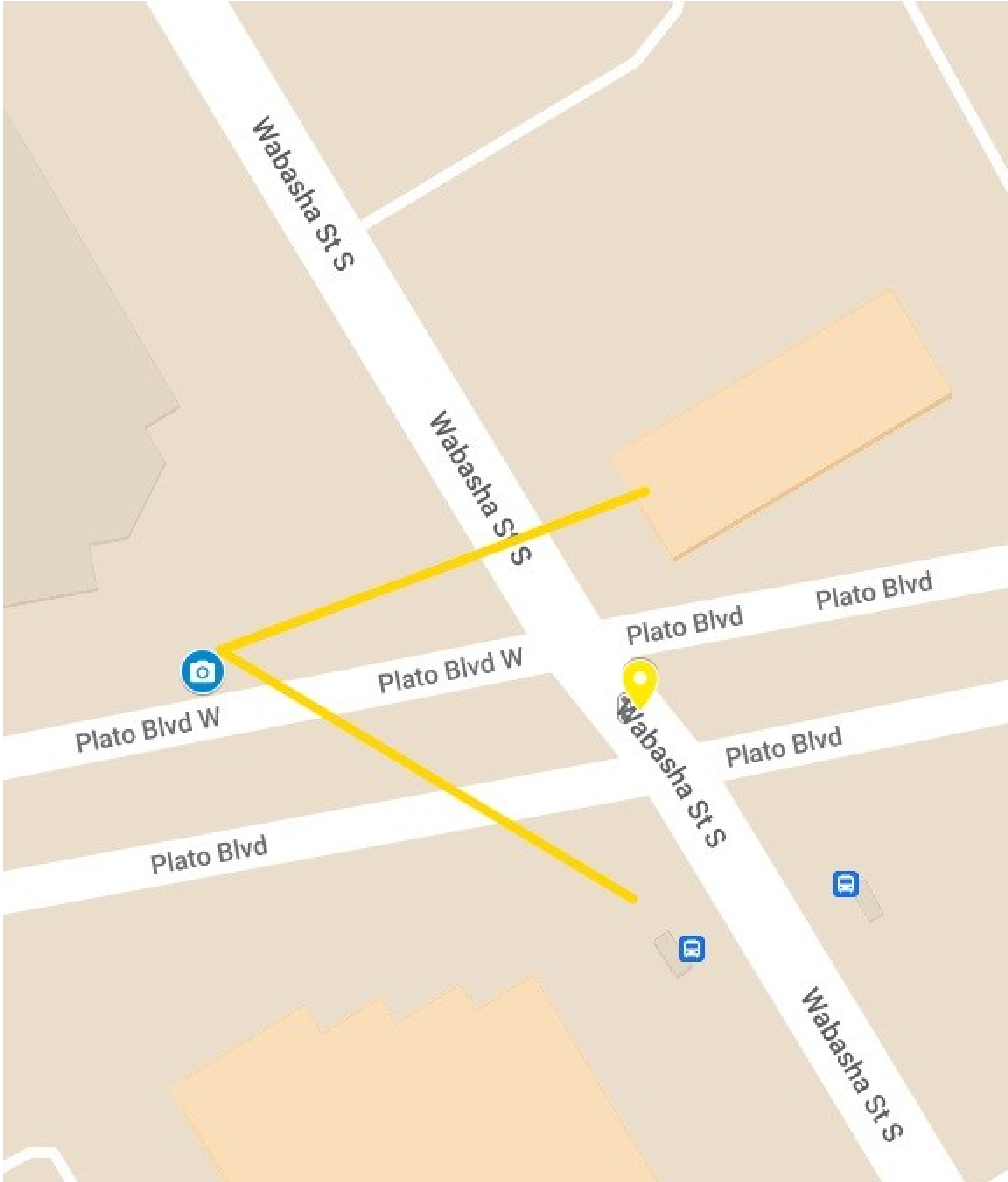
# Appendix E
# Camera Location and Angles for Video Data Collection




**Maryland & Payne (Dedicated Right-Turn Site).**

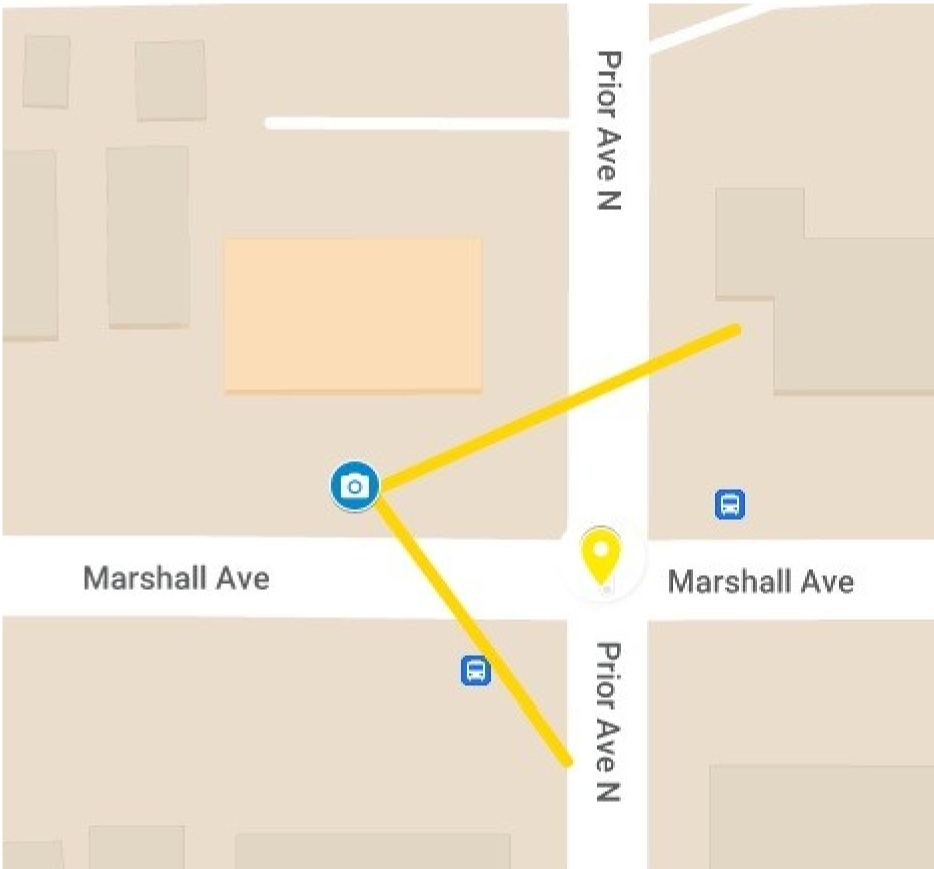



**Marshall & Cretin (Dedicated Right-Turn Site).**

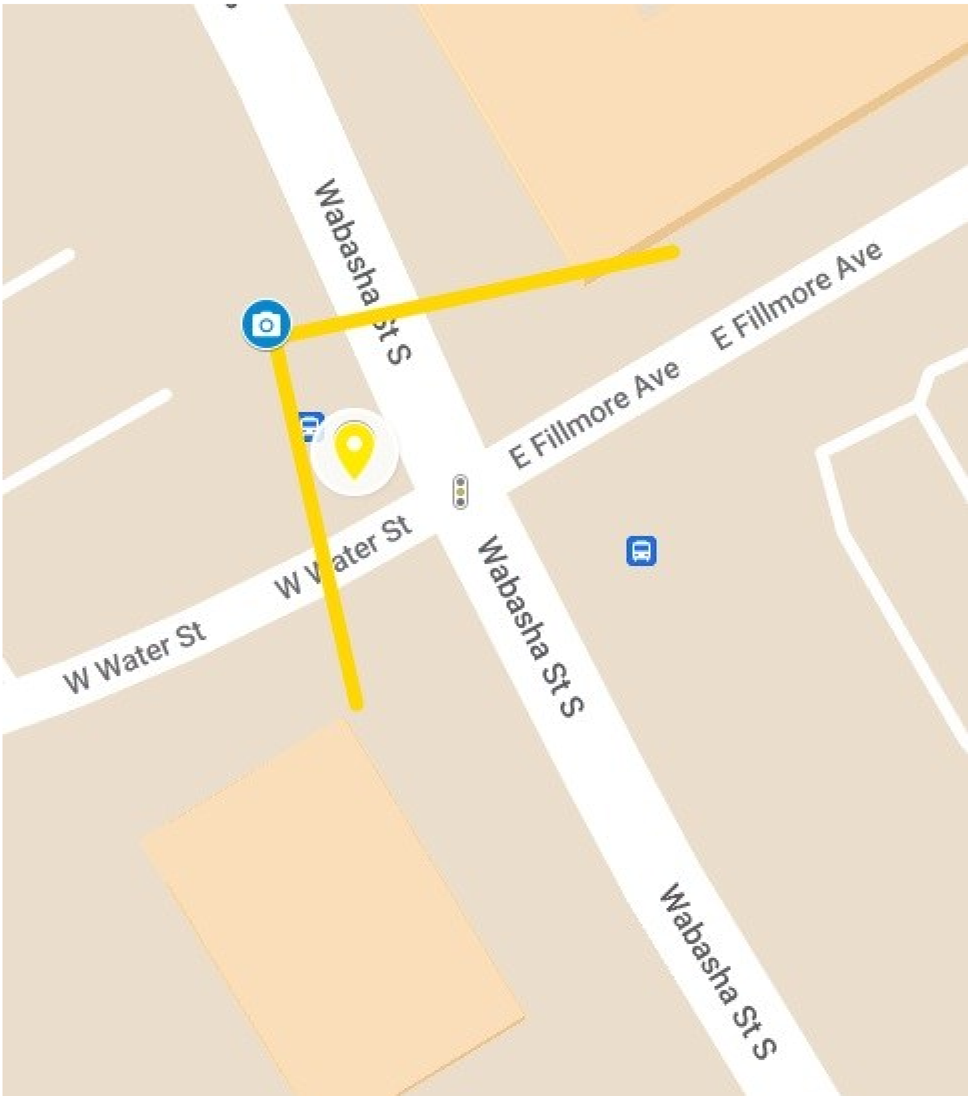



**Wabasha & Plato (Dedicated Right-Turn Site).**

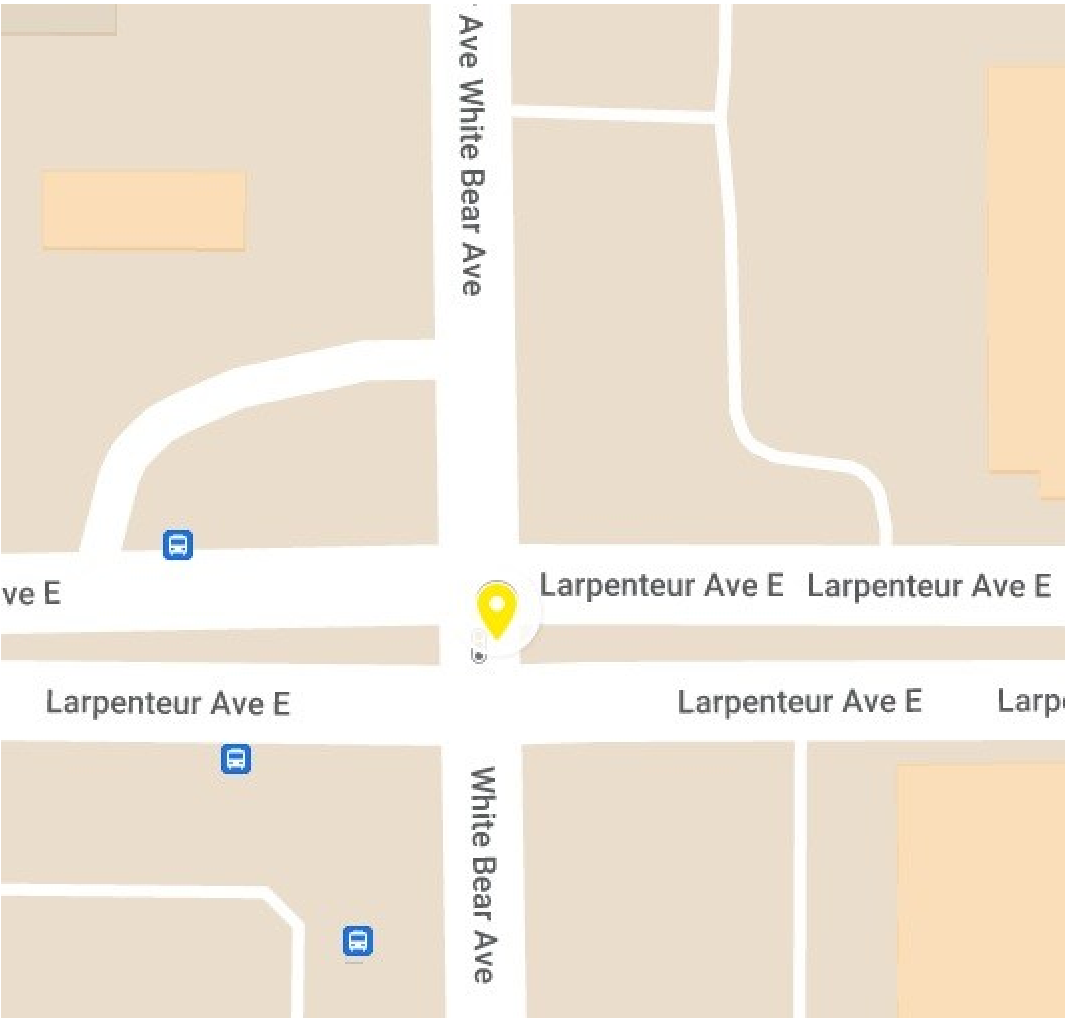

**Marshall & Snelling (Dedicated Right-Turn Site).**



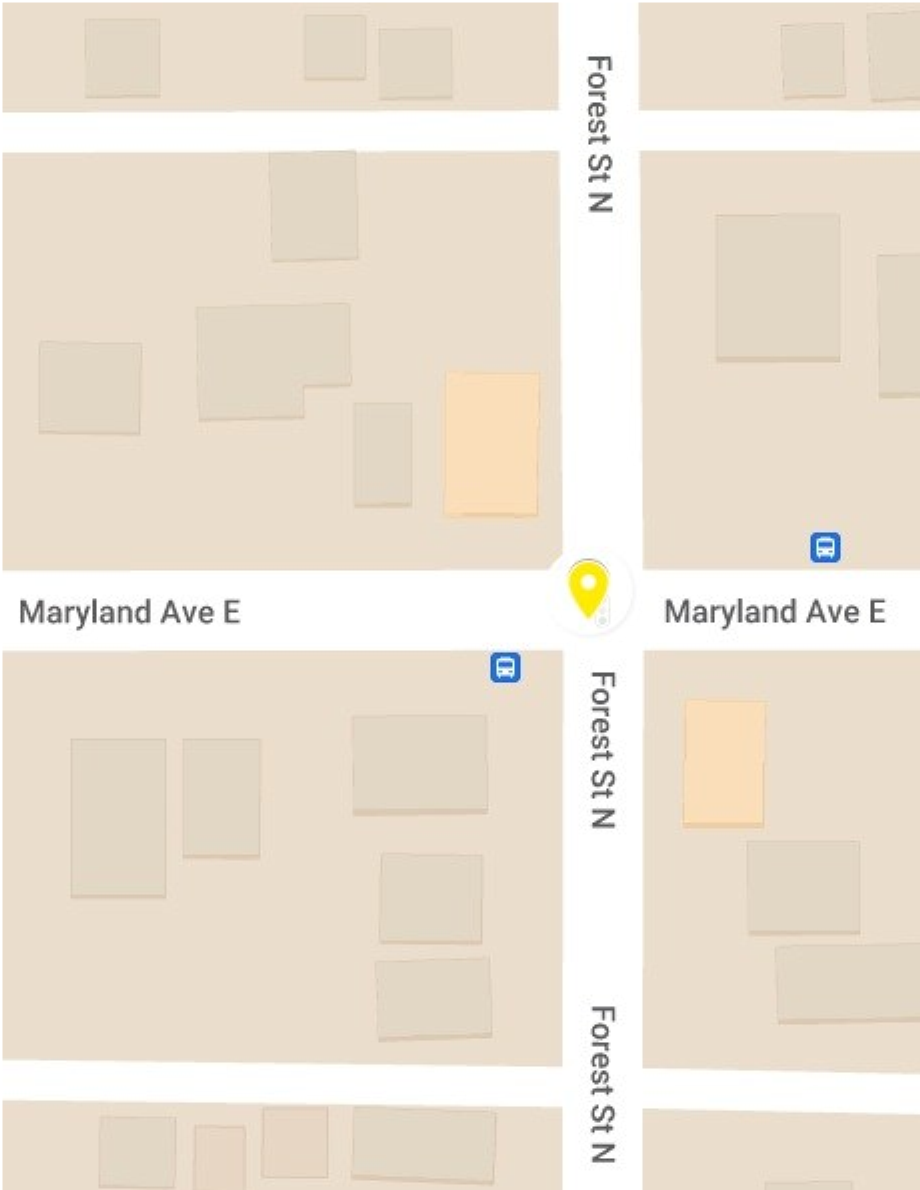

**Marshall & Prior (Right-Turn Through Site).**




**Wabasha & Fillmore/Water (Right-Turn Through Site).**




**Larpenteur & White Bear (Right-Turn Through Site).** *See note in Camera Field Data Collection section about camera angle specification.*




**Maryland & Forest (Right-Turn Through Site).** *See note in Camera Field Data Collection section about camera angle specification.*