DEPARTMENT OF TRANSPORTATION

Evaluation of the Effectiveness of Stop Lines in Increasing the Safety of Stop-Controlled Intersections

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Stop lines are ubiquitous, but do they really impact intersection safety? Prior to this project, no long-term studies on intersection safety with stop lines had been completed. This project was developed with two parallel research efforts: a safety study and an observational study. The safety study was developed to address stop lines' effects over the long term and used crash data from five cities' stop-controlled intersections to perform regression and see if stop lines actually influenced safety. The observational study was developed to determine if stop lines have an effect on driver behavior at intersections and to look at where drivers were stopping. Video was collected at 16 different intersections before and after a stop line was painted. The safety study and observational study showed that stop lines did not have a significant impact on driver behavior or intersection safety, but other factors like speed limits and sight distance did. Implications for practice include carefully examining sight distance at the intended stopping point to ensure drivers have adequate sight distance in both directions. If sight distance is not adequate, moving the intended stop location or reconsidering whether the intersection should have signage -- stop or yield -- or be uncontrolled could yield better driver compliance and safety.</td></tr>
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EVALUATION OF THE EFFECTIVENESS OF STOP LINES IN INCREASING THE SAFETY OF STOP-CONTROLLED INTERSECTIONS

FINAL REPORT

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EXECUTIVE SUMMARY

Stop lines are often installed with the hope of improving intersection safety for drivers and other road users. This project explores the effectiveness of stop lines in increasing the safety of two-way stop-controlled intersections (TWSC). Although the installation and maintenance of one or two stop lines is not a large sum for most jurisdictions, the cumulative cost of installing and maintaining stop lines at hundreds or thousands of stop-controlled intersections can be significant. In Minnesota and other northern states, due to the cold weather and plowing operations, road markings have a significantly shorter lifespan as opposed to posted signs and thus increase the frequency of which the lines must be repainted. Based on information provided by the city of Edina, the maintenance of latex paint stop lines at an intersection costs around $1,000 per year; the use of thermoplastic allows sparser maintenance, but due to higher material cost, the expense is comparable. The city of Edina has approximately 700 TWSC intersections, although only a fraction of these currently have stop lines implemented.

Currently, in the relevant guidelines (*Manual on Uniform Traffic Control Devices, AASHTO Design Manual, and Highway Capacity Manual*) as well as the literature of research efforts, there are no concrete statements or evidence regarding the effectiveness of stop lines in improving the safety of non-all-way stop-controlled (NAWSC) intersections. Prior to this project, studies on the subject of stop lines were very limited. Several studies have focused on the effect of advanced stop lines for cyclist (Wheeler 1993,1995; Allen 2005, Wall 2003, etc) or pedestrian safety (Van Houten 1988), but none that the research team could find specifically focused on the effect of stop lines on driver behaviors. Van Houten found that stop lines worked to "reduce motor vehicle-pedestrian conflicts (near-collisions) by almost 80%" (1988). The study presented in this report focused mainly on driver behavior and vehicle-to-vehicle collisions rather than pedestrian safety. Pedestrians were accounted for during the observational study and checked for significance, but the cases of pedestrian-vehicle interactions were rare and showed no significant differences. This project was developed with two parallel research efforts: a safety study and an observational study.

The safety study was developed to estimate the effect, if any, stop lines have on intersection safety. Following established highway safety manual (HSM) procedures, the study used historical crash records from all NAWSC intersections in five Twin Cities metropolitan area cities to quantify the effect and significance of stop lines on crash occurrence while controlling for other variables like Average Annual Daily Traffic (AADT), sight distance quality, speed limits, and other. The main finding from the safety study was that, when used as the only predictor, the presence of a stop line showed no association with crash occurrence. A negative association occasionally occurred when other predictors were added to a model, especially the presence of a painted crosswalk.

Although, in practical terms, the important factor of any traffic control device is to reliably reduce crashes. In cases like stop lines, or pedestrian crossing treatments, crashes are rare events simply because of the low exposure. When dealing with such low sample sizes, many times the subtler effects are lost or remain undetected. The observational study determines the effect, if any, stop lines have an on driver behavior at intersections. This behavior is expressed in the manner in which drivers "stop" at the stop sign and line, and when they actually stop, the location/distance they stop at in regard to the major road conflicting movements. The observational field study involves the collection of video from 16 different intersections before and after a stop line is implemented.

The report includes a very detailed analysis of the findings from each location as well as more general findings describing overall trends. For example, an overall observation is that, with or without stop lines, drivers always stop 10 feet or more after the stop line and/or sign. In some cases, that stop location is very close to the major road conflicting lanes. In fact, it is reliably determined that the more space there is between the stop line and the absolute edge of the conflicting driving lane the more drivers ignore the stop line and push forward. Although, available sight distance and sight distance quality are significant factors, the aforementioned trend is present even in locations with perfect sight distances.

Specifically, out of total 16 test sites, 7 exhibited a positive change, meaning that drivers started stopping closer to the stop line after it was installed. Still over it but less. At least three (3) sites showed no significant change. From the remaining 6 sites on which the drivers exhibited a counter behavior, meaning they started to stop even farther than before, three (3) had crosswalks, two (2) had considerable distance between the stop line and the conflicting lane, and the remaining one (1) (Lyndale Ave) had very bad sight distance to the right and a large distance between the stop sign and the edge of the conflicting lane. An encouraging observation trend involved the cases where drivers performed a “rolling” stop. The presence of a stop line resulted in a measurable reduction of the roll speed suggesting that the drivers, although technically performing a violation, do so with greater care and attention.

In summary, our conclusions follow:

DO STOP LINES HAVE AN IMPACT ON CRASHES?

Based on the results of the safety study, there is no evidence supporting that the presence of a stop line has a significant independent impact on crashes. Specifically, in the case of intersections with four or more approaches, even when other contributing factors are controlled for, there is no statistically significant association between the presence of a stop line and crash occurrence.

In the case of T-intersections, there still is no evidence supporting that the presence of a stop line has a significant independent impact on crash occurrence. Regardless, when the analysis controls for the effect of exposure, through AADT on the major road, we see that stop lines display a marginal significant beneficial effect, meaning that the presence of a stop line is associated with a decrease in the probability of a crash. A similar combined influence is observed also in the case of painted crosswalks, where it seems that the painted crosswalk increases the probability of a crash. Unfortunately, the sample population is not enough to explore this with certainty especially because of the lack of AADT information on the minor approach.

In conclusion, we do not see the use of stop lines as an effective intervention to improve the safety of TWSC intersections.

DO STOP LINES HAVE AN EFFECT ON OVERALL DRIVER BEHAVIOR?

From the observational study, some of the results suggest that stop lines do influence driver behavior. Unfortunately, the influence is rarely the desired one and is only beneficial in specific ways. Therefore, practitioners are advised to explore the contributing factors and the aspects of driving behavior they would like to influence before defaulting to the implementation of a stop line at a particular intersection.

Although there was no significant effect observed between the presence of a stop line and the decision of drivers to come to a complete stop instead of performing a “rolling” stop, the presence of the stop line reduced the roll speed for vehicles that didn’t come to a full stop. In most cases, the extreme high speeds (low decelerations) were greatly reduced. In the few worst cases, the stop line had no positive or negative effect.

Therefore, in cases where sight distances are challenging, or more time is needed to detect a conflicting vehicle approaching (busy background, horizontal or vertical curves on the major road, etc.), implementing a stop line may be a beneficial intervention. Still, avoid placing the stop line too far from the boundary of the nearest conflicting lane.

DO STOP LINES AFFECT WHERE DRIVERS ARE STOPPING, IF THEY STOP?

The answer to this question is yes but not always in a good way. It is important to clarify that, with or without the presence of a stop line, in all cases, drivers always stopped 10 feet or more after the stop line and/or sign. In fact, when there is a stop line present, the more space there is between the stop line and the absolute edge of the conflicting driving lane the more drivers ignore the stop line.

For this reason, we do not consider the use of stop lines an effective way to prompt drivers to stop at an appropriate location or distance from the major road lanes. In fact, if on a particular approach there is already a painted crosswalk, the use of stop line should be avoided.

In addition, if there are other visual cues indicating the boundary of the major road’s closest driving lane (pavement markings and seams, asphalt or concrete color, etc.), placing the stop line more than 10 feet upstream may result in drivers stopping even closer to the conflicting lane. Therefore, painting stop lines less than 10 feet from conflicting lanes should be avoided. A practice that makes the above cases very common is the habit of painting the stop lines at the same location as the stop sign. In many cases, due to the presence of a sidewalk or curvature of the curb, the stop sign is located much more than 10 feet away from the boundary of the nearest conflicting lane. The aforementioned practice results in drivers stopping closer to the conflicting lane, and should be reconsidered.

Implications for practice include carefully examining sight distance at the intended stopping point to ensure drivers have adequate sight distance in both directions. If sight distance is not adequate, moving the intended stop location or reconsidering whether the intersection should have signage at all – stop or yield -- or be uncontrolled may yield better driver compliance and safety.

CHAPTER 1: INTRODUCTION

Stop lines are ubiquitous and highly desired by residents and pedestrians. This project explores the effectiveness of stop lines in increasing the safety of stop-controlled intersection. Although the installation and maintenance of one or two stop lines is not a large cost for most jurisdictions, the cost of installing and maintaining stop lines at hundreds or thousands of stop-controlled intersections can be significant. Due to the cold weather and plowing operations in Minnesota and other northern states, road markings have a significantly shorter lifespan as opposed to posted signs and thus increase the frequency at which the lines must be repainted. Based on information from the city of Edina, the maintenance of latex paint stop lines at an intersection costs around $1,000 per year; the use of thermoplastic allows sparser maintenance, but due to higher material cost, the expense is comparable.

Currently, in the relevant guidelines (*Manual on Uniform Traffic Control Devices, Green Book, Highway Capacity Manual*) as well as the literature of research efforts, there are no concrete statements or evidence regarding the effectiveness of stop lines in improving the safety of non-all-way stop-controlled (NAWSC) intersections. This project will attempt to identify and produce quantifiable and statistically significant performance measures showing that stop lines have a positive effect on intersection safety. After determining the existence or absence of such surrogate safety measures, the goal of this project is to produce an estimate of the benefit that can be attributed to the presence of stop lines after controlling for any geometric or traffic features.

The project had two parallel research efforts to determine the effect of stop lines: a cross-sectional safety study and an observational before-after study. Three primary questions and related sub-questions drove the development of this study format:

1) Do stop lines have an impact on crashes?
2) Do stop lines have an effect on overall driver behavior?
    a) Do stop lines impact the number of drivers rolling, stopping or ignoring the stop sign?
    b) Are there substantial numbers of drivers ignoring the stop sign?
        i) Are they an extension of the general behavior or a separate population?
        ii) How does the presence of a stop line alter the above?
    c) Does the ratio of rolls to stops change after the placement of the stop line?
    d) Is the crossing behavior different among the three major turning movements?
    e) Did the amount of time that drivers who roll or ignore the stop line take to pass through the intersection change with the placement of the stop line?
3) Do stop lines affect where drivers are stopping, if they stop?
    a) Did the distribution of stopping distances change?
    b) Where were the most drivers stopping before the stop line was added, and did the stop line appear to impact that location?

The safety study was developed to address stop lines' effects on crashes. The observational study was developed to determine if stop lines have an effect on driver behavior at intersections and to look at where drivers were stopping.

In developing both the safety and observational study, a lack of organized information statewide regarding stop-controlled intersections and their markings greatly increased the time and effort required to produce comprehensive results regarding the effects of stop lines. The safety study's scope was reduced to five cities that were able to provide comprehensive GIS files containing the locations of all stop signs in their jurisdiction: Edina, Roseville, Richfield, St. Louis Park, and Golden Valley. Several different types of safety studies were considered but, due to the limitation of available information, a cross-sectional safety study format was chosen. Chapter 2 discusses the safety study in its entirety as well as results.

Similarly, the observational study faced challenges in identifying candidate intersections at which to paint stop lines. These challenges are described in greater detail in Section 3.1 . Ultimately, 16 intersections with 21 total approaches were chosen for painting. Not all sites were able to be painted, and not all sites were able to be filmed after painting. These sites are discussed further in the relevant sections. These intersections were filmed for a period of two weeks, both without the stop line in place and then after the drivers become acclimated to the change (at least two weeks) for two weeks with the stop lines in place. The amount of video collected took a huge amount of effort from undergraduate research assistants (UGRA) to reduce and analyze. Section 3.4 contains site-by-site results.

Overall, the goal of both the safety study and observational study is to determine whether placing stop lines is an effective way to increase intersection safety. This report will help city planners and engineers determine whether intersections in their city require stop lines by examining problematic intersections for other contributing safety factors found in the observational study, such as sight distance. Other recommendations are provided in Chapter 4.

CHAPTER 2: SAFETY STUDY

The objective of the safety study aspect of this project was to examine stop lines' effects on crashes for a large number of intersections across time. Ideally, the MTO would have used the entire state of MN's worth of data rather than the subpopulation described in this chapter; during the course of data collection for the safety study, researchers discovered such a statewide database of two-way stop controlled (TWSC) intersections does not exist in any organized way. Instead, the cities of Roseville, Edina, Golden Valley, St. Louis Park, and Richfield provided shapefiles of stop controlled intersections within their city limits; the research team determined these five cities would be a large enough population to be representative of stop lines' effects on safety. Crash records were also obtained for all intersections in the study. The data collection process is described detail later in this chapter. One possible drawback from including only 5 metro area cities is that biases can exist and remain undetected. For this reason, it is not advisable to draw direct conclusions between this studies results and TWSC intersection is rural areas or areas with considerable different land use patterns. In a state wide study such biases would have been detected and controlled for.

Once the data was collected and assembled, it was analyzed to identify statistically significant factors correlated to crash potential. Speed limits, cross walks, and the presence or absence of stop lines through the years of data were among the factors considered as part of the model. Section 2.6 explains the statistical modeling and results in more detail.

2.1 SAFETY STUDY FORMATS CONSIDERED

As part of the initial effort of designing the study, three potential formats that were considered. Each format has different levels regarding the accuracy and levels it can identify causal relationships between stop lines and crashes, as well as different costs in regard to data needs and tabulation. The following section describes the three potential formats that were considered as well as the reasoning behind the final selection.

2.1.1 Matched Case Control

This method would involve the definition of a number of key characteristics that could potentially influence driver behavior and therefore safety in TWSC intersections. Examples of such characteristics are speed limits, sight distances, AADTs, presence of stop lines, location and size of stop signs, crosswalks, etc. Following this determination, from the population of TWSC intersections matched pairs of locations (1 with stop lines to 2 no stop lines preferably) would be randomly selected. These "pairs" would have an exact match of all characteristics other than the presence of stop lines during historically recorded crashes. This method also would require the study of the crash reports to determine any non-road related causal reasons were involved with the crash (DWI, ice, etc.).

Several decisions would be involved regarding the method of selecting locations, including all or excluding some types of crashes (rear ends for example), but the biggest decision would be the determination of the matching characteristics. Normally for such a decision, the researcher would seek input from results of safety studies in the literature that have identified which factors are relevant and which are not. Knowing in detail the details and time of implementation for the matched characteristics is essential to this study format. Given the absence of organized records available even in a limited geographic area, the research team considered this study format infeasible in the scope of this project.

2.1.2 Empirical Bayes Before/After

This method would involve the comparison of before/after crash rates among crash sites in a geographic area that never had a stop line added to crash sites in that same geographic area that had a stop line added between 2007 and 2015. This time period was selected because of the correspondence between available aerial imagery and the latest Minnesota Crash Mapping Analysis Tool (MnCMAT) year information available.

This method would require at least 60 sites with stop lines and crash history along with 3-4 sites of similar characteristics but no stop lines to determine a 30% change in crash rate due to the stop line. From experience, assuming such information is available, this study format would require close to two years of effort for a researcher because of the accuracy involved in determining the exact set of site characteristics present during each of the recorded crashes. Although not impossible, the research team considered this format to be beyond the available resources in this project and did not pursue it further.

2.1.3 Cross-Sectional Safety Study

This method would involve identification and data collection on all NAWSC and TWSC intersections in a specific, large enough, geographic area. A regression model would be developed, where the dependent variable is each site's crash rate while the predictors are selected characteristics like the ones described in earlier sections. Naturally, one such characteristic is the presence of a stop line.

Performing this analysis would require the creation of one record for each year where matching aerial imagery, MNCMAT data, and AADT are all available for each approach of each TWSC intersection in the aforementioned geographic area. This study, although requiring more data than the other considered formats, has the least restrictions and effort to determine relevant characteristics and to match them to create specific groups of intersections. Naturally, the more factors controlled for in the regression the better the determination of the role of stop lines becomes. Additionally, a complete record for each approach of each intersection is not required. If for a specific year, there is not a complete account of # of crashes, existence of stop lines, or AADT, the record can simply be excluded that record from the data set, assuming enough records are left for a meaningful analysis.

Although this study format would not provide the quality of results of the 2.1.2 Empirical Bayes Before/After format, it would require considerably less effort. In comparison to the Matched Case Control format, the cross-sectional study provides similar accuracy; if the geographic area is adequately large and all TWSC intersections can be accounted for, the effort to form specific "pairs" of locations is excluded.

2.1.4 Chosen Safety Study

The research team decided to move forward with a observational cross-sectional safety study format. The geographic area the study covered was the combined area of the Cities of Edina, St. Louis Park, Roseville, Richfield, and Golden Valley, as those cities had provided the locations of all stop signs in their jurisdictions. Since the information received from the cities included All-Way Stop Controlled (AWSC) intersections, a manual inspection was conducted to identify the TWSC intersections.

2.2 DATA NEEDS

The cross-sectional safety study described required data on traffic volumes, crash counts, and site characteristics for every stop-controlled approach at every NAWSC in a specific geographic area. Ideally the entire state would be included; as that information did not exist in any organized way, researchers looked at including whole cities. Including all such approaches for a whole city helps to reduce the impacts of a sampling bias that might otherwise occur.

For every year included in the analysis, crash records for every crash occurring at a given intersection needed to be retrieved and assigned to an approach at that intersection. The second vital piece of information was the presence of a stop line and/or crosswalk at each approach for every year of the analysis. To help isolate the effects of a stop line, other characteristics from the intersections were included in the analysis as well, such as: vehicle volumes on the major road (opportunities for conflicts), available sight distances (linked to the ability to judge gaps in traffic on the major road), and vehicle speeds on the major road (a strong predictor of crash rates).

2.3 DATA SOURCES

The research team reached out to all large municipalities in the Twin Cities metropolitan area to request digital records of the locations of stop signs. The team received GIS shape files containing the locations of all stop signs in the jurisdiction from Richfield, Edina, Roseville, St. Louis Park, and Golden Valley. The research team also queried the MnDOT Streetnames and AADT GIS layers to retrieve the name, AADT, and rough geometry of roads in those five cities. Historical imagery from the Minnesota Geodetics (MnGeo) Geospatial Image Service, Google Earth, and Google Street View was used to determine the presence of stop lines and crosswalks and evaluate the available sight distances at each site. The majority of speed limits for the major road approaches were collected by querying OpenStreetMap (OSM). Crash records for each of the sites were retrieved from the Minnesota Crash Mapping Analysis Tool (MnCMAT).

2.4 DATA COLLECTION

The research team manually checked and cleaned the available data and used a combination of automated and manual methods to process the data and provide the necessary information for a cross-sectional safety study.

2.4.1 NAWSC Intersection Locations

Five cities, Richfield, Edina, Roseville, St. Louis Park, and Golden Valley, sent shape files containing markers for stop signs in their jurisdiction, but the datasets did not actually identify NAWSC intersections and, in some cases, they contained errors and/or omissions. Erroneous records generally took the form of stop sign markers with incorrect coordinates – up to 50 feet from the actual location of the sign. These errors were small enough that it was still clear which stop signs the markers were referring to. With few exceptions, stop signs that did not have a corresponding marker were located along the cities' borders or on a different agency's right-of-way (county or state). Stop signs at intersections on cities' borders were simple to find if they were located at a four-way intersection because there was a string of four-way intersections with only one stop sign. Because of the difficulty in finding missing stop sign markers at T-intersections on cities' borders, intersections were only included in a given city's dataset if at least one stop sign at that intersection was on that city's side of the intersection. Missing markers corresponding to stop signs in a different agency's right-of-way were particularly common at off-ramps in all five cities, but Roseville's dataset was missing all stop signs within county or state right-of-way. The stop signs at off-ramps that were missing a marker were located by using aerial imagery to inspect all off-ramps that did not have a marker or visible signal arms. Stop signs that were missing a marker and were located in state or county right-of-way in Roseville were identified by using aerial imagery to inspect every intersection on each multi-lane road that did not have visible signal arms. Figure 2.1 shows all stop sign markers present in the five cities that sent their NAWSC intersection information.

An Undergraduate Research Assistant (UGRA) used the Google My Maps feature to upload the stop sign shape files and add a pin with a unique label at each NAWSC intersection in the five cities. Stop signs that were located on driveways or at All-Way Stop-Controlled (AWSC) intersections were omitted. The intersection pins for each city were then saved in KMZ files and imported into ArcMap as shape files along with the stop signs shape files. In ArcMap, stop signs were generally added as needed to intersections that spanned a city's border so as to include both approaches of the intersection.

Manual adjustments were made to the stop sign and intersection pins to improve the accuracy of the approach identification process. Adjustments of intersection pins consisted of moving the pins to be closer to the center of the intersection (according to the 2016 MnGeo aerial imagery) and adding or removing pins that were erroneously included or omitted during the site identification process. Cases of accidental inclusion or omission commonly involved private driveways that resembled public roads or one-way roads that resembled two-way roads. Adjustments to the stop sign markers consisted of deleting duplicates, adding missing markers, and moving existing markers to their positions relative to the intersection of the polylines on the road layer. The vector from the intersection node to the intersection pin was used later to translate other objects at the intersection.

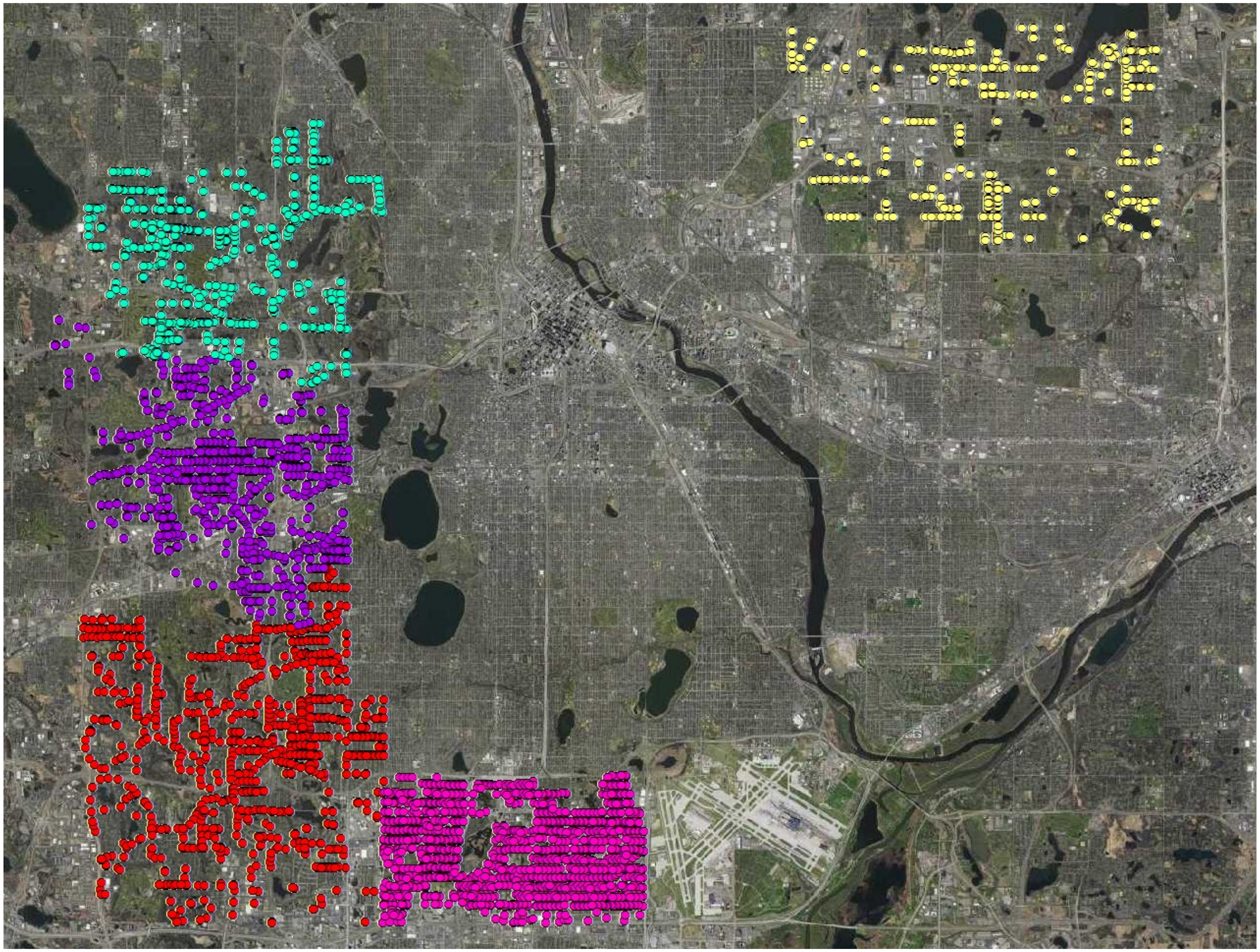

Figure 2.1 Stop sign markers for the five cities that provided data (clockwise from upper right: Roseville, Richfield, Edina, St. Louis Park, and Golden Valley)

The majority of adjustments consisted of moving stop sign markers so their position relative to the intersection node is correct. At site R.120 (see Figure 2.2) in Roseville, the stop sign to the south is about 10 feet west of its actual location on the aerial imagery and both stop sign markers are about 5 feet north of their actual locations on the aerial imagery. The intersection pin is in the correct location but the polylines in the road layer (the yellow lines) are skewed to the southeast. Once the stop signs are in their correct locations on the aerial imagery, they are both translated with the adjustment vector from the intersection pin to the intersection node.

(a) (b)

Figure 2.2 Site R.120 in Roseville before (a) and after (b) the stop sign markers were edited

(a) (b)

Figure 2.3 Site RF.311 in Richfield before (a) and after (b) the stop sign markers and intersection pin were edited

In Richfield, many stop signs were offset from their actual locations by more than 50 feet, as was the case with the two stop signs at site RF.311 in Richfield (see Figure 2.3). Both stop sign pins were moved to their correct locations. Additionally, the intersection pin at RF.311 was too far north of the center of the intersection.

2.4.2 Approach Assignment

The research team developed a methodology for identifying the existing approaches at each stop sign at each pinned intersection in a city. A more thorough explanation of the heuristic can be found in Appendix A and Appendix B. The methodology utilizes the shapefiles containing intersection pins and stop sign locations for a city as well as the MnDOT Streetnames layer to identify each approach controlled by a stop sign (the "minor" approach). Up to three total approaches to the left and/or right of a driver stopped at the minor approach (the "Left Hand Major" (LHM) and "Right Hand Major" (RHM) approaches, respectively) and across the major road from the minor road (the "Opposing" approach) are then identified. Up to two minor approaches are identified per intersection. The output is a list of locations and street names for each minor approach as well as the locations and street names of the LHM, RHM, and Opposing approaches relative to that minor approach. In some cases, an approach is flagged for manual assignment by the approach assignment algorithm or by a person during a later step in the review process. In those cases, a person uses a custom-made user interface to manually identify each applicable approach at the site. Approaches at intersections that had more than four legs, were on divided highways, were adjacent to another intersection, or had a minor road that intersected the major roads at an angle less than 45° were always flagged for manual assignment. This amounted to approximately 20% of all approaches.

2.4.3 Crash Counts

Following the identification of NAWSC intersections, MnDOT used the lists of intersection pins to query their crash databases and return lists of all crashes located within 60 feet of an intersection pin along with the name of that intersection. The records of crashes from 2006 to 2015 were provided in the same format as records from MnCMAT, but crashes from 2016 to 2017 were provided in the format used by MnDOT's new crash database. Because it was unclear how the new data format should be combined with the old one, the research team decided to focus solely on the crashes from 2006 to 2015.

The crash records were then assigned a crash type. The categories used are largely based on the "crash diagram" codes from the MnCMAT data format but also include two additional categories for crashes involving pedestrians or cyclists. The crash types included are as follows:

- Rear end
- Sideswipe passing
- Left turn into traffic
- Ran off road--left side
- Right angle
- Right turn into traffic

- Ran off road--right side
- Head on
- Sideswipe opposing
- Collision with pedestrian
- Collision with pedalcycle
- Other
- Unknown

In some cases, crash records were erroneously assigned to a NAWSC intersection. The most common causes of this were a highway or another intersection nearby. Intersections where this was likely to occur were identified using aerial imagery and the crash records mapped to those intersections were then checked manually. Crashes that occurred on a highway were usually identified by the high-speed limit listed in the crash record. Crashes that occurred at nearby intersections were usually identified by the listed location or the traffic control device (TCD). Crashes that occurred on the highway or at an intersection with a signal were removed and crashes that occurred at a nearby intersection were either reassigned to the correct intersection or were deleted if the crash had been assigned to two intersections. Crashes that did not include at least one other vehicle, a pedestrian, or a cyclist were also removed. Due to inconsistencies in the TCD field from record to record, crashes that did not have a listed TCD or had any other TCD that was not “Signal” or “Stop Sign – Other” were included in the dataset. These records occurred at NAWSC intersections but, for clarity’s sake, they are marked as being different from the records with the TCD listed as “Stop Sign – Other”. This distinction is used in the two sets of totals: SCI (stop-controlled intersection) and All (all crashes that were not removed from the dataset).

Crashes were not assigned to an approach but rather to an intersection. This means that, if an intersection has two minor approaches, both approaches will have the same set of crashes assigned to them. This duplication of records not only inflates the number of crashes at an approach, it prevents analysis of approach-specific characteristics – namely the presence of a stop line. Until a method for assigning crashes to a specific approach is found, only intersections with one minor approach can be included in this type of analysis.

2.4.4 AADTs and Street Names

Using the locations saved during the approach identification process, the AADTs (1995 to 2018) and street names for each approach were queried from a geodatabase. In the majority of cases, several years’ AADTs were not available between 1995 and 2018. Under certain circumstances, missing AADTs were estimated using a linear interpolation algorithm. The algorithm started the estimation process by iterating through the list of AADTs for a given site starting with the first and last years. If the first year (1995) was missing its AADT, it would be filled in with the next available AADT so long as that next AADT was within 5 years after 1995. Similarly, if the last year (2018) was missing its AADT, it would be filled in with an AADT up to 5 years prior to 2018. If an AADT was already known or could not be found, it was not altered. After the attempts to fill in AADTs for the first and last years were complete, the algorithm would attempt to fill in the missing AADTs for the remaining years. For each year that was missing an

AADT, the algorithm would search for two AADTs: the nearest known or estimated AADT up to 5 years before the year with the missing AADT and the nearest known or estimated AADT up to 5 years after the year with the missing AADT. If the algorithm found both of those AADTs, it calculated the percent difference between them. If the two AADTs differed by less than 10%, the algorithm calculated an estimated value using linear interpolation and updated the field with the new AADT. This process was repeated for each approach at each site in each city.

2.4.5 Speed Limits

To control for the effects of vehicle speeds on the major road, the speed limits of the LHM and RHM roads were used as a proxy for actual vehicle speed. This information was collected by querying Open Street Maps (OSM) data. First, a script was run that attempted to automatically collect speed limit information for the routes in question. Because the locations and street names of the major roads were originally gathered from MnDOT sources, there were discrepancies in the naming of roads between the names originally recorded from the MnDOT Streetnames layer and the street names listed in OSM that needed to be resolved. To address these discrepancies, this script utilized an address normalization natural language processing library to express MnDOT route names in as many ways as possible. The values returned are then filtered to remove results that were obviously wrong. For example, if MnDOT names a route "St. Paul St" the address normalization library would return a list of values such as "Saint Paul Saint", "Saint Paul Street", "Street Paul Street", "St. Paul Street", "St. Paul Saint", "Street Paul St", and "Saint Paul St". Once filtered, only the values Saint Paul Street, and St Paul Street were returned. To locate an intersection in OSM, all possible combinations of the names for the major and minor roads were queried against OSM data until a matching intersection was found or all of the combinations had been tried unsuccessfully. If a match was found, the major road was queried in OSM for speed limit. If no speed limit was listed for the segment of the major road at the intersection, another OSM query for speed limit was executed using that road's name and a search radius of 1.5 miles. If no record of the route's speed limit was found after the second query, the route classification was recorded instead.

A significant portion of the intersections missed by the script had roads with names that could not be resolved to the names of roads in OSM. To address these cases, a custom GUI-driven tool was employed that displayed the location of missed intersections along with their corresponding route names in OSM. This functionality allowed for the route name to be manually corrected to exactly as it exists in OSM. Once this correction was complete, the queries from the first script were run again on sites that had been corrected but without the address normalization. Any site with speed limits that were still not identified by the tool was manually visited with Google Maps and a member of the research team checked near major intersections to confirm the presence or absence of a speed limit sign. After that process, any remaining streets were assigned speed limits based on their OSM classifications.

2.4.6 Sight Distances

The points produced during the approach identification process were also used to create rudimentary required sight distance triangles for each minor approach. A full explanation of the methods used to create the sight triangles is included in Appendix B. Required sight distance triangles were calculated for both the LHM and RHM approaches from the perspective of a driver stopped next to the stop sign. The required sight distance triangles were plotted on the MnGeo 2016 aerial imagery with the Streetnames layer polylines for reference (see Figure 2.4). The 2016 imagery was used because it was the highest quality imagery available that was taken when trees had leaves – a necessary condition for incorporating the impact of vegetation on visibility. A single member of the research team used the aerial images with the overlays to estimate whether the available sight distance for each existing major road approach was sufficient.

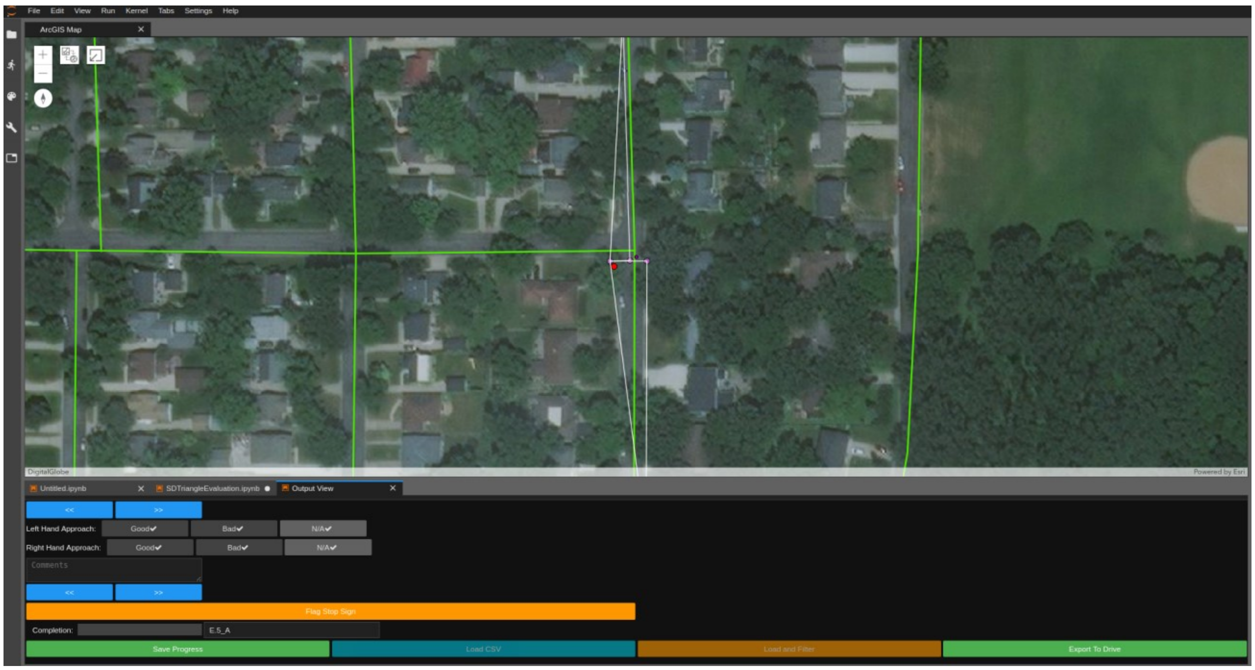

Figure 2.4 User interface of the program used to estimate the adequacy of the sight distances at each site

Using aerial imagery to judge sight distances is not without its drawbacks. Because imagery was not available for every year between 2006 and 2015, it was assumed that the available sight distance did not change from year to year. Cases where road geometries changed significantly were identified and handled during the step in which stop line and crosswalk presence were recorded. Similarly, the limited availability of aerial imagery led to the assumption that the available sight distance remains constant all year long. In reality, available sight distances are not constant and are likely to vary due to changes in the presence of vegetation, snow, or parked cars. Iterating through every site was not only necessary for estimating the adequacy of the available sight distances, it also provided an opportunity to review the approach assignments at each intersection and flag them for manual assignment if needed. The vantage point itself also poses problems for estimating available sight distances. Elevation differences that may limit visibility for drivers (i.e. hills, retaining walls, berms, etc.) are very difficult to perceive from above. Similarly, vertical elements like fences and signs are difficult to see. In some cases, the shadow cast by those elements are visible but not in all. The density and height of vegetation is also difficult to estimate. As a general rule, it was assumed that the branches on conifers (distinguished by their shape, texture, and color) extended all the way to the ground, that the space under deciduous trees was clear unless additional vegetation or landscaping was visible, and that shrubs would block a driver's view. As such, the sight distance ratings are assumed to have some errors.

2.4.7 Stop Line and Crosswalk Presence

Like the adequacy of the available sight distances, the presence of a stop line or crosswalk was determined using aerial imagery. However, for this process, aerial imagery from MnGeo for 8 years between 2004 and 2017, aerial imagery from Google Earth for up to 9 years between 2004 and 2018, and, in some cases, street-level imagery from Google Street View for years after 2007 was used to determine the presence of a stop line and/or a crosswalk for every approach-year. The manual effort took place in two phases: one phase to determine the presence of a stop line and/or crosswalk using the aerial imagery available from MnGeo and a second phase to fill in the gaps left by the first pass using the imagery available from Google.

To streamline the review of the MnGeo imagery, the research team created a program to take eight screenshots centered on each intersection in ArcMap – one for each of the available years of imagery. Street polylines and labelled stop sign markers were included to help identify each approach. The eight screenshots were then arranged in chronological order to form a mosaic like the example shown in Figure 2.5. For every approach, the presence of a stop line and the presence of a crosswalk on the near side of the major road was noted for each of the eight years shown in the mosaics. In some cases, the reviewer was unable to determine whether an image showed a crosswalk and/or a stop line due to an obstruction or low image quality. In those cases, the reviewer would look at the preceding and following images and determine whether the presence or lack of a stop line or crosswalk remained the same on either side of the year with the unclear stop sign and/or crosswalk presence. If there was no change on either side, the unclear stop sign and/or crosswalk presence was assumed to have remained constant, otherwise, the approach-year was flagged for further review using the Google imagery. Similarly, the presence of a stop line and/or crosswalk during the years not pictured in the mosaics was interpolated if possible and if not possible, the year was flagged for further review using the Google imagery. For example, the imagery from 2008 (top row, third from the left) in Figure 2.5 is too blurry to clearly see whether a stop line is present. The images from 2006 and 2010 (top row, second and fourth from the left, respectively) both show a stop line at the approach so it is assumed that a stop line would be present in 2008 as well. In 2004, the approach does not have a crosswalk or stop line but it does in 2006. As such, 2005 is flagged for further review.


Figure 2.5 Aerial imagery mosaic (left to right, top: 2004, 2006, 2008, 2010; bottom: 2012, 2015, 2016, 2017)

The second phase of the manual effort involved using Google Earth historical imagery and Google Maps Street View to review the approach-years flagged during the first pass and, if the Google imagery did not clarify the ambiguity, the approach-year would be removed from the dataset. If any of the imagery showed construction for an approach-year, the approach-year was removed. If the geometry significantly changed after the construction, the geometry that was present during the most usable years was kept and the approach-years that had the geometry that was present during fewer usable years were removed from the dataset. This aerial imagery, over two thousand intersections across all five cities, was reviewed by hand by a member of the research team looking for the presence of stop lines and crosswalks across all years included.

As was the case with the estimation of available sight distances, using aerial imagery to determine the presence of a stop line and/or crosswalk for an approach-year has some limitations. The main issue is the infrequency at which aerial images are taken. For example, neither MnGeo nor Google had sufficiently detailed aerial images from 2005 at most of the intersections. The fact that aerial images tend to be taken in spring or late fall means that it can be difficult to determine when a stop line or crosswalk was painted or paved over. The time of year that the available images are taken varies from year to year, further complicating the assumption that the conditions shown in the aerial image for a given year are representative of conditions during that whole year.

2.5 DATA REDUCTION

Table 2.1 contains an explanation of the contents of the sheet created for the safety analysis. The data was divided by city with one city per sheet. Each year for each approach was a new row. After this data was assembled, it was given to Professor Gary Davis who did the regression analysis.

Table 2.1 Contents of the StpLns All Cities All Data spreadsheet by column

Column Name	Units	Description
Site	[ ]	Unique code for the minor approach
City	[ ]	Letter code for the city that the minor approach is in
Intersection	[ ]	Number code for the intersection that the minor approach is at
Approach	[ ]	Letter code denoting which minor approach at the intersection is being referred to
Year	[ ]	Year for which the record contains data
Minor AADT	[vpd]	Annual Average Daily Traffic for the minor approach ("-1" if the data cannot be found or interpolated, "-2" if the approach does not exist)
LHM AADT	[vpd]	Annual Average Daily Traffic for the Left Hand Major (LHM) approach ("-1" if the data cannot be found or interpolated, "-2" if the approach does not exist)
RHM AADT	[vpd]	Annual Average Daily Traffic for the Right Hand Major (RHM) approach ("-1" if the data cannot be found or interpolated, "-2" if the approach does not exist)
Opposing AADT	[vpd]	Annual Average Daily Traffic for the opposing approach ("-1" if the data cannot be found or interpolated, "-2" if the approach does not exist)
Minor Name	[ ]	Street name of the minor approach ("None" if the name could not be found or the approach does not exist)
LHM Name	[ ]	Street name of the Left Hand Major (LHM) approach ("None" if the name could not be found or the approach does not exist)
RHM Name	[ ]	Street name of the Right Hand Major (RHM) approach ("None" if the name could not be found or the approach does not exist)
Opposing Name	[ ]	Street name of the opposing approach ("None" if the name could not be found or the approach does not exist)
Left SD Good?	[Boolean]	Boolean denoting whether available sight distance to the left is estimated (via aerial imagery) to be sufficient ("1" if yes, "0" if no, "-1" if there is no major road to the left)
Right SD Good?	[Boolean]	Boolean denoting whether available sight distance to the right is estimated (via aerial imagery) to be sufficient ("1" if yes, "0" if no, "-1" if there is no major road to the right)

Column Name	Units	Description
Left SL	[mph]	Speed limit on the major road to the driver's left. If no speed limit was found on OpenStreetMap (OSM), the speed limit was estimated ("30" if the road is classified as "residential" on OSM, same speed limit as other segments on the major road within 1.5 miles of the intersection, educated guess or Google Street View if no other speed limits can be found)
Right SL	[mph]	Speed limit on the major road to the driver's right. If no speed limit was found on OpenStreetMap (OSM), the speed limit was estimated ("30" if the road is classified as "residential" on OSM, same speed limit as other segments on the major road within 1.5 miles of the intersection, educated guess or Google Street View if no other speed limits can be found)
Stop line?	[Boolean]	Boolean denoting whether the minor approach had a stop line at the time the available aerial or Street View imagery was available for a given year ("1" if yes, "0" if no). If imagery was not available for a given year but there was no change in the stop line presence for the years preceding and following the gap, the stop line presence was assumed to be the same. If there was a difference, the year was omitted.
Crosswalk?	[Boolean]	Boolean denoting whether the minor approach was crossed by a crosswalk at the time the available aerial or Street View imagery was available for a given year ("1" if yes, "0" if no). If imagery was not available for a given year but there was no change in the crosswalk presence for the years preceding and following the gap, the crosswalk presence was assumed to be the same. If there was a difference, the year was omitted.
Tot Num. of Approaches	[ ]	Number of "legs" at the intersection (including minor approach)
Num. Stop Signs	[ ]	Number of stop-controlled approaches at the intersection (including minor approach)
Line Presence Code	[ ]	Combined code consisting of three parts: - Number of stop signs at the intersection (see "Num. Stop Signs") - The stop line presence of the minor approaches at the intersection (see "Stop line?") ("1" if all minor approaches have a stop line, "0" if no minor approaches have a stop line, "-1" if the approaches do not have the same stop line presence) - The crosswalk presence of the minor approaches at the intersection (see "Crosswalk?") ("1" if all minor approaches have a crosswalk, "0" if no minor approaches have a crosswalk, "-1" if the approaches do not have the same crosswalk presence)
Tot_All	[crashes]	Number of crashes* ** at the intersection for a given year.

Column Name	Units	Description
Tot_SCI	[crashes]	Number of crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC10_All	[crashes]	Number of “sideswipe passing” (diag = 02) crashes* ** at the intersection for a given year.
MOC11_All	[crashes]	Number of “sideswipe opposing” (diag = 09) crashes* ** at the intersection for a given year.
MOC12_All	[crashes]	Number of “rear end” (diag = 01) crashes* ** at the intersection for a given year.
MOC13_All	[crashes]	Number of “head on” (diag = 08) crashes* ** at the intersection for a given year.
MOC50_All	[crashes]	Number of “right angle” (diag = 05) crashes* ** at the intersection for a given year.
MOC51_All	[crashes]	Number of “ left turn into traffic” (diag = 03) crashes* ** at the intersection for a given year.
MOC52_All	[crashes]	Number of “right turn into traffic” (diag = 06) crashes* ** at the intersection for a given year.
MOC61_All	[crashes]	Number of “collision with Pedalcycle” (type = 06) crashes* ** at the intersection for a given year.
MOC62_All	[crashes]	Number of “collision with pedestrian” (type = 07) crashes* ** at the intersection for a given year.
MOC90_All	[crashes]	Number of “other” (diag = 90) crashes* ** at the intersection for a given year.
MOC99_All	[crashes]	Number of “unknown” (diag = 99) crashes* ** at the intersection for a given year.
MOC10_SCI	[crashes]	Number of “sideswipe passing” (diag = 02) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC11_SCI	[crashes]	Number of “sideswipe opposing” (diag = 09) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC12_SCI	[crashes]	Number of “rear end” (diag = 01) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC13_SCI	[crashes]	Number of “head on” (diag = 08) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC50_SCI	[crashes]	Number of “right angle” (diag = 05) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC51_SCI	[crashes]	Number of “left turn into traffic” (diag = 03) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC52_SCI	[crashes]	Number of “right turn into traffic” (diag = 06) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.

Column Name	Units	Description
MOC61_SCI	[crashes]	Number of “collision with Pedalcycle” (type = 06) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC62_SCI	[crashes]	Number of “collision with pedestrian” (type = 07) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC90_SCI	[crashes]	Number of “other” (diag = 90) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
MOC99_SCI	[crashes]	Number of “unknown” (diag = 99) crashes* ** at the intersection for a given year where the crash record lists the traffic control device as “stop sign - other”.
Include	[Boolean]	Boolean denoting whether a given approach-year should be included in the dataset (“1” for yes, “0” for no)
T-Int?	[Boolean]	Boolean denoting whether the minor approach is the base of a T-intersection – i.e. the “bottom” of the T (“1” for yes, “0” for no)
2006-2015?	[Boolean]	Boolean denoting whether the record refers to a year between 2006 and 2015 – the years covered by the MnCMAT crash dataset (“1” for yes, “0” for no)

* If there are two approaches at an intersection, crashes at the intersection will be assigned to both approaches
** Crashes where the traffic control device is listed as “signal” were excluded

2.6 DATA ANALYSIS

This section describes exploratory analyses regarding the value of stop lines as possible crash mitigation measures. As described above in Section 2.4 , data from five Twin Cities Metro area cities were assembled for this analysis. Cross-sectional analyses using the observational database described in

Table 2.1 are used to determine if there is a reliable association between the presence of stop lines and the occurrence of relevant crashes. If such an association is found, then future work using more rigorous designs would be needed to determine if there is a causal relation between stop lines and crash risk. On the other hand, if no association is found then a causal connection is unlikely.

The crashes relevant to stop lines on stop-controlled intersection approaches are those involving collisions between a main road vehicle and a minor road vehicle. The minor road driver could be attempting to cross the road or to turn right or left. Similarly, the major road driver might be attempting cross the intersection or attempting to turn left. Ideally, analyses should be based on crashes were where stop line-relevant configurations have been explicitly identified but such identification is difficult from the crash coding used in the Minnesota crash database prior to 2017. Prior to 2017 the best indicator of crash configuration is Diagram code, and a code of 05, “right-angle,” should indicate a collision between a minor road vehicle and a major road vehicle. On occasion, though, crashes involving turning vehicles have been coded as “right-angle” crashes. Again, ideally, an angle crash at a T-intersection should involve major road and minor road vehicles, but such crashes might also be coded as right or left turn-involved. Resolving these ambiguities has, in the past, usually required manual review of the drawings and narratives provided by investigating officers. For this exploratory research it was decided to conduct separates analyses for T-intersection and 4-legged intersection approaches, using both right-angle crashes only and right-angle plus turn crashes as measures.

As indicated previously, the basic unit of analysis was the crash frequency associated with a particular intersection approach during a particular year. The data files for Edina, Golden Valley, Richfield, and Roseville all contained indicators as to whether an approach was at a T-intersection and so each of these files was split into T-intersection and four-legged sub-files. (St. Louis Park did not initially have that information; a corrected datafile was later provided to the research team.) The type-specific sub-files for the cities were then aggregated to produce two master files, one for T-intersections and one for four-legged intersections. The files were loaded into the statistical package Minitab 14 for statistical analyses, and summary statistics were computed from each the two master files. Table 2.2 summarizes approach features for the T-intersection approaches while Table 2.3 summarizes crash frequencies by type at the T-intersections. Table 2.4 and Table 2.5 show similar information for the four-legged approaches.

Table 2.2 Feature Statistics for T-intersection Approaches

Location			**Speed Limit**		**Crosswalk**	
City	*Count*		*Value*	*Count*	*Present?*	*Count*
Edina	4213		25	228	No	12920
Golden Valley	2072		30	11349	Yes	1628
Roseville	3477		35	2201		
Richfield	2176		36	10		
St. Louis Park	2610		40	690		
Total	14548		50	40		
			55	30		
Sight Distance				**Stop Line**		
Good?	*Left Side*	*Right Side*		*Present?*	*Count*	
No	6013	5755		No	12731	
Yes	8299	8302		Yes	1817	
Missing Data	236	491				
Average Daily Traffic						
Approach	*Data Available*	*Average*	*Standard Deviation*	*Minimum*	*Maximum*	*Missing Data*
Major	11056	6296	5173	156	28000	3492
Minor	779	1908	1378	85	9200	13769

Table 2.3 Crash Frequencies at T-intersection Approaches

Crash Count	All Crashes	Right Angle	Left Turn	Right Turn	Pedalcycle	Pedestrian
0	13095	14106	14375	14509	14475	14510
1	1121	401	168	39	742	37
2	236	29	5		1	1
3	62	8				
4	20	3				
5	7	1				
6	5					
7	1					
8	1					

Table 2.4 Feature Statistics for Four-Legged Approaches

Location			**Speed Limit**		**Crosswalk**	
City	*Count*		*Value*	*Count*	*Present?*	*Count*
Edina	2937		20	40	No	15964
Golden Valley	1224		25	116	Yes	951
Roseville	1819		30	15221		
Richfield	7521		35	1288		
St. Louis Park	3414		40	250		
Total	16915					
Sight Distance				**Stop Line**		
Good?	*Left Side*	*Right Side*		*Present?*	*Count*	
No	6980	6507		No	15964	
Yes	9935	10408		Yes	951	
Average Daily Traffic						
Approach	*Data Available*	*Average*	*Standard Deviation*	*Minimum*	*Maximum*	*Missing Data*
Major	10618	5491	5324	154	28000	6297
Minor	610	1202	787	90	5017	16305

Table 2.5 Crash Frequencies at Four-Legged Approaches

Crash Count	All Crashes	Right Angle	Left Turn	Right Turn	Pedalcycle	Pedestrian
0	14552	15663	16694	16848	16812	16871
1	1721	1030	201	65	101	44
2	423	172	16	2	2	
3	120	32	4			
4	54	12				
5	25	4				
6	5	0				
7	11	2				
8	4					

Looking at Table 2.2, overall, there was a maximum of 14,548 approach-years of data available for the T-intersection approaches, but some data were missing for some variables. 13,769 rows were missing Minor approach ADTs. Looking at Table 2.3, the overwhelming majority of approach-years showed no reported crashes, with only one reported crash being the next most frequent outcome. This is especially true when we consider specific crash types like right-angle or left-turn. Table 2.4 and Table 2.5 show generally similar patterns for the four-legged approaches.

The first analysis looked at the relation between the presence/absence of stop lines and the occurrence of right-angle crashes on T-intersection approaches. Referring to Table 2.3, of the 14,548 approach-years of data available 14,106 showed no right-angle crashes, 401 showed one right-angle crash, 41 showed between two and five crashes, and none showed more than five crashes. The fraction of cases with one crash is 0.0275 and the fraction of cases with more than one crash is only 0.0028. In situations like this, where probability of one crash is approximately equally to the probability one or more crashes, a reasonable approximation is to model crash outcomes as binary, with the outcomes being zero crashes or 1 or more crashes. Using Minitab, the MOC50 column for the T-intersection approaches was recoded to value 0 when the right-angle crash count was 0 and to value 1 when at least 1 right-angle crash was reported. A series of binary logistic regression models were then fit to assess any association between the occurrence of right-angle crashes and intersection features such as ADT, sight distance, and the presence of stop lines. If P[Yi=1] denotes the probability that approach-year (aka row) i of the data file shows at least one right angle crash, then a binary logistic model of the form

$$P[Y_i = 1] = \frac{\exp\left(\beta_0 + \sum_j \beta_j x_{i,j}\right)}{1 + \exp\left(\beta_0 + \sum_j \beta_j x_{i,j}\right)}$$

captures the associations between this probability and a set of measurable features denoted by x_{i1}, x_{i2}, …, with the coefficients β_1, β_2, … reflecting the strength and direction of those associations. If $\beta_j=0$ then feature x_{ij} has no association with the probability of crash occurrence, $\beta_j>0$ means an increase in x_{ij} is associated with increases in probability of crash occurrence, and $\beta_j<0$ means an increase x_{ij} is associated with a decrease in this probability. If all coefficients including β_0 are equal to 0 then $P[Y_i=1]=P[Y_i=0]=0.5$.

Table 2.6 summarizes results from seven different models of the probability of occurrence of right-angle crashes at T-intersection approaches. The first model only contained the constant β_0 and the presence/absence of stop lines as predictors. The estimated value for the constant was -3.4440 and its associated standard error estimate was 0.0512. The Z-statistic for testing the hypothesis that $\beta_0=0$ was -67.30 and the probability (P-value) of getting a Z-statistic this large or larger had it been true that $\beta_0=0$ is essentially zero, indicating that, for this data set, crash and no-crash outcomes are not equally likely. On the other hand, the estimated coefficient for the presence/absence of stop lines was $\beta_1=-0.163$ with an associated standard error of estimate equal to 0.155. The Z-statistic testing the hypothesis that $\beta_1=0$ was -1.05 and the probability of getting a Z-statistic this large or larger if $\beta_1=0$ is true was 0.293, indicating that this data set is consistent with no association between the presence of stop lines and the occurrence of right-angle crashes.

Table 2.6 Binary Logistic Analyses for T-intersection Approaches: Occurrence of Right Angle Crashes as Dependent Variable.

Predictor	Estimated β	Standard Error	Z-statistic	P-Value	Significance
1. Constant	-3.4440	0.0512	-67.30	0.000	**
Stop Line	-0.163	0.155	-1.05	0.293	
2. Constant	-3.4909	0.0531	-65.78	0.000	**
Stop Line	**-0.562**	**0.183**	**-3.07**	**0.002**	**
Crosswalk	**0.702**	**0.158**	**4.46**	**0.000**	**
3. Constant	-4.0148	0.0924	-43.43	0.000	**
Stop Line	**-0.353**	**0.163**	**-2.16**	**0.031**	*
Major ADT	**0.000104**	**0.000008**	**13.08**	**0.000**	**
4. Constant	-4.343	0.132	-32.82	0.000	**
Stop Line	**-0.340**	**0.164**	**-2.07**	**0.038**	*
Major ADT	**0.000111**	**0.000009**	**12.89**	**0.000**	**
Left SD	0.119	0.111	1.07	0.286	
Right SD	**0.317**	**0.114**	**2.78**	**0.005**	**
5. Constant	-4.028	0.447	-9.00	0.000	**
Stop Line	**-0.332**	**0.164**	**-2.03**	**0.043**	*
Major ADT	**0.000114**	**0.000009**	**12.02**	**0.000**	**
Left SD	0.117	0.111	1.05	0.295	
Right SD	**0.326**	**0.115**	**2.83**	**0.005**	**
Major Spd Lim	-0.0107	0.0145	-0.74	0.461	
6. Constant	-4.078	0.457	-8.93	0.000	**
Stop Line	**-0.833**	**0.205**	**-4.07**	**0.000**	**
Crosswalk	**0.773**	**0.177**	**4.38**	**0.000**	**
Major ADT	**0.000114**	**0.000009**	**12.06**	**0.000**	**
Left SD	0.087	0.112	0.78	0.435	
Right SD	**0.330**	**0.115**	**2.87**	**0.004**	**
Major Spd Lim	-0.0105	0.0148	-0.71	0.478	
7. Constant	-5.69	1.56	-3.66	0.000	**
Stop Line	-0.168	0.374	-0.45	0.653	
Crosswalk	**1.043**	**0.368**	**2.84**	**0.005**	**
Minor ADT	**0.000564**	**0.000106**	**5.34**	**0.000**	**
Major ADT	**0.000153**	**0.000033**	**4.62**	**0.000**	**
Left SD	-0.107	0.363	-0.30	0.768	
Right SD	-0.050	0.329	-0.15	0.879	
Major Spd Lim	0.0205	0.0429	0.48	0.633	

Model 2 in Table 2.6 adds the presence or not of a crosswalk on the same approach as the Stop Line. From the results we see that, when the presence of a crosswalk is added, the model shows a strong association between the presence/absence of stop lines and the occurrence of right-angle crashes, with the presence of a Stop Line being associated with lower likelihood of crashes. Additionally, there is a strong association between the presence of a crosswalk and the right-angle crash occurrence, with the presence of a crosswalk being associated with higher likelihood of crashes.

As noted earlier, this study uses an observational, cross-sectional design. This type of design can identify correlations between an outcome measure (crash risk) and observed input measure, such as AADT or sight distance, but it cannot do by itself determine if the observed correlations indicate causal connections. For this, additional information, beyond what it is in the study, would be needed. In particular, a correlation between presence of crosswalks and crash occurrence cannot by itself be interpreted as indicating a causal effect. One definite possibility is that crosswalks tend to be installed at intersections having higher minor road traffic volumes. That is, the underlying causal pattern is given by Figure 2.6. Since intersections with more traffic on their minor roads create more opportunities for angle crashes than do those with low minor road volumes they will also tend to show higher crash frequencies, whether or not they have crosswalks. In this case the presence of crosswalk could simply be an indicator that that an intersection has higher minor road traffic.

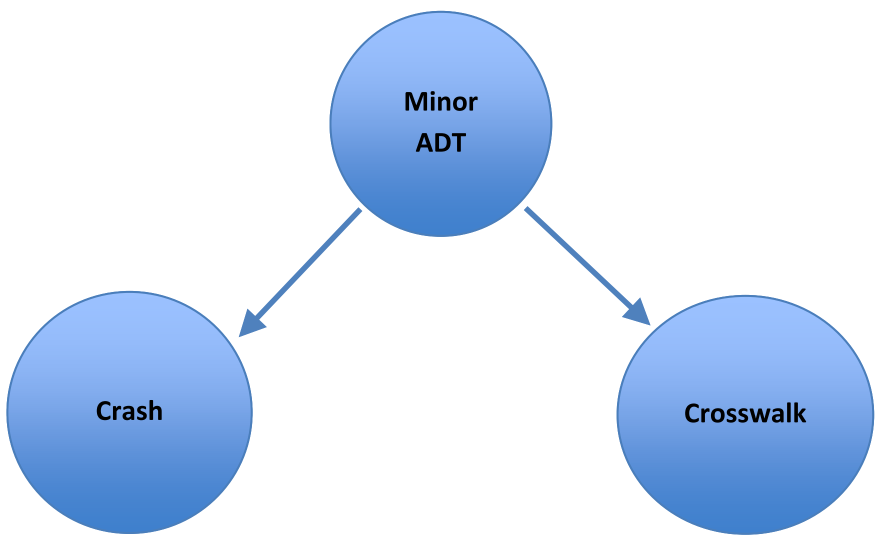

Figure 2.6 Example Causal Structure

In order to explore the crosswalk influence on crashes, controlling for the Minor ADT in the model is necessary. Although this is what Model 7 attempted, the fact that Minor ADT were missing for 13,769 cases out of 14,548 makes the result very unreliable. Exploring the causal relationship between crosswalk and crashes is beyond the scope of this project, although some additional discussion is offered in the chapter that discusses the results of the experimental study.

Model 3 in Table 2.6 takes a step back and instead adds the major approach ADT as a predictor. A weak association between the presence/absence of stop lines and the occurrence of right-angle crashes is revealed, again with the presence of a Stop Line being associated with lower likelihood of crashes. The model also shows that there is a strong association between major approach ADT and the right-angle crash occurrence, with higher ADTs being associated with higher likelihood of crashes. This is unsurprising.

Model 4 in Table 2.6 adds the adequacy of left and right-hand sight distances as predictors. The results tend to be consistent with those from model 3 except that there is now some evidence that adequate right-side sight distance might associated with higher likelihood of a right angle crash. Model 5 in Table 2.6 adds the major approach speed limit as a predictor. The results show no evidence for an association between speed limit and right-angle crash occurrence and are otherwise similar to those for model 4.

Models 6 and 7 in Table 2.6 explore a little more the influence of the presence of a crosswalk. Model 6 is an extension of Model 5 with the addition of the presence of a crosswalk. Again the same positive correlation between crosswalk and crashes is shown as well as the strengthening of the negative association of the presence of a Stop Line and crashes. Model 7 adds the minor approach ADT, which as expected shows a very high positive correlation to right angle crashes while the association with right-sight is no longer present. In this model, the association between the presence of a Stop Line and right angle crashes is also no longer present. The association with the presence of a crosswalk is weaker than that shown in Model 6, although still significantly different from zero. As discussed earlier, Model 7 is based on a small fraction of cases and we include it here only for completeness.

As noted earlier, right-angle and turning crashes can sometimes be confused, so the above set of models was again analyzed but now with the occurrence of right-angle, left-turn, or right-turn crashes as the dependent variables. That is, an approach-year was coded as 1 if at least one of the above mentioned crash types occurred, and coded as zero otherwise. Table 2.7 summarizes the results from fitting six models, these results are for the most part similar to those using only right-angle crash occurrence as a safety indicator. To record the influence from crosswalks, these models all include the presence of a crosswalk. As earlier, the only model that does not indicate an association between crash occurrence and the presence/absence of stop lines is the limited data model that includes minor approach ADT. Major approach ADT again had a strong association with crash occurrence and again adequate right-side sigh distance appeared to be associated with an increase in crash likelihood. The one difference appears to be an association between major approach speed limit and crash occurrence, with higher speed limits being association with greater crash likelihood.

Table 2.7 Binary Logistic Analyses for T-intersection Approaches: Occurrence of Right Angle, Right-Turn, or Left-Turn Crashes as Dependent Variable.

Predictor	Estimated β	Standard Error	Z-statistic	P-Value	Significance
1. Constant	-3.5868	0.0547	-65.53	0.000	**
Stop Line	-0.109	0.162	-0.68	0.499	
2. Constant	-3.6527	0.0573	-63.78	0.000	**
Stop Line	**-0.633**	**0.192**	**-3.29**	**0.001**	**
Crosswalk	**0.899**	**0.160**	**5.63**	**0.000**	**
3. Constant	-4.315	0.103	-41.69	0.000	**
Stop Line	**-0.905**	**0.208**	**-4.35**	**0.000**	**
Crosswalk	**0.990**	**0.172**	**5.75**	**0.000**	**
Major ADT	**0.000112**	**0.000009**	**13.19**	**0.000**	**
4. Constant	-4.608	0.143	-32.13	0.000	**
Stop Line	**-0.891**	**0.210**	**-4.23**	**0.000**	**
Crosswalk	**0.988**	**0.178**	**5.55**	**0.000**	**
Major ADT	**0.000125**	**0.000009**	**13.59**	**0.000**	**
Left SD	0.033	0.118	0.28	0.783	
Right SD	**0.294**	**0.121**	**2.42**	**0.016**	*
5. Constant	-4.997	0.456	-10.95	0.000	**
Stop Line	**-0.892**	**0.209**	**-4.27**	**0.000**	**
Crosswalk	**0.985**	**0.177**	**5.56**	**0.000**	**
Major ADT	**0.000121**	**0.000010**	**12.06**	**0.000**	**
Left SD	0.035	0.118	0.30	0.768	
Right SD	**0.283**	**0.122**	**2.32**	**0.020**	*
Major Spd Lim	0.0132	0.0147	0.90	0.369	
6. Constant	-7.28	1.37	-5.31	0.000	**
Stop Line	-0.247	0.357	-0.69	0.490	
Crosswalk	**1.485**	**0.357**	**4.16**	**0.000**	**
Minor ADT	**0.000516**	**0.000102**	**5.06**	**0.000**	**
Major ADT	**0.000123**	**0.000032**	**3.85**	**0.000**	**
Left SD	-0.409	0.353	-1.16	0.248	
Right SD	0.022	0.327	0.07	0.946	
Major Spd Lim	**0.0830**	**0.0354**	**2.34**	**0.019**	*

The above analyses focused on stop-controlled approaches at T-intersections, where we considered it likely that right-angle crashes would involve major and minor approach vehicles. At four-legged intersections, on the other hand, it is possible that a crash coded as an angle crash could involve a turning and through vehicle both coming from minor approaches. As another partial indicator of stop line effects we also looked at angle and turning crashes at four-legged intersections, recognizing that, as before, the most reliable way to clearly identify relevant crashes would be manual review of hard-copy crash reports. Table 2.8 presents results where the occurrence of right-angle crashes was taken as the dependent variable while Table 2.9 summarizes models where right-angle, left-turn, or right-turn crash occurrence was to be predicted.

The results summarized in Table 2.8 follow the same modeling sequence as the ones presented in Table 2.6. One difference with the results on T intersections is that Models 1 to 5 in Table 2.8 show no association between the presence of a Stop Line and the occurrence of right-angle crashes. Only with the inclusion of the presence of crosswalk as in Model 6 is an association between the presence of stop lines and occurrence of right-angle crashes reported. For right-angle crashes at four-legged intersections, again a strong association between the presence of a crosswalk and right-angle crash occurrence is reported, with the presence of a crosswalk being associated with higher likelihood of crashes. A weak association between the major approach speed limit and the right-angle crash occurrence is also reported, with the increasing speed limit being associated with higher likelihood of crashes. In contrast to the T intersections, on 4-legged intersections the left-side sight distance quality is associated with the occurrence of crashes, instead of the right-side one. As expected, the major approach ADT reports a very strong association with the occurrence of crashes.

In Table 2.9 the occurrence of right-angle, left-turn, or right-turn crashes is the dependent variable and the results show little difference with those presented in Table 2.8. For illustration, in these models the presence of a crosswalk is included on all models.

Table 2.8 Binary Logistic Analyses for 4-legged Approaches: Occurrence of Right Angle as Dependent Variable.

Predictor	Estimated β	Standard Error	Z-statistic	P-Value	Significance
1. Constant	-2.5326	0.0303	-83.56	0.000	**
Stop Line	0.103	0.123	0.84	0.400	
2. Constant	-2.5543	0.0309	-82.72	0.000	**
Stop Line	-0.189	0.141	-1.33	0.182	
Crosswalk	**0.568**	**0.124**	**4.60**	**0.000**	**
3. Constant	-2.9608	0.0558	-53.08	0.000	**
Stop Line	-0.094	0.134	-0.70	0.483	
Major ADT	**0.000100**	**0.000005**	**18.95**	**0.000**	**
4. Constant	-3.0805	0.0794	-38.82	0.000	**
Stop Line	-0.103	0.134	-0.77	0.442	
Major ADT	**0.000099**	**0.000005**	**18.62**	**0.000**	**
Left SD	**0.1750**	**0.0726**	**2.41**	**0.016**	*
Right SD	0.0271	0.0738	0.37	0.714	
5. Constant	-3.954	0.414	-9.55	0.000	**
Stop Line	-0.075	0.134	-0.55	0.579	
Major ADT	**0.000095**	**0.000006**	**16.60**	**0.000**	**
Left SD	**0.1618**	**0.0728**	**2.22**	**0.026**	*
Right SD	0.0193	0.0739	0.26	0.794	
Major Spd Lim	**0.0294**	**0.0137**	**2.15**	**0.031**	*
6. Constant	-3.970	0.411	-9.65	0.000	**
Stop Line	**-0.341**	**0.163**	**-2.09**	**0.036**	*
Crosswalk	**0.430**	**0.140**	**3.07**	**0.002**	**
Major ADT	**0.000094**	**0.000006**	**16.46**	**0.000**	**
Left SD	**0.1562**	**0.0730**	**2.14**	**0.032**	*
Right SD	0.0156	0.0740	0.21	0.833	
Major Spd Lim	**0.0297**	**0.0136**	**2.19**	**0.029**	*
7. Constant	-3.22	1.21	-2.68	0.007	**
Stop Line	-0.292	0.356	-0.82	0.411	
Crosswalk	**-0.683**	**0.326**	**-2.09**	**0.036**	*
Minor ADT	0.000228	0.000154	1.48	0.138	
Major ADT	**0.000063**	**0.000022**	**2.85**	**0.004**	**
Left SD	**0.722**	**0.258**	**2.80**	**0.005**	**
Right SD	0.309	0.256	1.21	0.228	
Major Spd Lim	0.0307	0.0359	0.85	0.393	

Table 2.9 Binary Logistic Analyses for 4-Legged-intersection Approaches: Occurrence of Right Angle, Right-Turn, or Left-Turn Crashes as Dependent Variable.

Predictor	Estimated β	Standard Error	Z-statistic	P-Value	Significance
1. Constant	-2.7525	0.0333	-82.56	0.000	**
Stop Line	0.204	0.129	1.58	0.114	
2. Constant	-2.7780	0.0340	-81.67	0.000	**
Stop Line	-0.131	0.150	-0.87	0.385	
Crosswalk	**0.642**	**0.131**	**4.90**	**0.000**	**
3. Constant	-3.0842	0.0586	-52.61	0.000	**
Stop Line	**-0.380**	**0.171**	**-2.23**	**0.026**	*
Crosswalk	**0.410**	**0.147**	**2.80**	**0.005**	**
Major ADT	**0.000100**	**0.000005**	**18.24**	**0.000**	**
4. Constant	-3.2135	0.0835	-38.49	0.000	**
Stop Line	**-0.385**	**0.171**	**-2.25**	**0.024**	*
Crosswalk	**0.399**	**0.147**	**2.72**	**0.006**	**
Major ADT	**0.000099**	**0.000006**	**17.95**	**0.000**	**
Left SD	**0.2143**	**0.0761**	**2.81**	**0.005**	**
Right SD	0.0005	0.0770	0.01	0.995	
5. Constant	-4.022	0.427	-9.41	0.000	**
Stop Line	**-0.361**	**0.171**	**-2.10**	**0.035**	*
Crosswalk	**0.403**	**0.147**	**2.75**	**0.006**	**
Major ADT	**0.000095**	**0.000006**	**16.12**	**0.000**	**
Left SD	**0.2012**	**0.0765**	**2.63**	**0.009**	**
Right SD	-0.0070	0.0771	-0.09	0.928	
Major Spd Lim	0.0272	0.0141	1.93	0.053	
6. Constant	-3.11	1.21	-2.56	0.011	*
Stop Line	-0.438	0.363	-1.21	0.227	
Crosswalk	-0.540	0.323	-1.67	0.094	
Minor ADT	0.000256	0.000157	1.64	0.102	
Major ADT	**0.000050**	**0.000022**	**2.29**	**0.022**	*
Left SD	**0.930**	**0.267**	**3.48**	**0.001**	**
Right SD	0.361	0.262	1.38	0.169	
Major Spd Lim	0.0217	0.0361	0.60	0.548	

2.7 CONCLUSION OF SAFETY STUDY

This chapter covered effort related to the Safety Study task of the project. Cross-sectional analyses of historical crash information from the cities of Edina, Golden Valley, Rosedale, St. Louis Park, and Richfield were used to determine if there is a reliable association between the presence of stop lines and the occurrence of relevant crashes. The analysis was performed separately for T intersections and for 4-legged ones. When used as the only predictor, the presence of a stop line showed no association with crash occurrence but a negative association occasionally occurred when other predictors were added to a model. This was often the case when the presence of a crosswalk was included in the model. Unfortunately, the lack of reliable data on the minor approaches prevented us from reliably decupling the effects between stop lines and crosswalks. The suggestion that the presence of crosswalks is associated with increases in the likelihood of crashes requires further investigation.

We did see a rather puzzling association between right-side sight distance and crash occurrence at T-intersections, and with left-side sight distance on 4-legged ones, which could merit more detailed investigation. There was some difficulty in reliably identifying relevant crashes from the available crash codes. In 2017, the Minnesota Department of Public Safety instituted a new coding system that should resolve some of these issues, and it would probably be useful to repeat these analyses once several years of data using the new system become available.

The effort to assemble the necessary information ended up being a lot greater than what was originally anticipated, and perhaps unreasonable given the remaining ambiguity of the final result. We feel that the data tabulation methodology, the tools developed, and the challenges encountered and overcome, as described earlier in this report, are relevant to any similar safety study on urban intersections. The process highlighted several shortcomings with the currently available data sources that result in substantial effort for assembling seemingly mundane kinds of information. We hope the described effort, which took advantage of all newly available online resources, can be used as a case study on the improvements and coordination between data owners that could dramatically reduce the cost of this and other studies.

CHAPTER 3: OBSERVATIONAL BEFORE AND AFTER STUDY

As described in the Introduction, an observational study of various intersections around the Twin Cities Metro Area before and after adding a stop line was planned in conjunction with the safety study. The goal of this observational study was to determine what effect stop lines have on driver behavior at intersections, and look at where drivers are stopping, differing from the safety study.

16 intersections with 21 approaches total were chosen for the observational study. How these intersections were chosen is detailed in Section 3.1. Video was collected both before the stop line was painted as well as after, to compare driver behavior in general as well as look for changes in stop location and the amount of time drivers spent passing through the stop sign.

Undergraduate Research Assistants (UGRAs) at the MTO painstakingly recorded vehicle counts and relevant event information from the video collected. Given the 7,763 hours of video collected from all sites in total, the field data reduction and analysis process took much longer than initially expected.

3.1 DATA COLLECTION

Sites for the observational study ideally would be provided to the MTO by organizations or individuals with firsthand knowledge of intersections with and/or without stop lines, crosswalks, or with other notable characteristics or driver behavior. In the search for candidate sites for stop line painting and video camera deployment, five cities (Edina, Roseville, Richfield, St. Louis Park and Golden Valley) provided the necessary information to proceed with the safety study as well.

As per the work plan, the research team solicited the help of the TAP in identifying stop-controlled intersections for the field study. The city of Edina provided several intersections of concern. The research team also identified several sites to investigate from their familiarity with certain areas around the Twin Cities but other methods for obtaining site locations were needed as well, described in the following sections.

3.1.1 Survey

The first method employed was a survey sent out to TAP members and city and county engineers throughout Minnesota. The survey asked the recipients to give the location of an intersection – either via the interactive map or by giving the coordinates – where stop lines were added or removed (Figure 3.1). For each intersection specified, the recipient was asked to provide the date the stop lines were added or removed, whether they were added or removed, and any additional information regarding the change. The survey did not result in any new information.

Recipients were asked to provide the location of two-way stop-controlled intersections that currently have stop lines or had stop lines in the past. For each intersection the recipients identified, they were asked to provide the date the stop lines were added or removed, whether they were added or removed, and any additional information regarding the change.

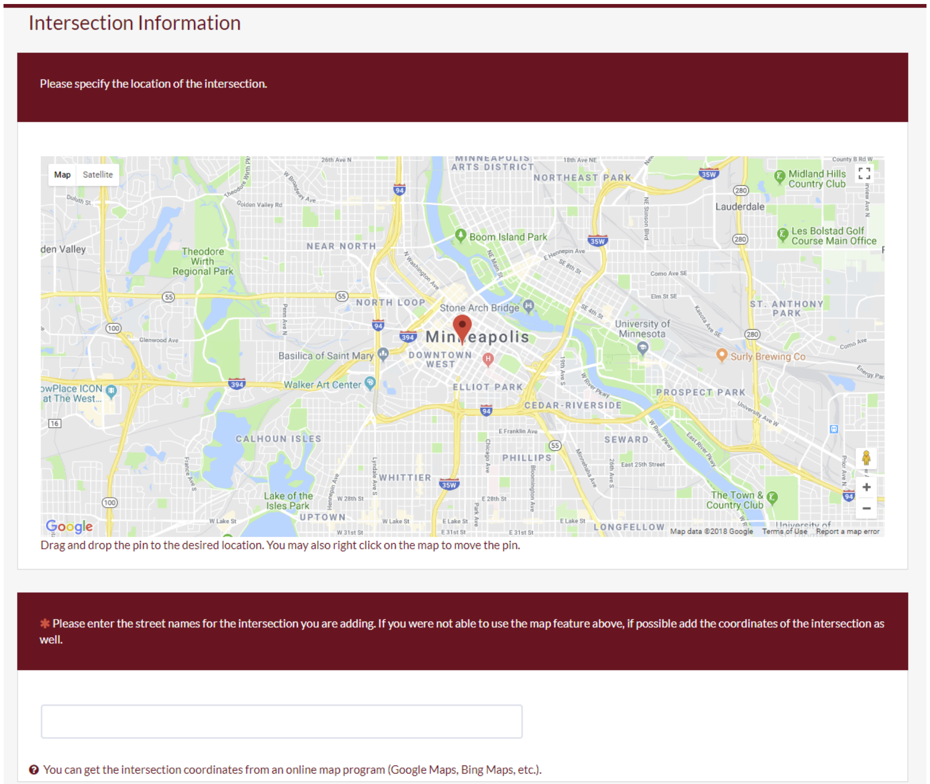

Figure 3.1 First part of stop line site survey sent to engineers and officials.

The first dissemination of the survey took place on February 1st, 2018. In the following three weeks only two replies were received. On March 1st the MTO solicited the help of CTS in disseminating the survey but it did not result in any new entries. Following this second failed attempt, the MTO decided to target specific people and send personal emails calling for their help. The recipients list included the county engineers for the counties in the Twin Cities Metro area as well as public works employees at mid-sized cities around the Twin Cities Metro area. No new information was gathered with this attempt, either.

3.1.2 Crash Records

The second method attempted was a search into the MnCMAT database for high concentrations of failure-to-yield crash events at two-way stop-controlled (TWSC) intersections in the Twin Cities Metro area. The intention was to investigate the sites that showed relatively high numbers of crashes (two or more crashes in the last 10 years). Unfortunately, no intersections had more than two crashes and fewer than 10 had two crashes. Additionally, many of the sites returned in the list of 100 crashes from the intersections with the most crashes have been since signalized. As a result, the crash record method was also deemed insufficient in providing suggested sites for the field study.

3.1.3 Before/After Study

Due to the insufficient number of sites for an observational matched case-control study, the research team decided that a before/after study would be more effective and require fewer actual sites (same number of camera deployments). The team communicated to all Twin Cities metro jurisdictions asking for digital records of the locations of stop signs. The MTO received GIS records with complete information from Edina, St. Louis Park, Roseville, Richfield, and Golden Valley (selected sites shown in Table 3.1).

Using the stop sign locations obtained from those five cities in the Twin Cities Metro area and the AADT data from the MnDOT Traffic Forecasting and Analysis tool, TWSC intersections with a major road AADT of at least 2000 vehicles per day and a minor road AADT of at least 500 vehicles per day were identified. Roughly 250 sites were identified using this method. The reasoning was that with such information, preferably in a GIS layer, the MTO could quickly identify all the TWSC intersections and use either site visits or other means to find out if a stop line was present and, if one was present, the current state of the paint. Preliminary analysis of the GIS records revealed 132 locations where a field study was feasible. Additionally, from the communications with the cities of St Paul and Minneapolis, although no GIS information was supplied, a list of TWSC intersections was made by suggestions and personal inspection. This resulted in an additional 96 TWSC intersections that could support a field study.

Following the inspection of the GIS data and the selection of potential candidate sites, the MTO communicated with each of these cities to determine their willingness to participate in the field study by allowing the MTO to either paint new or repainting faded-out stop-lines on selected intersections after 2 weeks of data without a stop-line were collected. The list of sites identified using the cities' stop sign locations was narrowed down based on each city's directions and criteria regarding which sites could have cameras deployed at them or have stop lines added. Basic geometric characteristics such as the number of lanes on the major and minor roads, road widths, and the angles the roads meet at were then recorded using aerial imagery from late 2017.

Sites of interest were then selected based on the known data with priority being given to sites in cities that agreed to allow stop lines to be painted on their roads. These sites were visited to confirm the initial stop line conditions, estimate the available sight distances, and determine whether there was a suitable location for a camera to be deployed.

68 candidate sites were considered for video collection, from which 21 approaches at 16 intersections were selected for video collection. Sites were selected in such a way as to give a variety of combinations of site characteristics. Particular emphasis was placed on selecting sites with a variety of left and right available sight distances, angle at which the major and minor road meet, major road speed limit, Average Annual Daily Traffic (AADT) of the major and minor roads, presence of traffic islands, number of lanes, and number of approaches at the intersection. Sites with a history of crashes were prioritized and any site without a pole or tree on which to brace a camera was excluded from the list.

The initial list of 68 candidate site is shown in Table 3.1. The sites had confirmed cities that would cooperate with the study, had high enough AADTs, and had confirmed locations to mount a camera. The columns refer to the following:

- “No. of Legs” – the number of approaches at the intersection
- “Total Width” – the distance from one curb face to the other
- “No. of Lanes” – the number of lanes for vehicle traffic
- “AADT” – the most recent AADT recorded by MnDOT (“?” means not available)
- “Approach Angle” – the angle between the minor approach and the major road approach to the drivers’ right
- “Stop Line?” – whether there was a stop line in place before filming (“Maybe” meant the site had not been visited in the last six months)
- “Crosswalk?” – whether there is a crosswalk in place before filming (“Maybe” meant the site had not been visited in the last six months)
- “AADT 500+?” – whether the AADT of the minor approach is above 500 vehicles per day – the minimum to make studying the approach worthwhile (“?” means not available)
- “Left SD” – whether the sight distance to the drivers’ left is adequate for a driver to make a left turn (the longest maneuver) safely (“x” means the sight distance was not measured, as the site was not included in the final study)
- “Right SD” – whether the sight distance to the drivers’ right is adequate for a driver to make a left turn (the longest maneuver) safely (“x” means the sight distance was not measured, as the site was not included in the final study)

Note that approaches with site IDs ending with A or B are part of a pair of approaches at an intersection whereas those with site IDs ending with O are the only approach of interest at the intersection.

The candidate list (Table 3.1) of 15 to 20 potential sites for deployment was made based on the availability of mounting locations, cities’ approval, and TAP feedback. The only permits that were denied for this study were on two locations owned by the Minneapolis Park Board. The permit to deploy cameras to collect observations from the intersection of East River Road and Harvard Ave and East River Road and Oak St at the U campus were denied. Requests for permits were made twice.

Altogether, 16 intersections, with 21 approaches total, were chosen for observational study deployments. Each site had two deployments, one week before the stop line was painted and one week after. Sites were selected based on geometries, volumes, and sight distances, as well as similarities and differences to other candidate sites. The final list of sites is shown in Table 3.2.

Video collection took place over late summer and early fall of 2018. Once sites had been selected for video collection, the research team deployed the Minnesota Traffic Observatory (MTO)’s standalone camera systems at the sites for approximately two weeks, stop lines were painted, drivers were given at least two weeks to become accustomed to the new lines, and the systems were then re-deployed for another two weeks. To effectively calculate distances in the camera view relative to the real world, a series of measurements were taken and beads strung onto a cord at five-foot intervals were stretched out with known endpoints to provide a reference for future data reduction work.

Table 3.1 List of Candidate Sites for Before/After Study

Intersection			Major Road			Minor Approach						
Site Name	Map (Bing)	No. of Legs	Total Width	No. of Lanes	AADT	Approach Angle	No. of Lanes	Stop Line?	Cross-walk?	AADT 500+?	Left SD	Right SD
P002O - Edina, Valleyview Rd & 62nd St W, WB	Map	3	35	3	9000	Obtuse	2	No	No	Yes	x	x
P017O - Minneapolis, Walnut St SE & Beacon St SE, EB	Map	2	27	2	?	Right	2	Faded	Faded	Yes	Approx. Adequate	Approx. Adequate
P018O - Minneapolis, E River Pkwy & Harvard St SE, SB	Map	3	35	3	3650	Acute	2	Faded	Faded	Yes	Approx. Adequate	Approx. Adequate
P019O - Minneapolis, E River Pkwy & Oak St SE, SB	Map	3	18	2	3650	Acute	2	Yes	Yes	Yes	Approx. Adequate	Inadequate
P034O - Richfield, Lyndale Ave S & W 71st St a, WB	Map	3	46	4	11700	Obtuse	2	No	No	Maybe	More Than Adequate	Approx. Adequate
P036O - Richfield, Lyndale Ave S & W 72nd St , WB	Map	3	46	4	11700	Right	2	No	No	Maybe	Inadequate	Inadequate
P040A - Richfield, Nicollet Ave and E/W 68th St, EB	Map	4	52	3	12100	Right	2	No	No	Yes	Inadequate	Inadequate
P040B - Richfield, Nicollet Ave and E/W 68th St, WB	Map	4	52	3	12100	Right	2	No	No	Yes	Inadequate	Approx. Adequate
P042A - Richfield, Nicollet Ave and E/W 72nd St, EB	Map	4	50	3	9100	Right	2	No	No	Maybe	Approx. Adequate	Inadequate
P045A - Richfield, Nicollet Ave and E/W 75th St, EB	Map	4	50	3	9100	Right	2	No	No	Maybe	Approx. Adequate	More Than Adequate
P088O - Roseville, Western Ave N & Co Rd C2 W, WB	Map	3	32	2	?	Right	2	No	No	Yes	x	x
P089A - Roseville, Dane St N & Iona Ln, WB	Map	4	33	2	2250	Right	2	No	No	Yes	x	x
P090A - Roseville, Western Ave N & Iona Ln, EB	Map	4	33	2	?	Right	2	No	No	Yes	x	x
P093A - Roseville, Lincoln Dr & Co Rd C-2, NB	Map	3	44	2	3600	Right	2	No	No	Yes	x	x
P093B - Roseville, Lincoln Dr & Co Rd C-2, SB	Map	3	44	2	3600	Right	2	No	Yes	Yes	x	x
P094O - Roseville, Lincoln Dr & Lydia Ave W, NB	Map	3	54	4	?	Right	3	No	Yes	Yes	x	x

Intersection			Major Road			Minor Approach						
Site Name	Map (Bing)	No. of Legs	Total Width	No. of Lanes	AADT	Approach Angle	No. of Lanes	Stop Line?	Cross-walk?	AADT 500+?	Left SD	Right SD
P101O - Roseville, Oakcrest Ave & Prior Ave N, NB	Map	3	37	4	?	Right	4	No	No	Yes	x	x
P102O - Roseville, Hwy 36 Service Rd & Prior Ave N, SB	Map	3	35	3	8075	Right	4	No	No	Yes	x	x
P104O - St. Louis Park, W 36th St & Raleigh Ave, SB	Map	3	70	4	14600	Right	2	No	No	Yes	x	x
P106O - St. Louis Park, W 35th St & Beltline Blvd, EB	Map	3	46	4	?	Right	2	No	No	Yes	x	x
P107O - St. Louis Park, MN-7 Frontage Rd & W Lake St, NB	Map	3	41	3	2650	Right	2	No	No	Yes	x	x
P108O - St. Louis Park, Edgewood Ave S & Cambridge St, WB	Map	3	36	2	2900	Right	2	No	No	Yes	x	x
P109A - St. Louis Park, Excelsior Blvd & Yosemite Ave S, NB	Map	4	68	5	23300	Obtuse	1	No	No	Yes	x	x
P111O - St. Louis Park, Yosemite Ave S & Brookside Ave, EB	Map	3	33	2	?	Right	2	No	No	Yes	x	x
P112O - St. Louis Park, Minnetonka Blvd & Aquilia Ave S, NB	Map	3	39	2	11200	Right	2	No	No	Yes	x	x
P113O - St. Louis Park, Ford Rd & Wayzata Blvd, SB	Map	3	30	2	?	Right	2	No	No	Yes	x	x
P114O - St. Louis Park, Wayzata Blvd & Texas Ave S, NB	Map	3	35	2	7050	Acute	2	No	No	Yes	x	x
P119B - St. Louis Park, Cedar Lake Rd & Virginia Ave S, NB	Map	4	45	3	9950	Obtuse	2	No	No	Yes	x	x
P121O - St. Louis Park, Cedar Lake Rd & Flag Ave S, SB	Map	3	47	3	?	Obtuse	2	No	Yes	Yes	x	x
P122O - St. Louis Park, Cedar Lake Rd & Colorado Ave S, SB	Map	3	40	2	11750	Obtuse	2	No	No	Yes	x	x

Intersection			Major Road			Minor Approach						
Site Name	Map (Bing)	No. of Legs	Total Width	No. of Lanes	AADT	Approach Angle	No. of Lanes	Stop Line?	Cross-walk?	AADT 500+?	Left SD	Right SD
P123O - St. Louis Park, Cedar Lake Rd & Edgewood Ave S, NB	Map	3	49	3	?	Obtuse	3	No	No	Yes	x	x
P124O - St. Louis Park, W 26th Street & France Ave S, EB	Map	3	38	2	6450	Obtuse	2	No	No	Yes	x	x
P125O - St. Louis Park, 26th St W & Barry St W, SB	Map	3	40	2	?	Right	2	No	Yes	Yes	x	x
P126B - St. Louis Park, France Ave S & Cedar Lake Ave, WB	Map	4	36	2	7600	Right	2	No	No	Yes	x	x
P128O - St. Louis Park, Wayzata Blvd & Colorado Ave S, NB	Map	3	33	2	6250	Acute	2	No	No	Yes	x	x
P129O - St. Louis Park, W 36th Street & Alabama Ave S, NB	Map	3	50	4	3900	Right	2	No	No	Yes	x	x
P130O - St. Louis Park, Wayzata Blvd & Pennslyvania Ave S, NB	Map	3	34	4	6750	Right	2	No	No	Yes	x	x
P131O - St. Louis Park, Shelard Pkwy & Nathan Ln N, SB	Map	3	41	2	4800	Obtuse	2	No	No	Yes	x	x
P132A - Richfield, Penn Ave S & 65th St W, EB	Map	4	50	4	12350	Right	2	No	No	Yes	x	x
P138A - Richfield, Penn Ave S & 70th St W, WB	Map	4	50	3	11900	Right	2	No	No	Yes	x	x
P138B - Richfield, Penn Ave S & 70th St W, EB	Map	4	50	3	11900	Right	2	No	No	Yes	x	x
P140O - Richfield, 76th St W & Humboldt Ave S, SB	Map	2	38	3	?	Right	2	No	Yes	Yes	x	x
P144B - Richfield, Nicollet Ave & 64th St W, WB	Map	4	52	4	11300	Right	2	No	No	Yes	x	x
P145O - Richfield, Lyndale Ave S & 68th St W, WB	Map	3	47	4	13200	Right	2	No	No	Yes	x	x
P148A - Richfield, Portland Ave & 68th St E, EB	Map	4	48	3	11700	Right	2	No	No	Yes	x	x
P152A - Richfield, Bloomington Ave S & 76th St E, SB	Map	4	21	2	?	Right	2	No	Yes	Yes	x	x

Intersection			Major Road			Minor Approach						
Site Name	Map (Bing)	No. of Legs	Total Width	No. of Lanes	AADT	Approach Angle	No. of Lanes	Stop Line?	Cross-walk?	AADT 500+?	Left SD	Right SD
P154A - Richfield, Cedar Ave S & Diagonal Blvd, EB	Map	4	39	2	?	Acute	2	No	Yes	Yes	x	x
P159A - Edina, Xerxes Ave S & 54th St W, WB	Map	4	42	2	8900	Right	2	No	No	Yes	x	x
P160A - Edina, Xerxes Ave S & 60th St W, EB	Map	4	42	2	11050	Right	2	No	No	Yes	x	x
P160B - Edina, Xerxes Ave S & 60th St W, WB	Map	4	42	2	11050	Right	2	No	No	Yes	x	x
P161O - Edina, France Ave S & 62nd St W, EB	Map	3	44	3	16600	Right	2	No	No	Yes	x	x
P165O - Edina, 78th St W & Gleason Rd, SB	Map	3	63	5	9300	Right	2	No	No	Yes	x	x
P166O - Edina, Interlachen Blvd & Blake Rd S, NB	Map	3	32	2	8500	Right	2	No	No	Yes	x	x
P168O - Edina, Parklawn Ave & Gallagher Dr, SB	Map	3	34	2	2200	Right	2	No	Yes	Yes	x	x
P175O - Edina, France Ave S & 60th St W, WB	Map	3	43	3	16600	Right	2	No	No	Yes	x	x
P176B - Richfield, Xerxes Ave S & 64th St W, WB	Map	4	106	5	17600	Right	2	No	No	Yes	x	x
P177O - Edina, Edinborough Way & Minnesota Dr, EB	Map	3	52	2	3500	Right	2	No	No	Yes	x	x
P179O - Edina, Eden Ave & 50th St W, NB	Map	3	63	5	?	Obtuse	2	No	No	Yes	x	x
P181O - Edina, Gus Young Ln & Arcadia Ave, EB	Map	3	29	2	?	Right	2	No	No	Yes	x	x
P182O - Edina, Vernon Ave S & Arcadia Ave, NB	Map	2	39	3	18700	Obtuse	2	No	No	Yes	x	x
P188O - Roseville, Perimeter Dr & Hwy 36 Service Dr, SB	Map	3	34	3	11300	Acute	4	No	Yes	No	x	x
P190A - Richfield, Portland Ave & E 73rd St, EB	Map	4	48	3	11200	Right	2	No	No	Yes	Approx. Adequate	Inadequate
P190B - Richfield, Portland Ave & E 73rd St, WB	Map	4	48	3	11200	Right	2	No	No	Yes	Approx. Adequate	More Than Adequate
P278B - St Louis Park, Quentin Ave and W 29th St, SB	Map	4	30	2	?	Right	2	No	No	Yes	Inadequate	Inadequate

Intersection			Major Road			Minor Approach						
Site Name	Map (Bing)	No. of Legs	Total Width	No. of Lanes	AADT	Approach Angle	No. of Lanes	Stop Line?	Cross-walk?	AADT 500+?	Left SD	Right SD
P279A - St Louis Park, Raleigh Ave and W 27th St, NB	Map	4	28	2	?	Right	2	No	No	Yes	Inadequate	Inadequate
P280A - St Louis Park, Raleigh Ave and W 28th St, NB	Map	4	30	2	?	Right	2	No	No	Yes	Inadequate	Inadequate
P280B - St Louis Park, Raleigh Ave and W 28th St, SB	Map	4	30	2	?	Right	2	No	No	Yes	Inadequate	Inadequate

Table 3.2 Chosen sites for observational study

Site
S017O - Minneapolis, Walnut St SE and Beacon St SE, EB
S036O - Richfield, Lyndale Ave S and W 72nd St , WB
S040A - Richfield, Nicollet Ave and E/W 68th St, EB
S040B - Richfield, Nicollet Ave and E/W 68th St, WB
S051O - St. Paul, Como Ave and Knapp St, EB
S087O - Roseville, Woodhill Dr and Civic Center Dr, NB
S089A - Roseville, Dale St N and Iona Ln, WB
S094A - Roseville, Lincoln Dr and Lydia Ave W, NB
S179O - Edina, 50th St W and Eden Ave, NB
S182O - Edina, Vernon Ave S and Arcadia Ave, NB
S190A - Richfield, Portland Ave and E 73rd St, EB
S190B - Richfield, Portland Ave and E 73rd St, WB
S221O - St. Paul, Warner Rd and Fish Hatchery Rd N, NB
S227O - St. Paul, W Territorial Rd and Cromwell Ave, NB
S280A - St. Louis Park, Raleigh Ave and W 28th St, NB
S280B - St. Louis Park, Raleigh Ave and W 28th St, SB
S282O - Roseville, County Rd C W and Civic Center Dr, SB
S283A - Roseville, County Rd B2 and Prior Ave, NB
S283B - Roseville, County Rd B2 and Prior Ave, EB
S283C - Roseville, County Rd B2 and Prior Ave, SB
S283D - Roseville, County Rd B2 and Prior Ave, WB
S284A - St. Louis Park, Quentin Ave and W 28th St, NB
S284B - St. Louis Park, Quentin Ave and W 28th St, SB

Once sites had been selected for video collection, the MTO's standalone camera systems were deployed at the sites for approximately two weeks, stop lines were painted, drivers were given at least two weeks to become accustomed to the new lines, and the systems were then re-deployed for another two weeks.

3.1.4 Camera System Deployment

The MTO used nine custom-built camera systems to collect video at the 15 intersections included in the study. The camera systems (shown in Figure 3.2) are self-contained systems include a high-resolution camera mounted to an extendable mast or directly to existing infrastructure via non-invasive steel bands. A weatherproof steel container houses recording equipment and independent battery power. The entire system attaches non-invasively to any conveniently placed pole or tree.

Figure 3.2 MTO camera systems braced on sign post (left) and utility pole (right)

Two of the cities being filmed in required permits be obtained but the others did not require any permit applications before filming. As noted in the Task 1 & 2 deliverable, the only agency that did not allow the MTO to film with or without a permit was the Minneapolis Park Board which denied two permit requests on East River Pkwy.

Cameras were deployed before stop lines were painted and allowed to record for approximately two weeks. Painting was done either by the city with jurisdiction at the site or, in three cities, by a contractor hired by the MTO. Filming was resumed no less than two weeks after the stop lines were painted so as to allow local drivers to become accustomed to the new lines. At all but 6 sites, cameras were moved to other sites to film during this waiting period. While the camera systems were in the field they were checked on approximately once per week. In cases where problems arose with video recording, the systems were left up for additional time.

3.1.5 Site Measurement

When designing the methods to measure every site, consistency, accuracy, and safety were the main considerations. The steps needed to be repeatable, generalizable, and able to produce the information required to fully describe the site. The methods also needed to minimize the time spent in the major road and block traffic for as little time as possible. The solution arrived upon involved establishing a mainline parallel to the minor approach along which nearly all measurements were taken. The mainline runs from an arbitrary point upstream of the intersection through a reference point and to the centerline of the major road. By measuring all points of interest from the upstream point, the tape measure only needs to be lined up once and only needs to extend into the intersection long enough to record the distance to the centerline. Once the distance from the reference point to the centerline of the major road is known, all measurements are recorded relative to the reference point from the relative safety of the minor approach. In addition to measuring distances from the centerline, a second parallel line with a second reference point even with the original reference point is added. To provide points in the camera view with known real-world positions, a rope with seven two-inch PVC beads strung onto it at five-foot intervals is stretched out on each of the two lines with care being taken to line one of the beads up with the reference points. The following are the complete steps taken to measure a site:

1. Establish main line (ML) - Measure minor road width (and mark both edges and midpoint) at two points upstream of the stop line that are at least 50 feet apart. Extend the line to the center line of the major road (can be measured or approximate - mark either way).
2. Pick reference point (RP) - Pick a point on the ML that is near the stop line but is a comfortable distance from the major road. Mark with a nail (only pound in halfway) and paint. Record the distance to the major road centerline. On the ML, mark one point 10 feet downstream of the RP and a second 10 feet upstream of it.
3. Establish parallel line (PL) - using the RP and the two adjacent points on the mainline, establish a line between the main line and the right curb that is parallel to the mainline. Note that this can be done in a number of ways.
    a. Using the nail and the two marks adjacent to the RP, construct two 3-4-5 triangles with the tape measure and mark the resulting vertices on the pavement. Record the distance between the PL and the ML.
    b. Using the nail and at least one other point, construct a parallelogram with the tape measure and mark the resulting vertices on the pavement. Record the distance between the PL and the ML.
4. Mark point on PL that is even with RP (RP2) - to make sure that the distance of points on the PL is known, mark a point even with the RP using one of the following methods:
    a. Use the first option for establishing the PL above.
    b. Use existing features such as pavement lines or saw cuts to extend the PL to a point even with the RP
5. Stretch beads along main line - place the string of beads along the ML and extend such that the bead furthest downstream is in or on the edge of the major roadway. For convenience, orient the string of beads such that one bead is on the RP (note the number of the bead on the RP).
6. Stretch beads along parallel line - repeat the previous step but with the PL and RP2
7. Record distance relative to RP - record the distance along the ML from the RP to a point even with the stop sign, a point even with the stop line, and the edge of the major road.
8. Create snapshots of bead locations - using the video from the camera at the site, create snapshots of the bead locations at the end of steps 5 and 6.

At the end of the measurement process, the following measurements will be available for the site:

1. Minor road width and distance from minor road centerline to each curb, lane line, etc.
2. Distance on mainline from RP to major road centerline, point even with stop sign, point even with stop line, edge of major road, and any lane lines or medians on the major road
3. Distance between ML and PL
4. Number of bead on RP during snapshots

3.1.6 Site Painting

Two of the six cities filmed in asked that the MTO be responsible for the painting of stop lines, the other four offered to do the painting themselves. Because the MTO does not have the equipment or experience to paint stop lines, it contracted the work out. The MTO solicited bids from five area pavement marking companies. Only three responded with bids of which one was significantly lower than the others. The MTO selected the contractor with the lowest bid to paint the lines in the two cities.

Figure 3.3 Painting of stop lines

The contractor was instructed to follow MnDOT best practices for line width, line location, and materials. This translated to two-foot-wide lines composed of latex paint with retroreflective beads and centered on the stop sign posts. Painting was delayed while University of Minnesota confirmed that the contractor possessed the appropriate insurance coverage before adding the contractor to the list of University-approved vendors. Figure 3.3 shows a site being painted.

3.1.7 Video Collected

Video was collected at these 21 approaches at 16 intersections between June and September of 2018. Table 3.3 shows the total number of days with 15+ hours of video at each site that were gathered during the video collection process.

Table 3.3 Days of video collected by site before and after stop lines were painted

Site	Days with 15+ Hours of Video	
	Before Painting	After Painting
S017O - Minneapolis, Walnut St SE and Beacon St SE, EB	19	12
S036O - Richfield, Lyndale Ave S and W 72nd St , WB	10	15
S040A - Richfield, Nicollet Ave and E/W 68th St, EB	14	*
S040B - Richfield, Nicollet Ave and E/W 68th St, WB	14	*
S051O - St. Paul, Como Ave and Knapp St, EB	3	13
S087O - Roseville, Woodhill Dr and Civic Center Dr, NB	13	15
S089A - Roseville, Dale St N and Iona Ln, WB	17	13
S094A - Roseville, Lincoln Dr and Lydia Ave W, NB	16	16
S179O - Edina, 50th St W and Eden Ave, NB	10	13
S182O - Edina, Vernon Ave S and Arcadia Ave, NB	11	13
S190A - Richfield, Portland Ave and E 73rd St, EB	15	13
S190B - Richfield, Portland Ave and E 73rd St, WB	15	13
S221O - St. Paul, Warner Rd and Fish Hatchery Rd N, NB	8	10
S227O - St. Paul, W Territorial Rd and Cromwell Ave, NB	11	13
S280A - St. Louis Park, Raleigh Ave and W 28th St, NB	13	16
S280B - St. Louis Park, Raleigh Ave and W 28th St, SB	13	16
S282O - Roseville, County Rd C W and Civic Center Dr, SB	15	17
S283A - Roseville, County Rd B2 and Prior Ave, NB	13	11
S283B - Roseville, County Rd B2 and Prior Ave, EB	13	11
S283C - Roseville, County Rd B2 and Prior Ave, SB	13	11
S283D - Roseville, County Rd B2 and Prior Ave, WB	13	11
S284A - St. Louis Park, Quentin Ave and W 28th St, NB	13	**
S284B - St. Louis Park, Quentin Ave and W 28th St, SB	13	**

*filming prevented by construction and the removal of the pole that the camera had been attached to
**stop lines were not added at the intersection

The amount of video collected at Warner Rd and Fish Hatchery Rd N was reduced so that filming could occur before a construction project started. Due to a malfunction in the camera station, only three days of video were collected at Como Ave and Knapp St. before the stop line was painted. However, both these sites had enough video collected to reduce and analyze, so they are included in the observational results.

Due to construction work on Nicollet Ave and the temporary removal of the pole the camera was mounted on, no video of the intersection with stop lines was collected at Nicolette Ave and 68th St in Richfield. This site is not included in the final results section.

Quentin Ave and W 28th St was included in the video collection process following locals' reports that stop sign compliance was worse than at the nearby Raleigh Ave and W 28th St. However, a stop line was not painted at this site due to budget constraints and the site's geometric similarity to the Raleigh Ave site. Quentin Ave's analysis is included as Appendix C.

3.2 DATA ASSEMBLY

Video data for this project was captured in two phases: for approximately two weeks before the stop line was painted and for another two weeks after drivers were given at least two weeks to become accustomed to the new stop line. This video was then reduced in two phases: vehicle volumes were collected for each approach in 15-minute intervals for four days before and after the stop lines were painted and detailed information about each vehicle approaching the stop line was collected for one day before and after the stop lines were painted. Site visits were conducted after filming was completed to determine sight distances and any other notable characteristics not recorded during initial visits.

3.2.1 Sight Distances

Initially, the research team noted whether the sight distance to the left and right at a given site were "adequate" or "inadequate" based on field observations. After video was collected, researchers again visited the final sites with a LIDAR gun. Researchers took measurements to the left and right at the stop line, where the driver's eye would be when the front tire is on the stop line (approximately five feet behind the stop line), and at the preferred stopping distance found during the observational study. Required sight distance was calculated based on road geometry and speed limits. Diagrams of required site distance versus available site distance as measured with the LIDAR are found in the site-specific sections of the observational results.

3.2.2 Video Calibration

Using the site measurements and screenshots of the beads being stretched out, the relationship between the camera view and world view was calculated for each camera placement. The calibration images were formed by taking screenshots at the two times when the beads were stretched out, merging the two screenshots, and highlighting the beads for clarity. The annotated calibration images for the two approaches used are shown below. Figure 3.4 shows Site 017O – Beacon St SE and Figure 3.5 shows Site 190A – Portland Ave.

Figure 3.4 Calibration image for Site 017O with beads outlined in red.

Figure 3.5 Calibration image for Site 190A with beads outlined in red (zoomed in)

The coordinates of each point in the screenshots (in pixels, relative to an arbitrary point) and the corresponding coordinates in the world plane (in feet, relative to the same point) were input into the R code developed for this project. The R code then output the projection parameters (C[1] to C[8]) which were, in turn, used to project the points from the camera view coordinate plane (Xc, Yc) into the world view coordinate plane (Xr, Yr) using the following formulas:

$$X_r = \frac{C[1] + C[2] \times X_c + C[3] \times Y_c}{C[4] \times X_c + C[5] \times Y_c + 1}$$

$$Y_r = \frac{C[6] + C[7] \times X_c + C[8] \times Y_c}{C[4] \times X_c + C[5] \times Y_c + 1}$$

The error between the actual and projected coordinates was then calculated for each point in terms of percent error and feet. The results of the projections are presented in Table 3.4, Table 3.5, and Table 3.6. As predicted, error decreased when more points were used. The projected points were within one foot of the actual location with the exception of point 1A at Site 190A. This error was likely caused by the point's proximity to the high distortion area near the edge of the frame that is produced by a wide-angle lens.

Table 3.4 Error between actual and back-calculated point measurements at Site 017O using 10 points

Point	Actual Dist. to CL (feet)	Calculated Dist. to CL(feet)	Error (%)	Error (feet)
	D_cl,a	D_cl,c	E_p	E_ft
5A	13.5	13.5	0.01%	0.0
5B	24.3	24.0	-1.23%	0.3
2A	13.5	13.8	2.06%	-0.3
2B	24.3	24.4	0.52%	-0.1
1A	13.5	13.4	-0.72%	0.1
1B	24.3	24.4	0.45%	-0.1
3A	13.5	13.2	-2.31%	0.3
3B	24.3	24.5	1.19%	-0.3
7A	13.5	13.8	1.92%	-0.3
7B	24.3	24.0	-1.02%	0.2

Table 3.5 Error between actual and back-calculated point measurements at Site 017O using 5 points

Point	Actual Dist. to CL (feet)	Calculated Dist. to CL(feet)	Error (%)	Error (feet)
	D_cl,a	D_cl,c	E_p	E_ft
7B	13.5	13.4	-0.43%	0.1
3B	33.5	33.8	0.95%	-0.3
1B	43.5	43.2	-0.65%	0.3
7A	13.5	13.5	0.00%	0.0
1A	43.5	43.5	0.04%	0.0
6B*	18.5	18.3	-1.14%	0.2
5B*	23.5	23.3	-0.64%	0.2
4B*	28.5	28.0	-1.85%	0.5
2B*	38.5	38.3	-0.54%	0.2

*not used to calculate calibration coefficients (only included to check accuracy)

Table 3.6 Error between actual and back-calculated point measurements at Site 190A using 11 points

Point	Actual Dist. to CL (feet)	Calculated Dist. to CL(feet)	Error (%)	Error (feet)
	D_cl,a	D_cl,c	E_p	E_ft
1A	26.8	27.8	3.98%	-1.1
2A	31.8	31.5	-0.69%	0.2
3A	36.8	35.9	-2.31%	0.8
4A	41.8	41.1	-1.63%	0.7
5A	46.8	46.6	-0.42%	0.2
6A	51.8	52.1	0.59%	-0.3
7A	56.8	57.2	0.76%	-0.4
1B	26.8	27.1	1.23%	-0.3
2B	31.8	31.6	-0.57%	0.2
3B	36.8	36.2	-1.51%	0.6
7B	56.8	57.4	1.11%	-0.6

As shown in Table 3.4, Table 3.5, and Table 3.6, the calibration method described above is almost always accurate to a tolerance of one foot. The error was mitigated by aiming the cameras in such a way that the area around the stop line was near the center of the frame.

3.3 DATA REDUCTION

As previously mentioned, the video was reduced by UGRAs in two phases: a bin count and event-logging. During the bin count, vehicle volumes were collected in 15-minute intervals. This ensured the more detailed event-logging would take place on a day with average conditions and vehicle volumes.

3.3.1 Vehicle Volume Bin Counts

Due to the large amount of video collected at each site (over 7,000 hours total in all sites), a first pass through the video where approach volumes and visibility conditions were recorded was used to narrow down candidate days for event logging at each site. Four days before and after the stop lines were added were selected for each intersection based on the day of the week – Tuesdays, Wednesdays, and Thursdays were preferred due to the higher likelihood of “normal” traffic on those days – and the availability of video data. For each of those eight days, UGRAs recorded the number of vehicles entering the intersection via a given approach in 15-minute intervals for all of the available video from a given day. In addition to the approach volumes, the visibility for drivers was recorded (daylight, night, raining, or raining at night). Sites with simple geometries and camera angles were the highest priority and the more complicated sites were handled after all of the simple sites were complete.

To aid UGRAs in identifying approaches at an intersection and screenshots of the camera frame from each site were captured and annotated with arrows and labels for each major and minor approach. The reference lines created during the video calibration process (see Section 3.2.2 above) were also added for use during the event-logging process. Figure 3.6 and Figure 3.7 show the reference images for Raleigh Ave and W 28th St before and after the stop line was added, respectively. The two major road approaches (1 and 2) and the two minor road approaches (A and B) are labeled with the green arrows and text.

Figure 3.6 Raleigh Ave and W 28th St, pre-stop line reference image approach labels and reference lines (5-ft spacing)

Figure 3.7 Raleigh Ave and W 28th St with-stop line reference image approach labels and reference lines (5-ft spacing)

At first, UGRAs were trained to collect bin counts using either a commercially available traffic counting keypad and software or handheld clicker counters. These methods proved to be slow and, at times, inaccurate due to the difficulty of undoing mistakes. When using the clicker counters, the limit on the number of clickers that could be held at once often exceeded the number of approaches, thereby necessitating multiple passes. The counting software also proved to be slow because it was prone to crashing and the user interface did not have a rewind function. To remedy these issues, a UGRA developed a MatLab function to help students collect the data quickly and accurately in one video pass, while being able to easily undo mistakes.

Table 3.7 breaks down the number of hours of video collected, watched during the bin counting phase, and the event logging phase by site. It also shows the bin counts (total 47,951 vehicles) and events (total 20,825 events) logged by the UGRAs.

Table 3.7 Data collection and reduction progress

Site ID	Intersection Name	Video Collected [hrs]		Bin Counts [hrs]		Bin Counts [minor veh]		Events Logged [hrs]		Events Logged [minor veh]	
		Before	After	Before	After	Before	After	Before	After	Before	After
Total		**4,125**	**3,548**	**850**	**590**	**25,499**	**22,452**	**215**	**147**	**10,979**	**9,846**
S017O	Walnut St SE and Beacon St SE	264	165	48	69	3,921	4,339	16	16	825	1,199
S036O	Lyndale Ave S and W 72nd St	183	283	52	8	986	144	16	8	282	91
S040A	Nicollet Ave and E 68th St	240	0	0	0	0	0	0	0	0	0
S040B	Nicollet Ave and W 68th St	240	0	0	0	0	0	0	0	0	0
S051O	Como Ave and Knapp St	62	190	46	55	582	1,366	17	15	215	395
S087O	Woodhill Dr and Civic Center Dr	211	212	67	68	1,356	1,380	17	16	344	324
S089A	Dale St and Iona Ln	258	210	57	56	817	875	16	15	261	249
S094A	Lincoln and Lydia Ave W*	249	259	82	19	2,384	730	16	18	463	614
S179O	50th St W and Eden Ave	127	201	40	33	3,989	3,337	15	16	1,573	1,671
S182O	Vernon Ave S and Arcadia Ave	184	216	19	62	1,092	3,809	16	0	932	908
S190A	Portland Ave and E 73rd St EB	264	240	17	17	897	699	0	0	838	614
S190B	Portland Ave and E 73rd St WB	264	240	7	0	0	0	7	0	469	0
S221O	Warner Rd and Fish Hatchery Rd N	168	165	14	12	413	358	14	12	411	360
S227O	W Territorial Rd and Cromwell Ave*	187	209	19	17	590	546	0	2	574	541
S280A	Raleigh Ave and W 28th St NB	162	223	142	71	1,762	1,230	16	14	522	656
S280B	Raleigh Ave and W 28th St SB	162	223	142	71	3,056	2,725	16	14	892	1,316
S282O	County Rd C W and Civic Center Dr	242	257	50	17	1,827	457	0	0	697	454
S284A	Quentin Ave and W 28th St NB	242	257	50	17	1,827	457	0	0	697	454
S284B	Quentin Ave and W 28th St SB	209	0	0	0	0	0	16	0	301	0
S283A	County Rd B2 W and Prior Ave N**	210	0	0	0	0	0	0	0	0	0
S283B	County Rd B2 W and Prior Ave N**	210	0	0	0	0	0	0	0	0	0
S283C	County Rd B2 W and Prior Ave N**	210	0	0	0	0	0	0	0	0	0
S283D	County Rd B2 W and Prior Ave N**	210	0	0	0	0	0	0	0	0	0

*Approach broken down by lane in final analysis **Not used due to project scope constraints, as it is a 4-way stop

3.3.2 Event Logging

Once the bin counts from all eight days for a given site had been collected, two days were selected for further data collection – one before the stop line was painted and one after. Pairs of days with highest traffic volumes were the highest priority. When possible, the same day of the week was selected before and after the line was painted in an effort to reduce the impacts of differences in driver volumes that might be influenced by drivers' weekly schedules. In cases where video was broken or the minor road vehicle volumes were drastically different, the day of the week was discarded and the days were selected based on the similarity of the traffic volumes.

For both of the days selected for further data collection, information on every vehicle entering the intersection from the minor approaches was collected – AKA an "event". The data consisted of the intersection, approach, and time at which the event occurred, information on the event vehicles' behavior, and the presence and location of other vehicles and pedestrians at the time of the event. Table 3.8 shows an example of the data collected from six events at the Raleigh Ave site.

Table 3.8 Sample of event coding at Raleigh Ave

Part 2: Event Information																
Minor Approach	Arrival Time	Minor Veh. in Front?	Stopping Behavior	Stopping Location	Veh. Type	Vehicle Movement	Minor Veh. Locations	Near Ped Present?	Yield to Near Ped?	Far Ped Present?	Yield to Far Ped?	Maj. 5 Sec Before?	Maj. 10-Sec After?	Arrive Frame	Depart Frame	Logged By
[A, B]	[HHMMSS]	[0 or 1]	[ ]	[ ]	[B,M,C,L,S]	[L, R, T, U]	[N, A, O, B]	[0 or 1]	[0, 1, -1]	[0 or 1]	[0, 1, -1]	[0 or 1]	[0 or 1]	[ ]	[ ]	[ ]
A	062029	0	S	3	C	U	N	0	-1	0	-1	0	1	X	X	PD
A	062032	1	X	X	X	X	X	X	X	X	X	X	X	X	X	PD
A	063122	0	R	X	C	T	N	1	0	0	-1	1	1	27255	27294	PD
B	064440	0	R	X	C	L	N	0	-1	1	1	1	0	39229	39260	PD
B	064537	0	R	X	C	R	N	0	-1	0	-1	1	0	40027	40071	PD
A	065148	0	I	X	C	R	N	0	-1	0	-1	0	0	X	X	PD

Using the explanation of the columns found in Table 3.9, the sample events can be decoded. For example, the events at 6:20:29 and 6:20:32 correspond to a passenger vehicle that stopped at reference line 3 before making a U-turn and a second vehicle that closely followed it. No pedestrians were present but at least one vehicle entered the intersection via a major road approach within 10 seconds of the event vehicle entering the intersection. The second vehicle was close enough to the event vehicle that it was assumed that the second vehicle's behavior was due to the fact that there was already a vehicle stopped at the intersection and not the presence or lack of a stop line. The event at 6:31:22 corresponds to a passenger vehicle that rolled through the intersection without fully stopping. There was at least one vehicle entering the intersection up to five seconds before the event vehicle and at least one vehicle entering the intersection up to 10 seconds after the event vehicle. There was a pedestrian crossing the minor road which the event vehicle yielded to – likely by slowing down enough for the pedestrian to clear the lane.

Table 3.9 Event data attribute names and definitions

Column Name	Units/Options	Description
Minor Approach	[A, B]	Approach the event vehicle arrived at
Arrival Time	[HHMMSS]	Timestamp the vehicle arrived at the stop sign
Minor Vehicle in Front?	[0, 1]	Whether there was another vehicle on the minor approach within 30 ft (two car lengths) in front of the event vehicle. "1" if yes* "0" if no *"1" would result in the rest of the data being entered as "X", as that vehicle was assumed to have its stopping behavior determined by the vehicle in front of it.
Stopping Behavior	[S, R, I]	The manner in which the event vehicle decelerated before entering the intersection. • "S" if the vehicle stopped for 10+ frames, which was the amount of time determined to be a complete stop with enough time for the driver to look left and right at the approach. • "R" if the vehicle rolled through. Rolling was a tricky thing to identify and define qualitatively. If a vehicle stopped, but for less than 10 frames, it was considered a roll. If the vehicle did not come to a full stop at any point but noticeably reduced its speed to 3mph or less as it approached the sign, it was also considered a roll. • "I" if the vehicle ignored the sign. This was defined as not reducing its speed to below 3mph at any point during the event.
Stop location	[ ]	The numeric value of the reference line the front wheel of the event vehicle stopped at. See Figure 3.9 for an example of a vehicle stopped with its front tire on the stop line. • "X" if the event vehicle never came to a full stop. • Otherwise, this value is the number of the line nearest to the front wheels when the event vehicle stopped.
Vehicle Type	[B, C, M, L, S]	The FHWA classification of the event vehicle (see Figure 3.8) • "B" for bicycles in the road. If there were multiple cyclists biking in a group, they were treated as one vehicle, but "multiple bikes" would be commented on the event. • "M" for motorcycles. • "C" for cars. • "L" for large single-unit vehicles with fewer than 4 axles. • "S" for semis and other large vehicles with more than three axles.

Column Name	Units/Options	Description
Vehicle Movement	[L, R, T, U]	The maneuver the event vehicle made. • "L" for left turn. • "R" for right turn. • "T" for through or straight. • "U" for U-turn.
Minor Vehicle Locations	[N, A, O, B]	Location(s) of other vehicles on minor road at the same time as the event vehicle. This could result in combinations like "OB". • "N" for no other vehicles. • "A" for vehicles that were waiting or driving in the same direction as and on parallel trajectory with the event vehicle, within 30 feet ahead of or behind the event vehicle. Compared to "B", the vehicle must have been in a different lane. • "O" for vehicles at the stop control of the opposing minor approach at any point between the time the event vehicle was 30 feet upstream of the stop sign and the time the event vehicle entered the intersection. If the opposing approach was not visible, it was noted. • "B" for vehicles that were waiting or driving in the same direction as and behind the event vehicle, in the same lane.
Near Pedestrian Present?	[0, 1]	Whether there were any pedestrians on the near side of the intersection that would conflict with the event vehicle, i.e., the pedestrian or the car needed to stop to avoid collision. • "1" if yes • "0" if no
Yield to Near Pedestrian?	[0, 1, -1]	Whether the event vehicle waited for any present pedestrians on the near side of the intersection • "1" if the event vehicle waited for all of the pedestrians. • "0.5" if the event vehicle waited for some of the pedestrians. • "0" if the event vehicle waited for none of the pedestrians. • "-1" if there were no pedestrians (corresponding to a "0" in the "Near Pedestrian Present?" column).
Far Pedestrian Present?	[0, 1]	Whether there were any pedestrians on the far side of the intersection that would conflict with the event vehicle, i.e., the pedestrian or the car needed to stop to avoid collision. • "1" if yes • "0" if no

Column Name	Units/Options	Description
Yield to Far Pedestrian?	[0, 1, -1]	Whether the event vehicle waited for any present pedestrians on the far side of the intersection. • "1" if the event vehicle waited for all of the pedestrians. • "0.5" if the event vehicle waited for some of the pedestrians. • "0" if the event vehicle waited for none of the pedestrians. • "-1" if there were no pedestrians, (corresponding to a "0" in the "Near Pedestrian Present?" column).
Major Vehicle 5 Seconds Before?	[0, 1]	Whether any vehicles from the major road that would conflict with the event vehicle were in the intersection between 5 seconds before the event vehicle arrived and the time the event vehicle started accelerating to enter the intersection. • "1" if yes • "0" if no
Major Vehicle 10 Seconds After?	[0, 1]	Whether any vehicles from the major road that would conflict with the event vehicle exited the intersection up to 10 seconds after the time the event vehicle started accelerating to enter the intersection. • "1" if yes • "0" if no
Arrive Frame	[ ]	Video frame the event vehicle's front wheel crossed a specified reference line upstream of the stop line. • Frame number if Roll event • "X" if a Stop or Ignore event
Depart Frame	[ ]	Video frame the event vehicle's front wheel crossed a specified reference line downstream of the stop line. • Frame number if Roll event • "X" if a Stop or Ignore event
Logged By	[ ]	The initials of the person who added the event to the log, in case there were questions about the data.
Event Comments	[ ]	Notes or explanations of any strange or noteworthy events or circumstances.

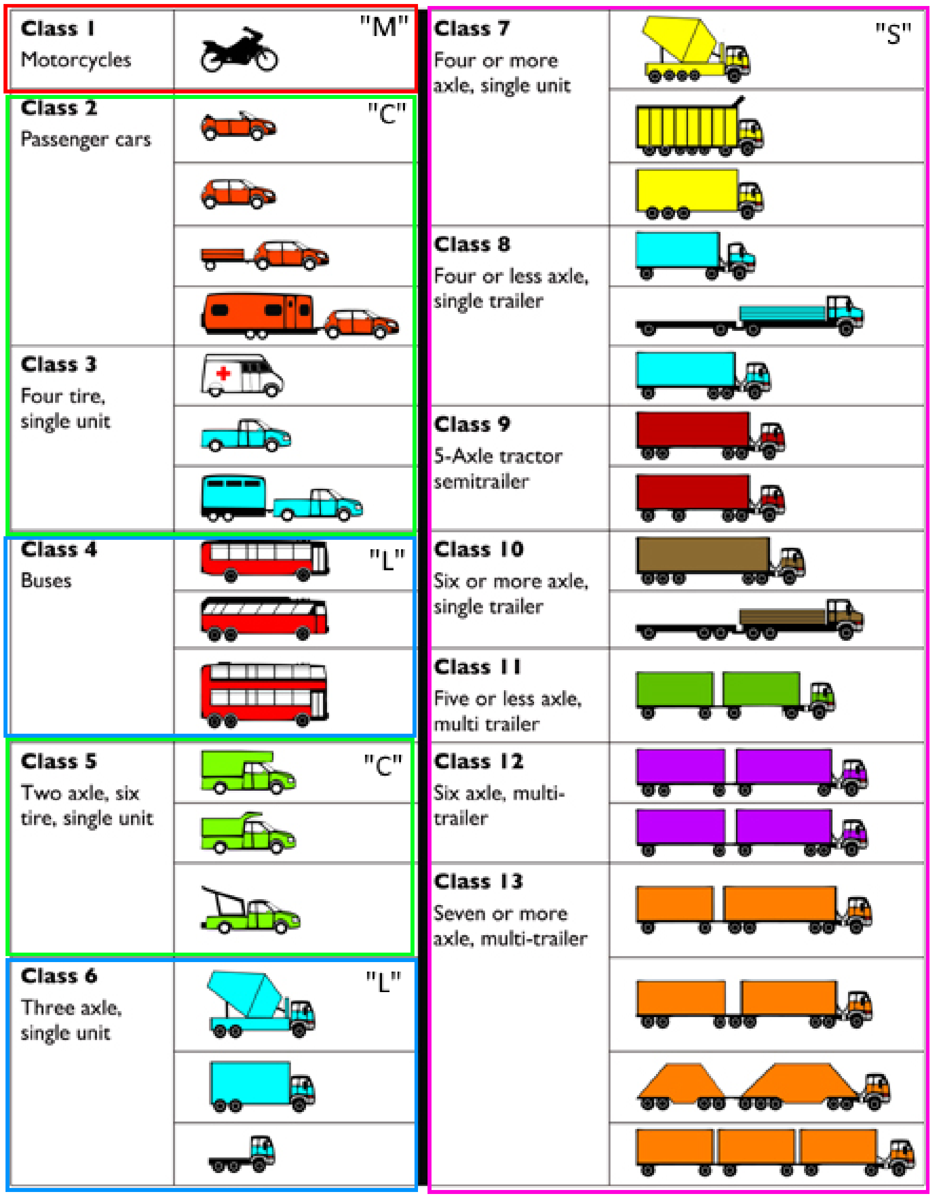

Figure 3.8 Vehicle classification types [1]

Figure 3.9 Vehicle stopped with front tire on stop line

UGRAs were trained using a double-blind data set. After being trained by the research team, a new UGRA would watch part of a control day. A second UGRA would then watch that same portion of the control day and a researcher would sit down with both UGRAs to compare the data sets and review any events with discrepancies to determine the ground truth. Over the iterations of training multiple UGRAs on event logging, the researchers were able to quickly identify what types of interactions UGRAs had trouble with as well as amass a knowledge of problematic types of events and how they should be coded. Following the review of a UGRA's work, any misunderstandings or mistakes were discussed and the UGRA would collect event data for another portion of the control day. This cycle of logging event data for a portion of the control day and then reviewing that data with a researcher continued until no errors were found. To reduce the risk of observer bias creating false trends in the data, one UGRA was responsible for both event logging days for a given site.

Initially, UGRAs did not capture "arrive frame" and "depart frame". Due to some of the initial sites' analysis showing far higher numbers of drivers ignoring the stop sign than expected, the research team decided to capture more information during "roll" and "ignore" events. The team hypothesized that some of the high numbers of ignores were due to UGRAs having trouble differentiating between roll and ignore events. Adding in the arrive and depart frames allowed the research team to verify the distribution of roll and ignore events as recorded by the UGRAs.

The vehicle location during arrival and depart frames were based on the overlay lines created for each site; at most sites, a distance of 30 feet between overlay lines was used. At some sites, because of geography or camera angle, shorter or longer distances between arrival and depart frames was used. To create the histogram of roll and ignore event times at each site, all the data was normalized for a distance of 30 feet. To make the data easier to read, frame numbers were converted into seconds to travel between the two lines.

3.4 DATA ANALYSIS

Two of the selected sites, Nicollet Ave and E/W 68th St and County Rd B2 and Prior Ave N, did not undergo bin counts or event logging. At Nicollet Ave, video was collected before the sites were painted, but delays in roadwork prevented the collection of video after the stop lines were put in place. County Rd B2 was eliminated as it was the only AWSC intersection with video footage. While it would provide valuable insight into how drivers interact at AWSC intersections with and without stop lines, due to time and budget constraints the video could not be reduced for this project. All other sites had a minimum of two days reduced, one before the stop line was painted and one after. The results are gathered here, broken down by approach and lane. As mentioned previously, in all cases where drivers stopped, the stop location was recorded as the location of the bottom of the front wheel. Graphs in the sections below regarding stop location reflect that definition.

At all sites, events with and without pedestrians were gathered. Initially, the analysis was done twice for each site, one time with pedestrian events included and one time with them excluded. Examining those results showed no difference in driver behavior when a pedestrian was present versus no pedestrian present. The results shown in this section include pedestrian events.

Site 017O, Beacon St SE and Walnut St SE, was geometrically the simplest intersection studied in this portion of the project. As such, Section 3.4.1 will not only contain results for Beacon St SE, but also act as a tutorial for how to interpret the rest of the intersections' results.

At each site, a table of relevant measurements is given. This table may include the following abbreviations, depending on the geometry of the site.

Table 3.10 Aerial image marking definitions

Abbreviation	Definition
CL_maj	Centerline of the major road.
C1_maj (C2_maj, etc)	Distance from CL_maj to Curb line(s) of the major road in feet.
C1_min (C2_min, etc)	Distance from center of minor road to curbs of minor road in feet.
CW_1 (CW_2, CW_3, etc.)	Distance from CL_maj to CrossWalk, if present. Measured both to the front and the back of the crosswalk in feet.
FL_1 (FL_2, etc)	Distance from CL_maj to Fog Line, if present, in feet.
RP	Distance from CL_maj to Reference Point – Arbitrary location in the roadway marked for reference by the research team, in feet.
SL	Distance from CL_maj to the front of the painted Stop Line, in feet.
SS	Distance from CL_maj to the Stop Sign location, in feet.

3.4.1 S017O – Beacon St SE and Walnut St SE

This section presents the results from Beacon St SE and Walnut St SE as well as a brief explanation of each graph and how to interpret the results. Each site will have a brief description, aerial view with relevant measurements marked, camera view, and annotated map with required sight distance versus available sight distance at the intersection.

The intersection of Walnut St SE and Beacon St SE is a T-intersection located in Minneapolis, on the University of Minnesota campus. Figure 3.10 shows an aerial view of the intersection annotated with key measurements. Figure 3.11 shows the camera view for the site. The site is somewhat unique in that Walnut St is a one-way road (NB) to the north of the intersection. Beacon St had a faded stop line and faded crosswalk prior to this project. Both Walnut St and Beacon St have observed ADTs of approximately 1000 vehicles. This site was chosen because of its unique geometry and proximity to the MTO, which allowed for it to be a testing ground for methods and equipment. The righthand available sight distance was adequate, unless vehicles occupied the parking lot immediately to the right of the intersection, in which case it fell short as seen in Figure 3.12.

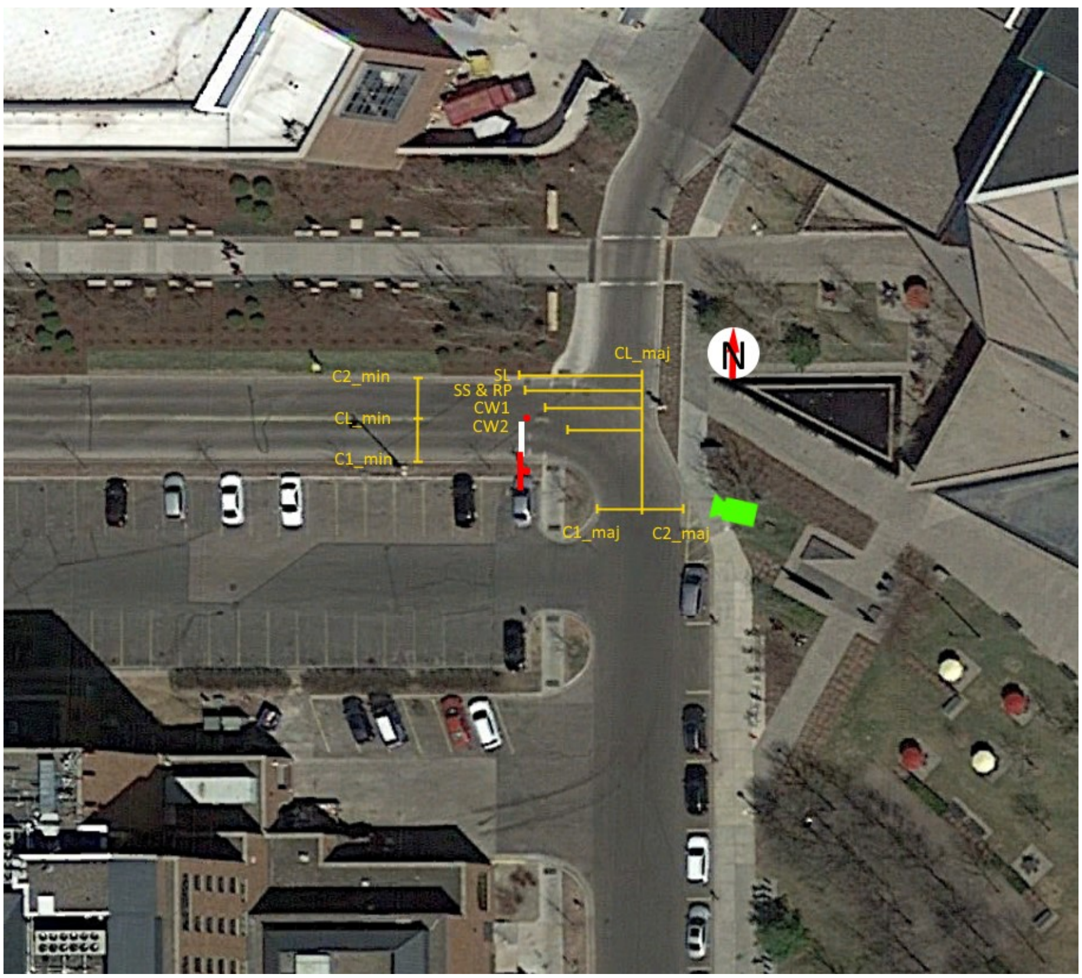

Figure 3.10 Aerial view of the intersection of Walnut St SE and Beacon St SE with measurements marked

Measurements noted on Figure 3.10 are listed in Table 3.11.

Table 3.11 Relevant measurements at Walnut St SE in feet

From CL_maj to...	SL	SS & RP	CW1	CW2	C1_maj	C2_maj	
	34.50	33.50	29.50	23.50	13.25	13.25	
From CL_min to...	C1_min	C2_min					
	10.75	11.67					

Figure 3.11 shows the camera view of the intersection with overlay lines marked. As described in Section 3.2.2, the overlay lines were generated by marking five-foot increments with a specially created beaded string that would be visible on camera, compiling images with the measurements marked, and annotating the camera image with a photo manipulation program. These overlay lines were consistently five feet apart at each site, though placement varied due to geometry of the sites. UGRAs marked stop location by indicating the overlay line the front tire of the vehicle stopped at during a stopping event; during data processing, these overlay distances were converted into feet from the centerline and feet from the near-side curb of the major road to generate results that were normalized by intersection.

Figure 3.11 Camera view of the intersection of Walnut St SE and Beacon St SE with 5-ft overlay lines marked

Figure 3.12 Available sight distance and required sight distance at Beacon St SE and Walnut St SE

After the site description and accompanying images, the site specific results will be presented. These results include Crossing Behavior, Crossing Behavior by Movement Type, Distance from Curb Line for Stopping Vehicles, and a histogram of roll and ignore events. Each graph will be presented in more detail below.

The primary research questions for the observational study are:

1. Do stop lines have an effect on overall driver behavior?
    a. Do stop lines impact the number of drivers rolling, stopping or ignoring the stop sign?
    b. Are there substantial amounts of drivers ignoring the stop sign?
    c. Did the ratio of rolls to stops change after the placement of the stop line?
    d. Are different turning movements affected differently by the stop line?
    e. Did the amount of time drivers who roll or ignore take to pass through the intersection change with the placement of the stop line?
2. Do stop lines affect where drivers are stopping, when they stop?
    a. Did the distribution of stopping distances change?

b. Where were the most drivers stopping before the stop line was added, and did the stop line appear to impact that location?

Following the addition of a stop line, EB Beacon St experienced an increase in roll events and decreases in stop and ignore events, as seen in Figure 3.13. Because the majority of drivers roll at this intersection, the impact of the stop line appears minimal. Additionally, the number of drivers ignoring the stop line is high as compared to other locations as well as an expected violation rate of ~5%. Additional information on the roll and ignore events captured by the UGRAs is presented in Figure 3.16.

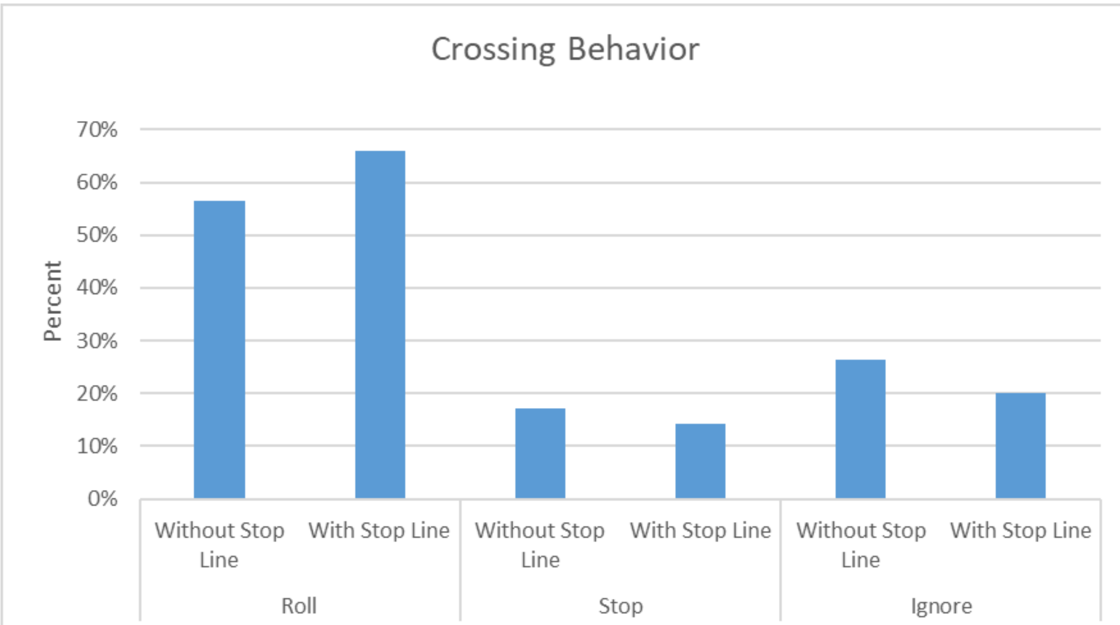

Figure 3.13 EB Beacon St SE distribution of driver crossing behavior as a percentage of all events pre- vs with-stop line

The Crossing Behavior graph addresses research questions 1.a, 1.b, and 1.c. This graph shows the percentage of drivers who came to a complete stop versus those who rolled through (slowed briefly) or ignored (did not change speed). The total 100% for each period, Without and With Stop Line, can be found by adding the Roll, Stop and Ignore percentages. The Without and With are presented next to each other so the change in individual behavior type can more easily be seen. Additionally, the ratio of behaviors (stop to roll, stop to ignore) and the change in that ratio becomes apparent in this graph. In this case, the stop to roll ratio without the stop line was 15%:65%; with the stop line, this became 12%65%. This graph strives to answer the question of the stop lines' general effect – did driver behavior change significantly after the placement of the stop line?

The Crossing Behavior by Movement graph is similar to the Crossing Behavior graph, but breaks down the roll, stop and ignore behaviors by whether the driver performed a right- or left-turn, or a through movement. (Some intersections, like Beacon St SE, did not have one or more movements available to drivers depending on the geometry of the roadway.) This graph attempts to answer the question of the stop lines' effect on behavior, but controlling for driver movement – do drivers stop more often when making a left turn movement? If so, is that due to AADT of the major road, sight distance, other factors, or the stop line?

At Beacon St SE, the distribution of driver behavior during turning movements did not appear to change with or without the stop line, as seen in Figure 3.14.

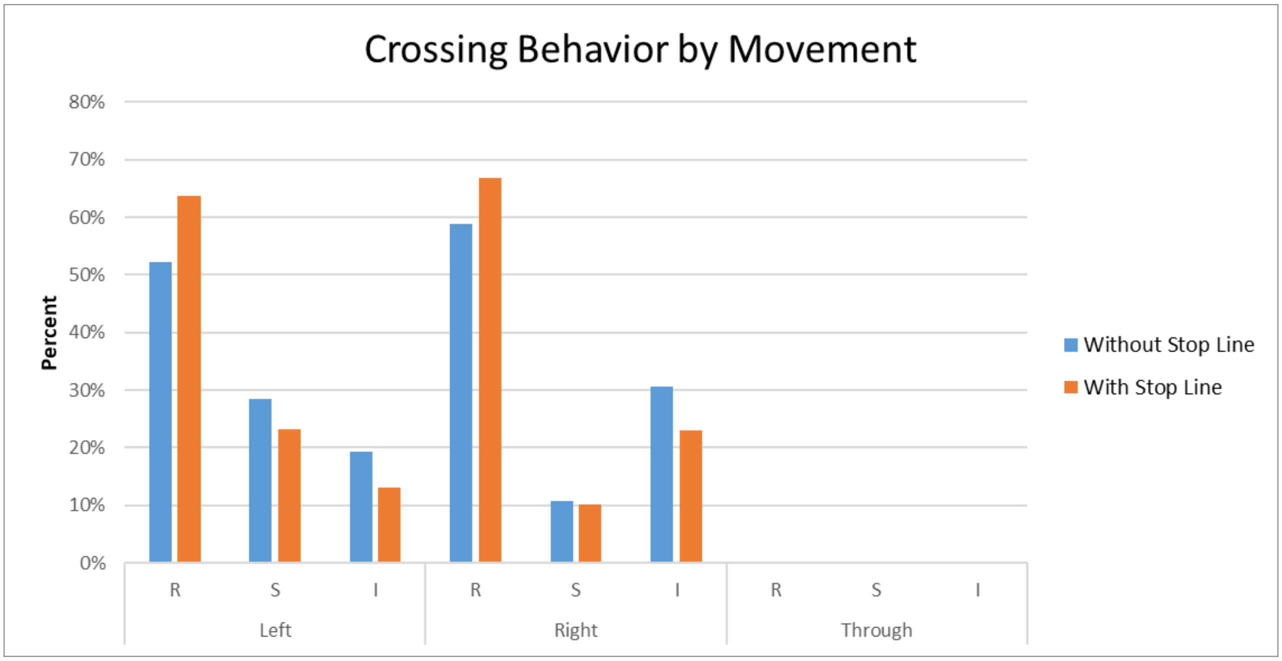

Figure 3.14 EB Beacon St SE distribution of driver crossing behavior as a percentage of all events pre- vs with-stop line, by driver movement

The next graph, "Distance from Curb Line for Stopping Vehicles", looks only at drivers who stopped. In Beacon St SE's case, this graph only represents that 15% of drivers without and 17% of drivers with the stop line who came to a complete stop. The percentages in the Distance from Curb Line graph are out of only stopping events and will add to 100% across each of the without and with-stop line periods.

The graph is normalized around the curb line, as marked in the aerial image of each site. The curb line becomes 0 feet on the graph. At some sites, the curb line may be the point of collision with the major road; some sights have fog lines, cross walks, or bike lanes past the curb line toward the center of the road. These are marked with vertical lines at their location. Overall, this graph shows the shift, if any, the stop line caused of the driver's front wheel during stop events. As shown in Figure 3.9, the front tire being on the stop line still has several feet of car in front of it, possibly intruding into the major lane.

As seen in Figure 3.15, both with and without the stop line, vehicles tend to stop between the stop line and the edge of the major road. While this is still upstream of the conflict point with vehicles on the major road, drivers hardly ever stop behind the stop line. Following the addition of a stop line, the distribution of stop locations shifted upstream towards the stop line, suggesting that the stop line had some impact on drivers' stop location. However, whether ignoring or rolling, two-thirds of drivers at this site did not stop. The stop line did not appear to have an impact on the percent of drivers that stopped, and only shifted by approximately 5 feet the location they stopped relative to the intersection.

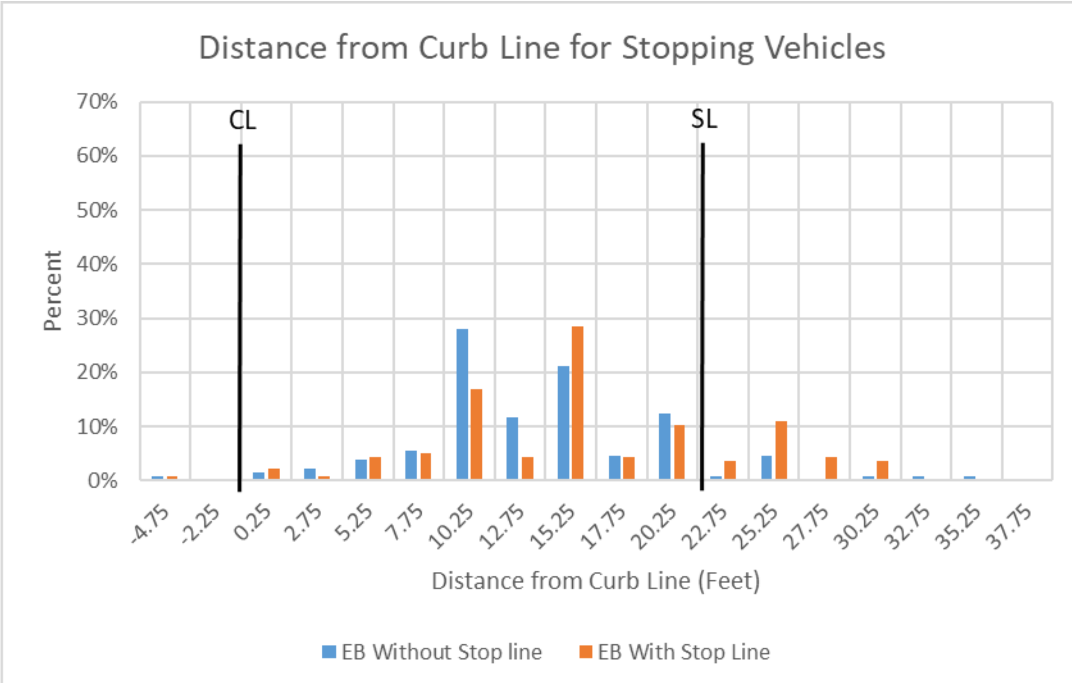

Figure 3.15 Beacon St SE and Walnut St SE Distribution of Stopping Distance During Stop Events

The final graph presented in each section is a histogram of roll and ignore events. As discussed in 3.2.2 UGRAs seemed to have difficulty discerning between roll and ignore events at some sites. By collecting the arrival and departure frames, and normalizing that difference to seconds travelled across 30 feet, any patterns in roll and ignore events become apparent, as well as any difference between periods without and with the stop line in place.

At Beacon St, the stop line did appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.16, the average time to travel 30 feet increased by about 1 second after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down more as they enter the intersection.

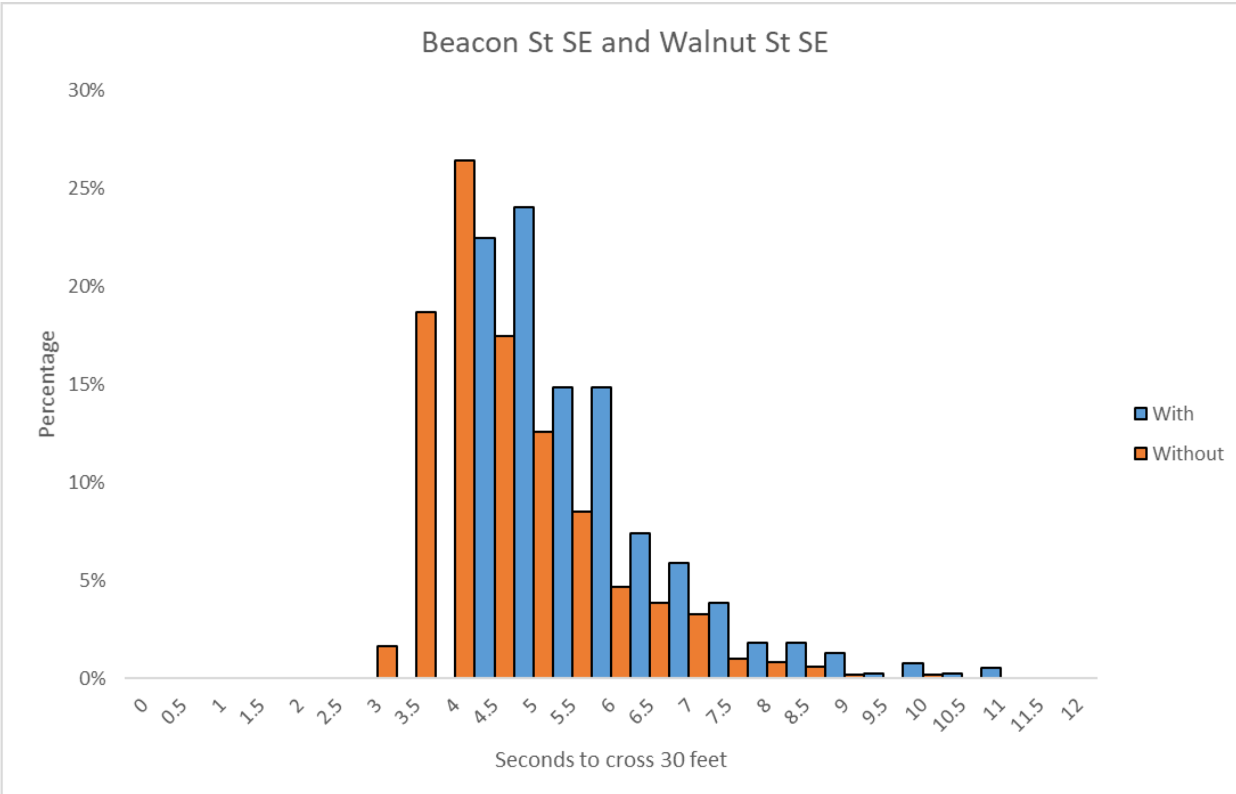

Figure 3.16 Beacon St SE and Walnut St SE Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

The rest of the site by site results will be presented following the format described in this section.

3.4.2 S036O – Lyndale Ave S and W 72nd St

The intersection of Lyndale Ave S and 72nd St is a T-intersection located in Richfield. The WB approach of 72nd St did not have a stop line or crosswalk prior to this project. Figure 3.17 shows an aerial view of the intersection annotated with key measurements. Lyndale Ave has an AADT of 11,700 vehicles and 72nd St has an estimated ADT of less than 500 vehicles based on project counts. The site was selected as it is a T-intersection with four lanes and has a high AADT on the major road. The research team determined that the available sight distance to both the left and right – but especially to the right – was insufficient as seen in Figure 3.19. Another notable feature of this site is the substantially different traffic demand in each direction of the major road; drivers headed southbound are typically connecting with Interstate 494, while drivers traveling northbound are headed toward downtown Richfield. For the purposes of this analysis, the left- and right-turning events are combined when examining stopping distance, but Figure 3.21 also breaks down the differences in behavior by type of turning movement.

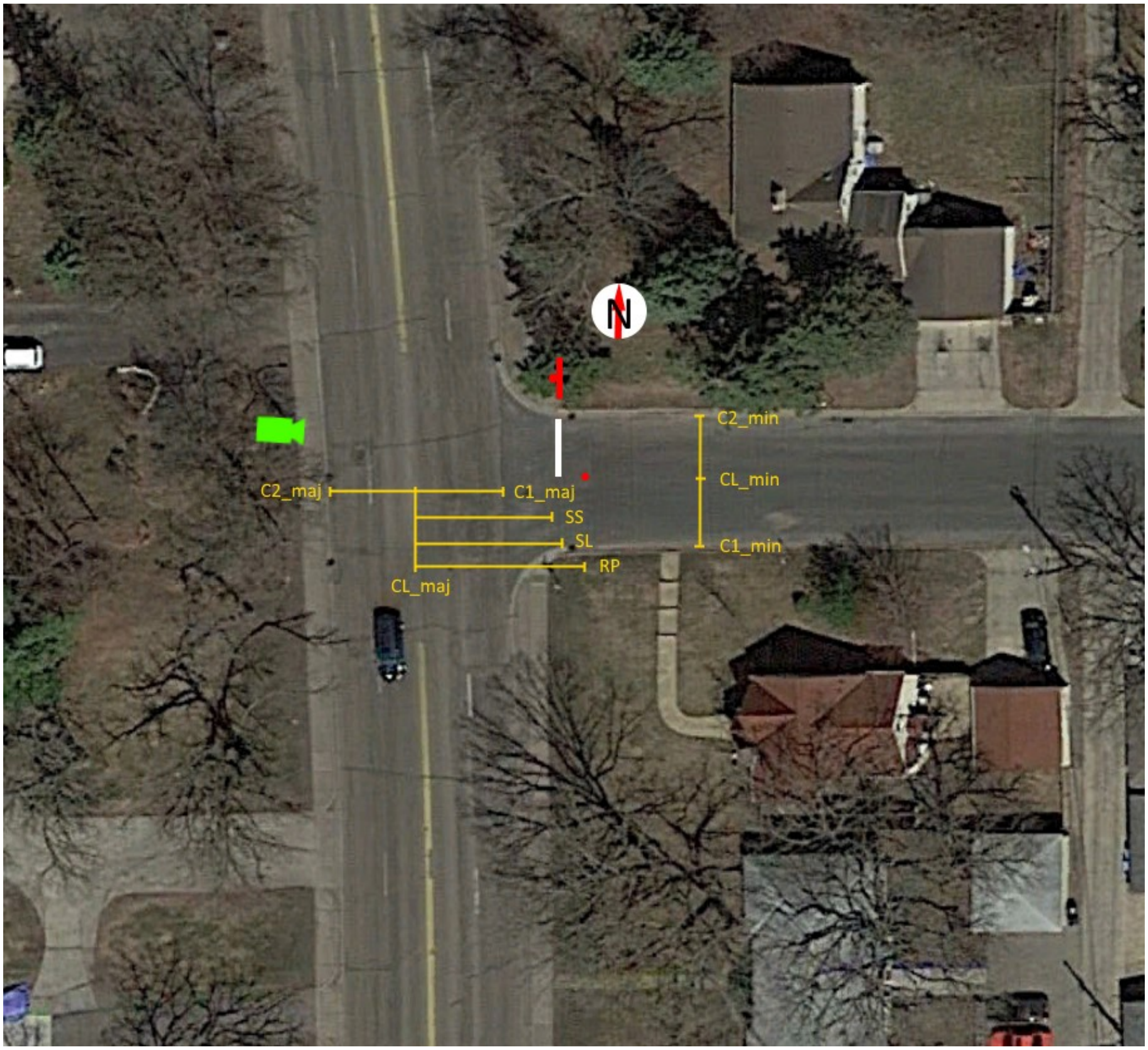

Figure 3.17 – Aerial view of the intersection of Lyndale Ave S and W 72nd St with measurements marked

Measurements noted on Figure 3.17 are listed in Table 3.12.

Table 3.12 Relevant measurements at Lyndale Ave in feet

From CL_maj to...	RP	SL	SS	C1_maj	C2_maj		
	44.00	41.58	38.58	24.83	21.17		
From CL_min to...	**C1_min**	**C2_min**					
	17.25	17.25					

Figure 3.18 shows the camera view of the intersection with overlay lines marked.

Figure 3.18 Camera view of the intersection of Lyndale Ave S and W 72nd St with 5-ft overlay lines marked

Figure 3.19 Available sight distance and required sight distance at Lyndale Ave S and W 72nd St

This site had the one of the highest percentages of stopping events among the observed sites. Portland Ave and Warner Rd also had high percentages of stopping events; all three of these sites have high AADTs on the major road. Following the addition of a stop line, the Lyndale Ave site experienced a minor decrease in roll and ignore events and a minor increase in stop events, as seen in Figure 3.20. This is expected, as Lyndale Ave is a high AADT road, which forces drivers on 72nd St to stop and wait for a gap to make their movement. The poor visibility to the right also gives drivers a reason to stop. The number of drivers that ignore the stop sign is at generally accepted levels.

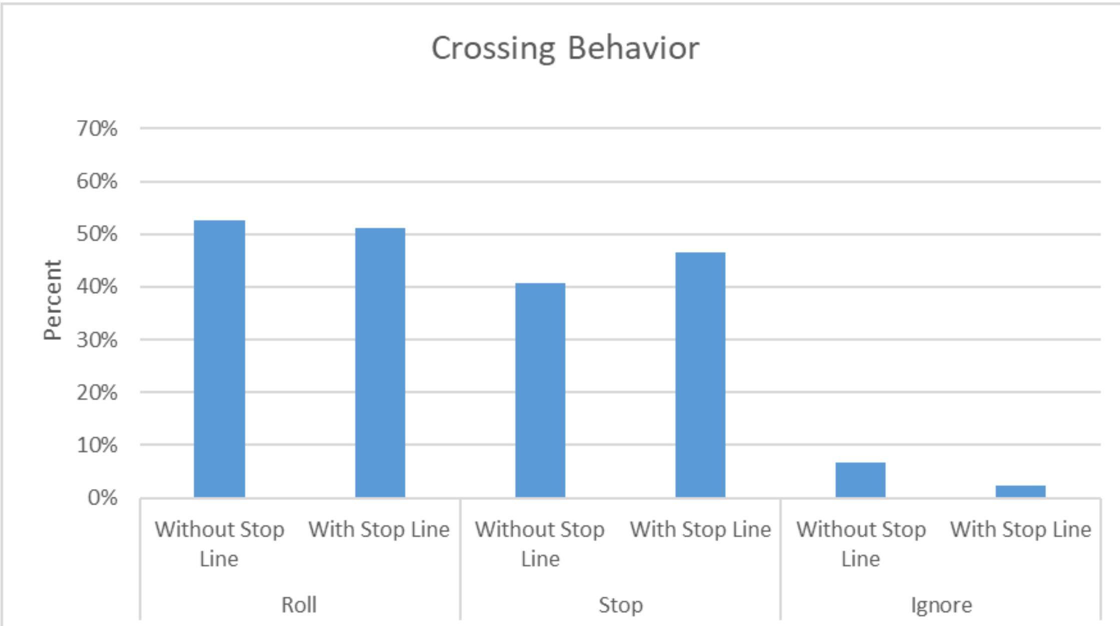

Figure 3.20 EB W 72nd St distribution of driver crossing behavior as a percentage of all events without vs with stop line

Figure 3.21 shows the breakdown of the crossing behavior by turning movement. In this graph we see that, for the right turn, the fraction of drivers who stop did not change with the addition of the stop line. On this movement we observe a significant reduction in the violations (ignores) accompanied with an increase in rolls. This shift is confirmed later when we look at the time to cross in the non-stop cases. This behavior change seems logical since the right turn has no sight distance issues, so the presence of the stop line only affects the level of care the drivers are showing in rolling pass the stop sign.

In difference, in left turning movement, which has a substandard sight distance to the right, the stop line seems to have made a change towards increasing the fraction of drivers that stop by reducing both rolls and ignores. These observations suggest a strong relationship between the effect of the stop line and the available sight distances.

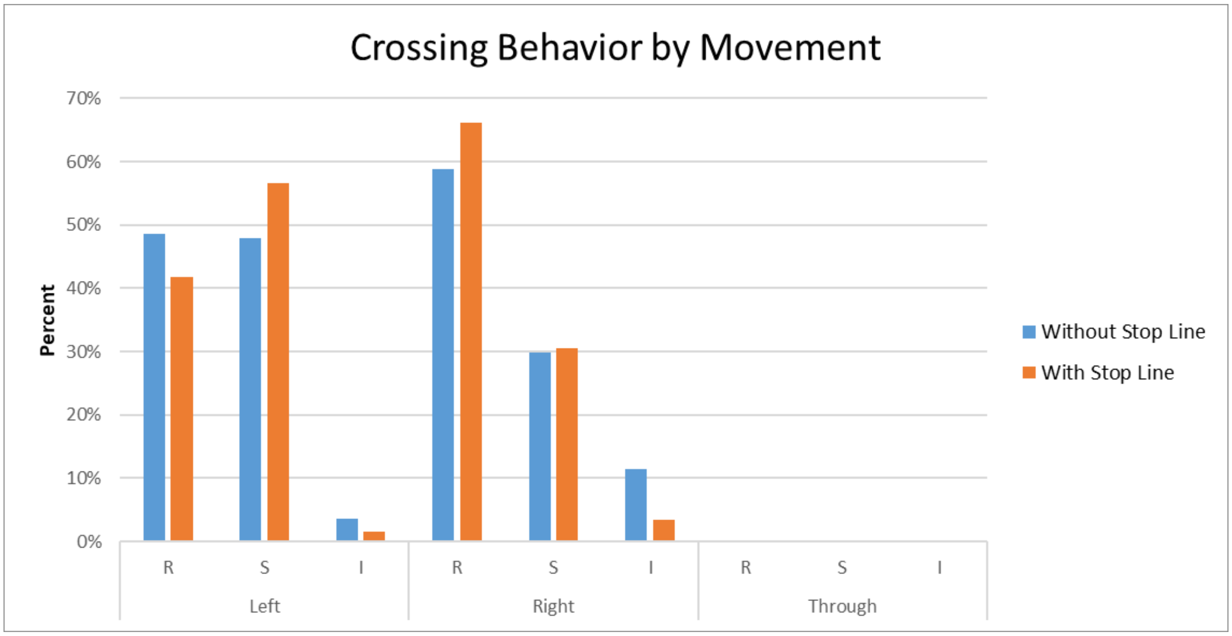

Figure 3.21 EB W 72nd St distribution of driver crossing behavior as a percentage of all events without- vs with - stop line, by driver movement

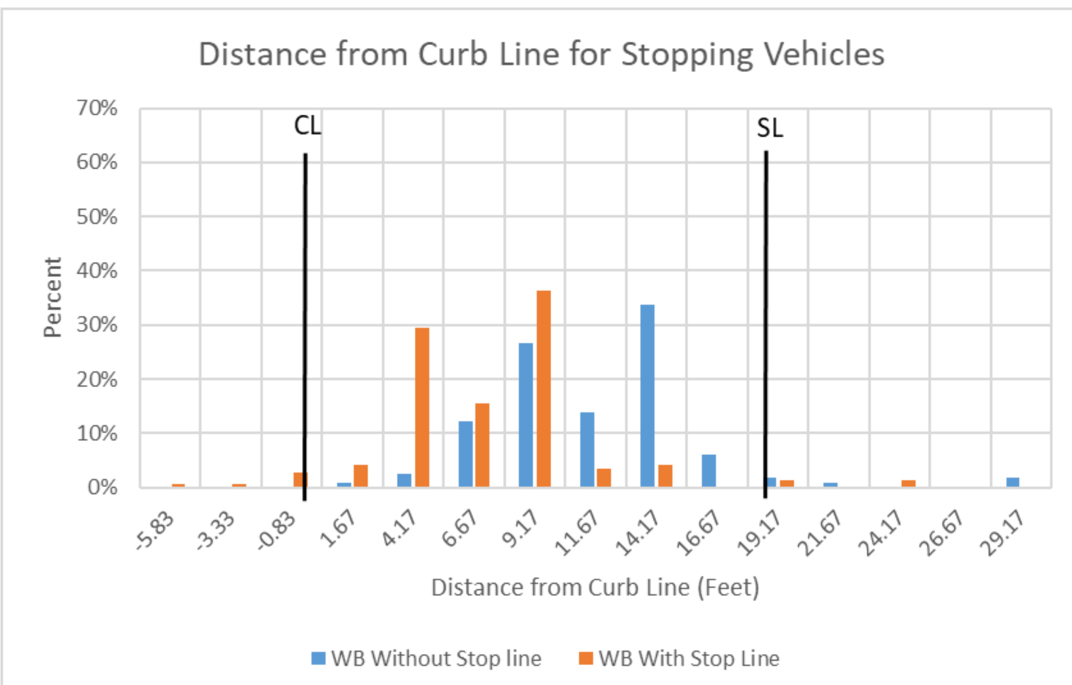

Figure 3.22 Lyndale Ave S and W 72nd St Distribution of Stopping Distance During Stop Events

Despite the comparatively high without-stop line stopping rate and observed increase in stopping events following the addition of the stop line, Figure 3.22 shows that drivers actually tended to stop approximately five feet closer to the intersection after the stop line was painted. Running t-tests for significance on both the stopping behavior of the drivers at this location as well as the location they stopped at showed both variables are not statistically significant at at least the 90% level; however, it is worth examining features of the intersection in more detail to try to explain why the shift occurred.

At both video collection periods, visibility to drivers' right was limited due to foliage. Combined with the large distance between the stop sign/line and the edge of the major road, this may have contributed to the trend of drivers stopping near the edge of the major road, even in the without-stop line video. The research team hypothesizes that adding the stop line gave drivers a frame of reference that didn't exist prior to painting it; without the stop line, drivers had fewer visual cues as to where they should stop. As a result, it is likely that most drivers stopped between the stop line and the edge of the major road to give themselves adequate sight distance without actually entering the major road. After the stop line was painted, drivers had a clear line roughly a car's length upstream of the intersection to use as a reference. Drivers could easily tell that their vehicle would fit between the stop line and the curb line, which has a clear discoloration between pavement types. Prior to the stop line being painted, drivers would judge—often conservatively – how far ahead they could infringe past the stop sign. After, with the stark white stop line in place, drivers knew if their vehicle could fit between the stop line and the curb line, allowing them to stop with adequate sight distance in both directions but without infringing on the major road. This is only a hypothesis, and within the constraints of the project, very difficult to test further.

Regardless, the suggestion here is that the stop line is in the wrong place since, at least from the driver's point of view, there is no satisfactory sight distance if they stop at the correct place. In addition, it may act as a visual cue to the driver to pull forward further towards the intersection, and further toward the point of collision. That said, the stop line did convince more left turning drivers to stop rather than roll and reduced the violations in right turning vehicles. This is further supported in Figure 3.23, where the average time to travel 30 feet increased by about 1 second after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down more as they pass through the intersection. In the same figure we also see a large reduction in the smallest travel times, supporting the observation of the shift from ignores to rolls for right-turning vehicles.

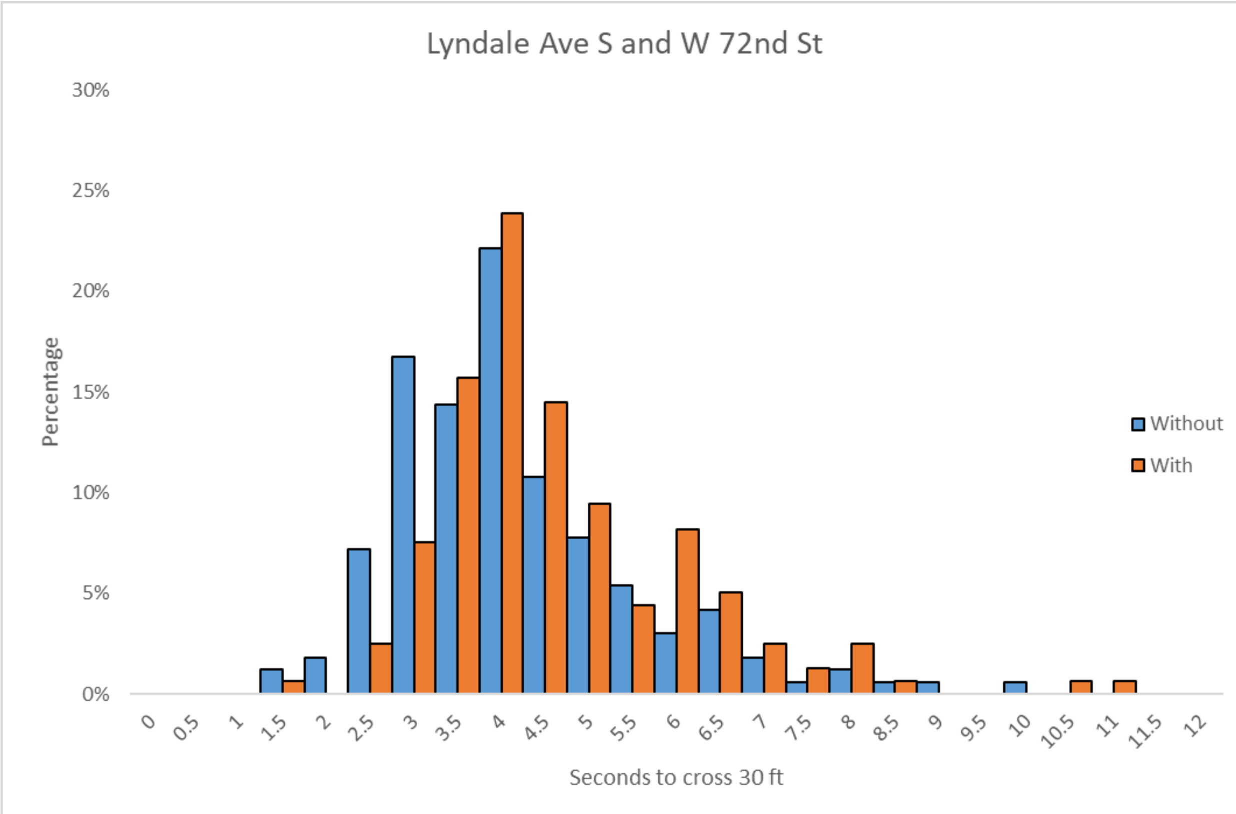

Figure 3.23 Lyndale Ave S and W 72nd St Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.3 S051O – Como Ave and Knapp St

The intersection of Como Ave and Knapp St is located in St. Paul, next to St. Anthony Park Elementary School. This site was selected due to its unique angle of approach, limited sight distance, and bike lanes running on both sides of the major road. The ADTs of both the major and minor roads are unknown, but appear to be low based on project counts. The minor road, Knapp St, has a slight upward grade as it approaches Como Ave.

An aerial view of the site is provided in Figure 3.24. A camera view with overlay lines marked is shown in Figure 3.25. During the summer months, sight distance to the left is obscured by foliage, and sight distance to the right is limited due to the upward grade on Como Ave, as seen in Figure 3.26.

Figure 3.24 Aerial view of the intersection of Como Ave and Knapp St with measurements marked

Measurements noted on Aerial view of the intersection of Como Ave and Knapp St with measurements marked are listed in Table 3.13.

Table 3.13 Relevant measurements at Como Ave in feet

From CL_maj to...	SL	SS	RP&C1_maj	BL1_maj	BL2_maj	FL2_maj	C2_maj
	36.50	36.08	18.00	11.50	11.58	17.83	26.75
From CL_min to...	**C1_min**	**C2_min**					
	14.84	14.84					

Figure 3.25 Camera view of the intersection of Como Ave and Knapp St with 5-ft overlay lines marked

Figure 3.26 Available sight distance and required sight distance at Como Ave and Knapp St

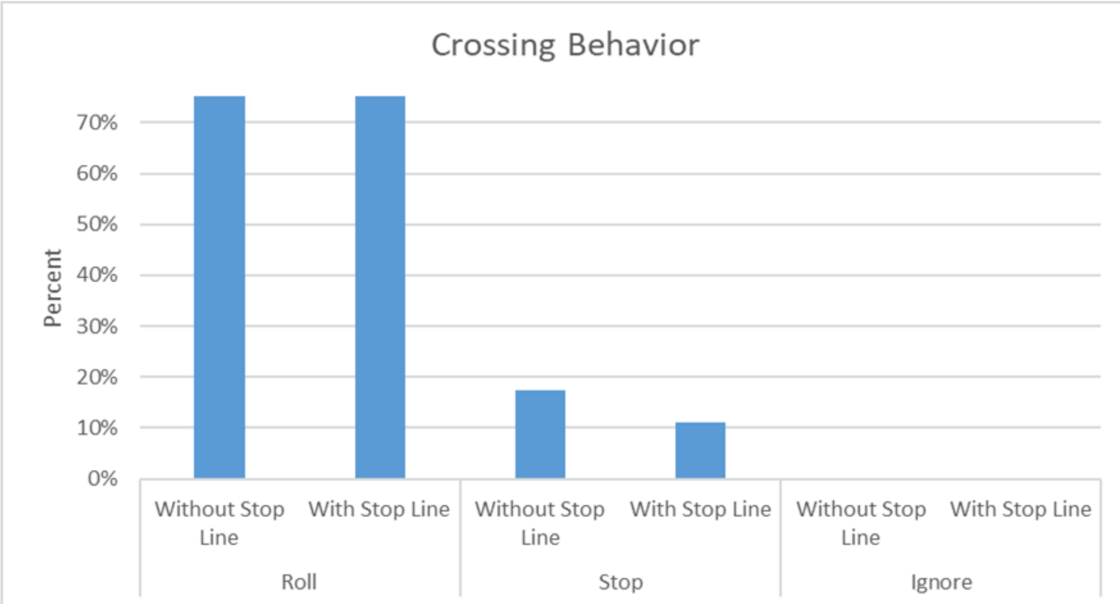

Figure 3.27 EB Knapp St distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

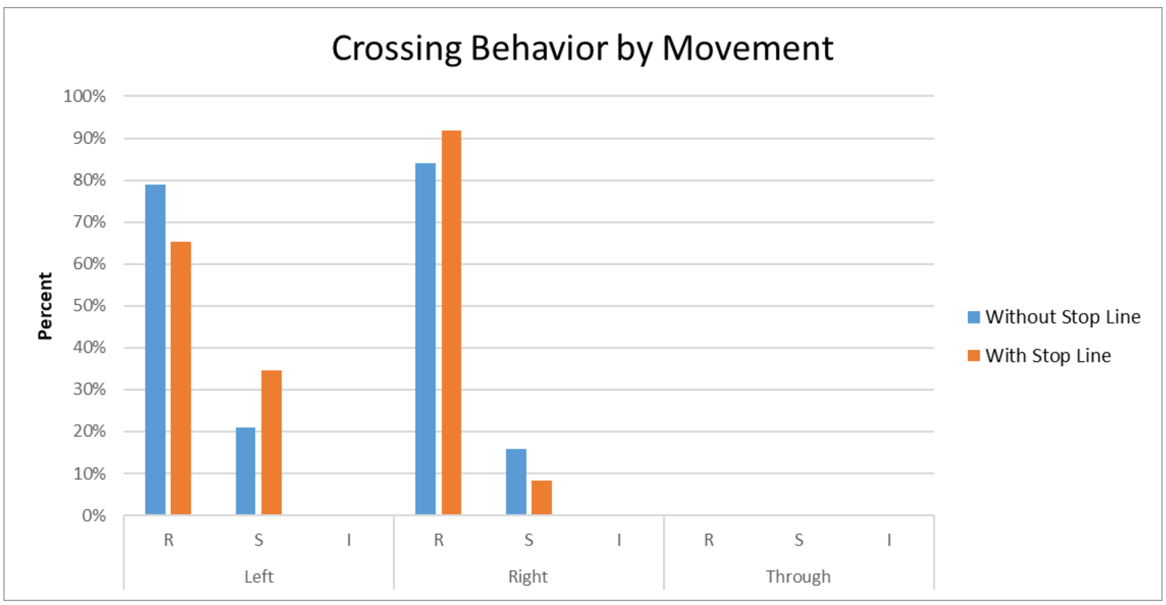

Figure 3.28 EB Knapp St distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

This site had a large number of rolls both without and with the stop line in place, as seen in Figure 3.27. However, no ignores were reported, which the research team found suspicious, and examined further by gathering the arrival and departure frames during roll events to see if there were distinct peaks representing a “roll” event versus an “ignore” event, thus testing the possibility that the UGRA that watched this site could not easily differentiate due to the angle of the camera view or other circumstances. This histogram is presented in Figure 3.30 and results will be discussed below.

A change in ratio of roll and stop events during both left and right turns was observed, as seen in Figure 3.28. The change in behavior, closely matches the changes we observed in the previous site of W72nd St and Lyndale Ave. In a similar way, the right turning movements had an increase in rolls, this time by reducing the stopping fraction. In the same way, the left turning movements, improved by increasing the number of vehicles that stopped, by more than 10%, and reduced the rolls accordingly.

As seen in Figure 3.29, without the stop line, most drivers stopped at the curb line or even more toward the centerline, with their front tires into the bike lane. After the placement of the stop line, the distribution of stop locations flattened, and drivers appear to be stopping farther behind the curb line. It is important to highlight here that, given that the vast majority of the rolls over the stops, this graph is based only on an approximately 15% of the observations, predominantly left turning movements. This differs from the earlier site, where the ratio between rolls and stops was closer to 1.

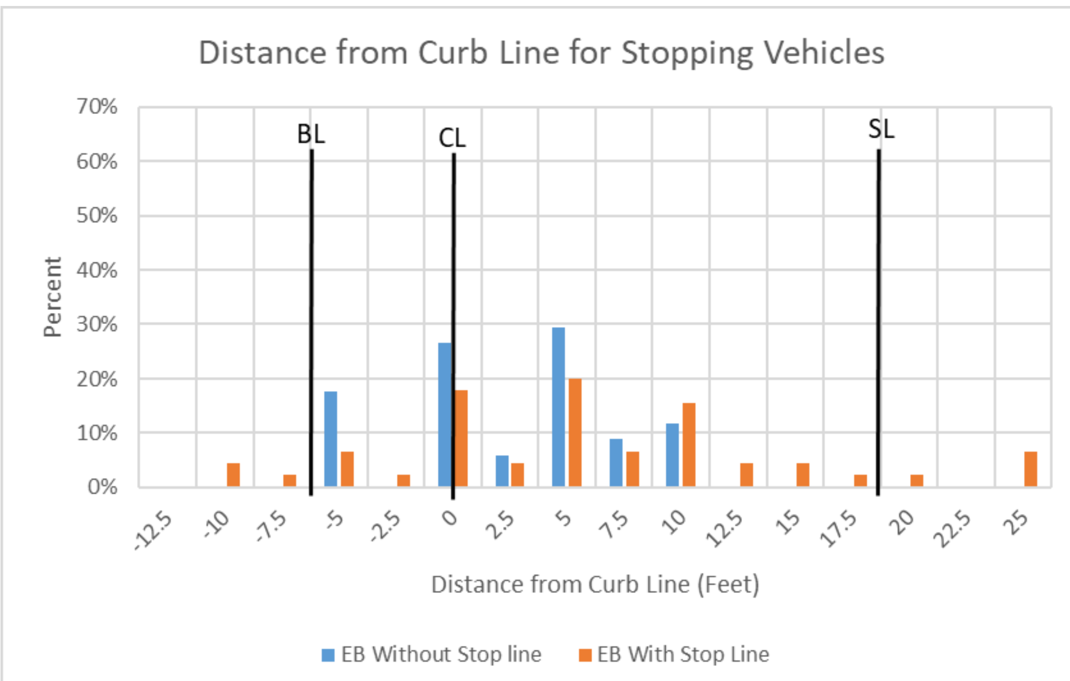

Figure 3.29 Como Ave and Knapp St Distribution of Stopping Distance During Stop Events

At Como Ave, the stop line did not appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.30, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop line at the same speed they were prior to painting. There is some small reduction in the very fast speeds (smallest travel times) indicating a shift between possible ignores and rolls. Finally, from this graph a bias by the UGRA reducing this site becomes apparent; a distribution between two and six seconds to travel 30 feet indicates both rolls and ignores were coded as rolls. Times less than three seconds (true ignores) are much less common than they are at Lyndale Ave.

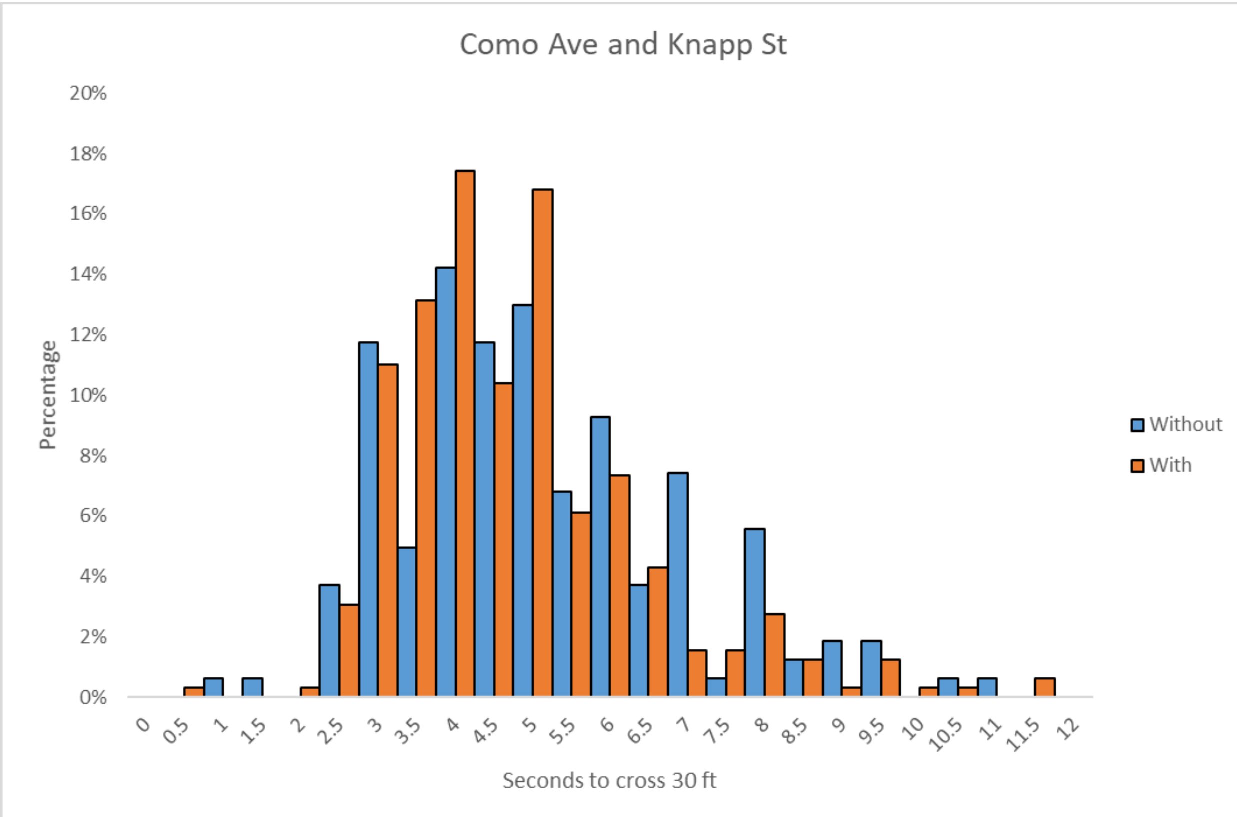

Figure 3.30 Como Ave and Knapp St Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.4 S087O – Woodhill Dr and Civic Center Dr

The intersection of Woodhill Rd and Civic Center Dr is a T-intersection located in Roseville with an entrance to a parking lot opposite the minor road. NB Civic Center Dr did not have a stop line or crosswalk prior to this project. The site was selected because of its wide shoulders and adequate sight distances. Woodhill Rd has wide shoulders on both sides of the roadway and has an AADT of 1,250 vehicles. Civic Center Dr has an estimated ADT of around 500 vehicles based on project counts. The available sight distance to both the left and right was deemed adequate by the research team (Figure 3.33) and the site has wide shoulders. An aerial view of the site is shown in Figure 3.31.

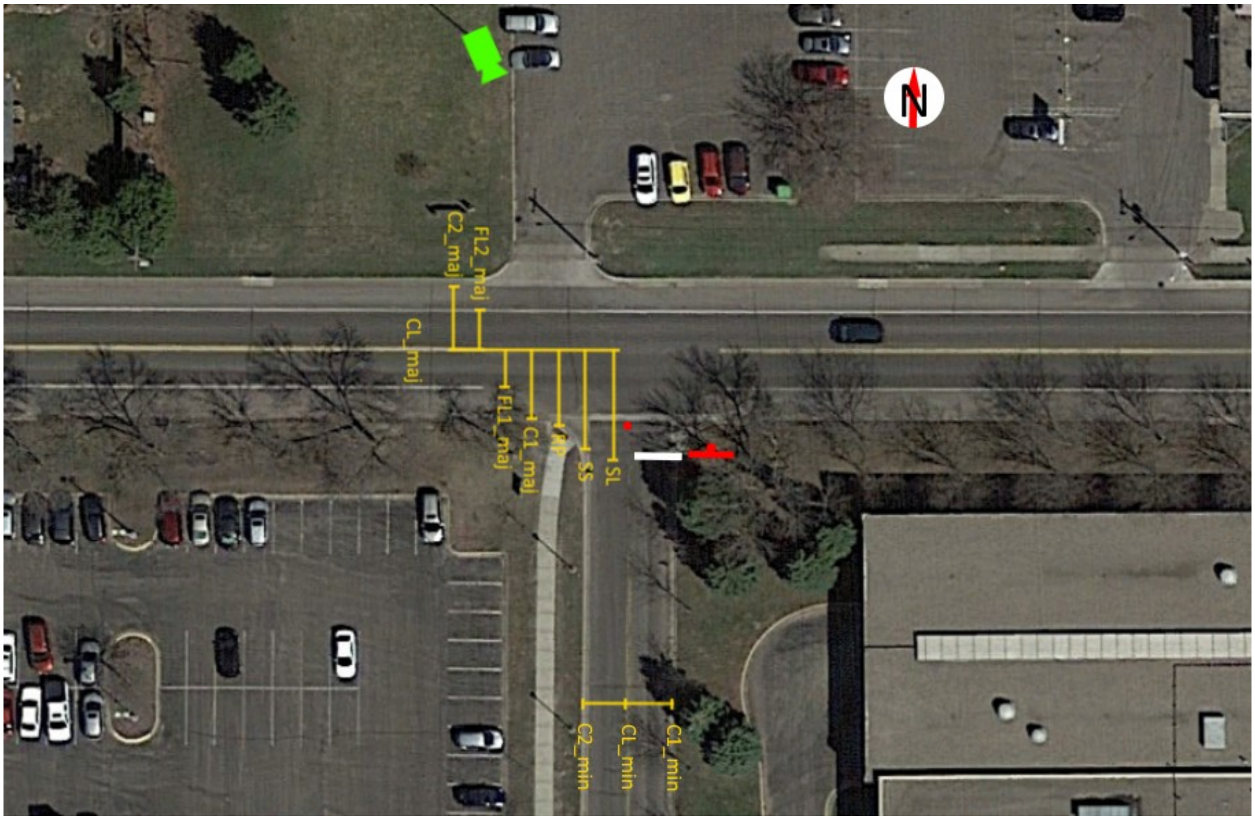

Figure 3.31 Aerial view of the intersection of Woodhill Dr and Civic Center Dr with measurements marked

Measurements noted on Figure 3.31 are listed in Table 3.14.

Table 3.14 Relevant measurements at Woodhill Rd in feet

From CL_maj to...	SL	SS	RP	C1_maj	FL1_maj	FL2_maj	C2_maj
	36.75	33.75	22.75	21.58	12.75	12.75	21.58
From CL_min to...	**C1_min**	**C2_min**					
	13.92	13.92					

A camera view with overlay lines marked is shown in Figure 3.32.

Figure 3.32 Camera view of the intersection of Woodhill Dr and Civic Center Dr with 5-ft overlay lines marked

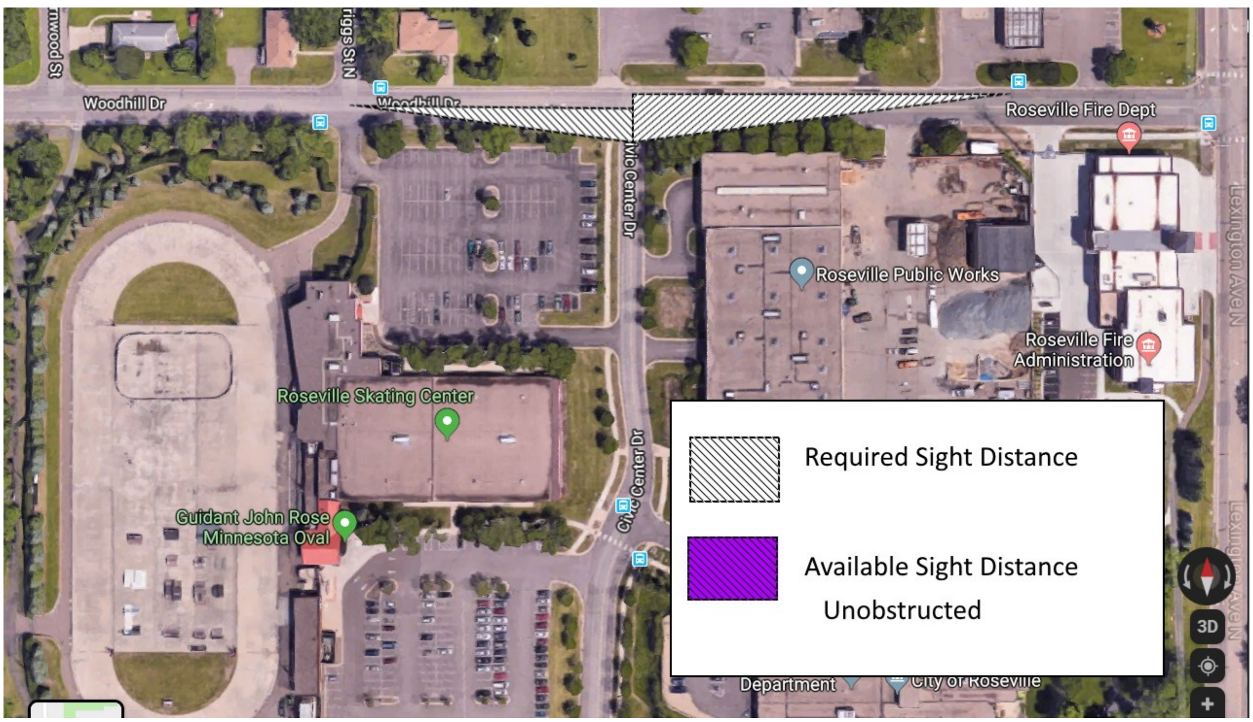

Figure 3.33 Available sight distance and required sight distance at Woodhill Dr and Civic Center Dr

As seen in Figure 3.34, NB Civic Center Dr experienced practically no change in the driver's crossing behavior with the addition of the stop line. The portion of drivers ignoring the stop sign at this site is high given the geometry of the site and it appears that, at least in general, the stop line has no observable effect on the driver crossing behavior at this location.

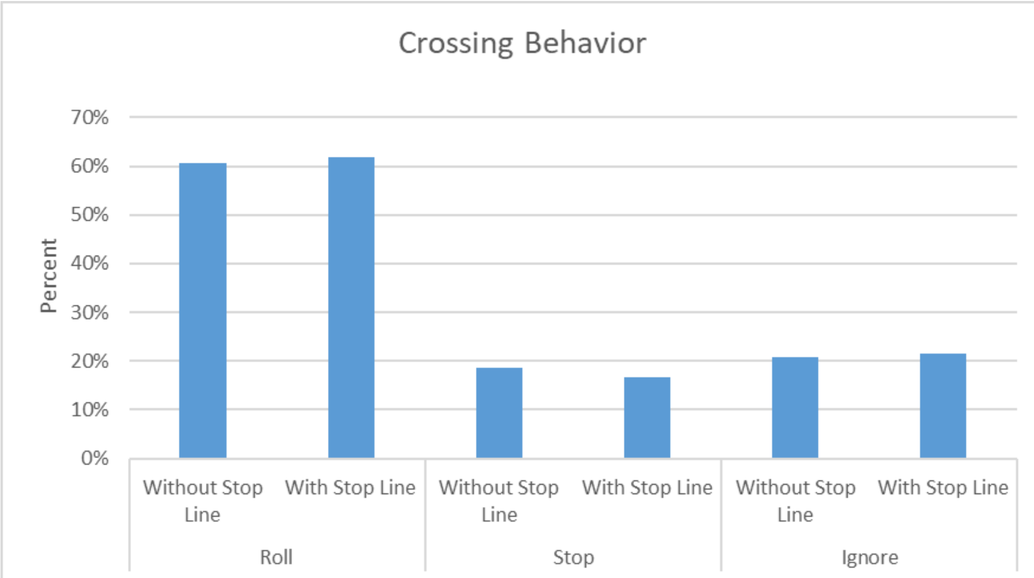

Figure 3.34 Civic Center Dr distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

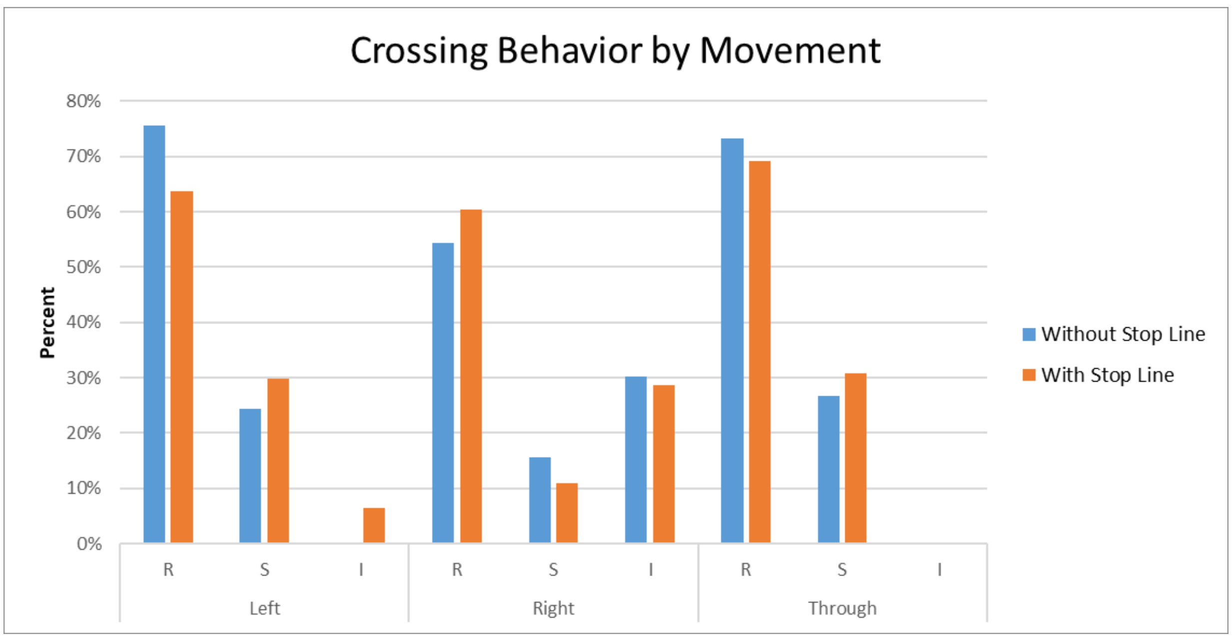

Figure 3.35 Civic Center Dr distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

The ratios of driver behavior during turning or through movements were not very affected by placement of the stop line, as seen in Figure 3.35.

As seen in Figure 3.36, most drivers stop between the stop line and the curb line. One hypothesis is that this level of encroachment is due to the sight distance available. Vehicles that stopped appear to be influenced by the stop line; roughly 10% of stopped vehicles stopped a little farther upstream from the major centerline.

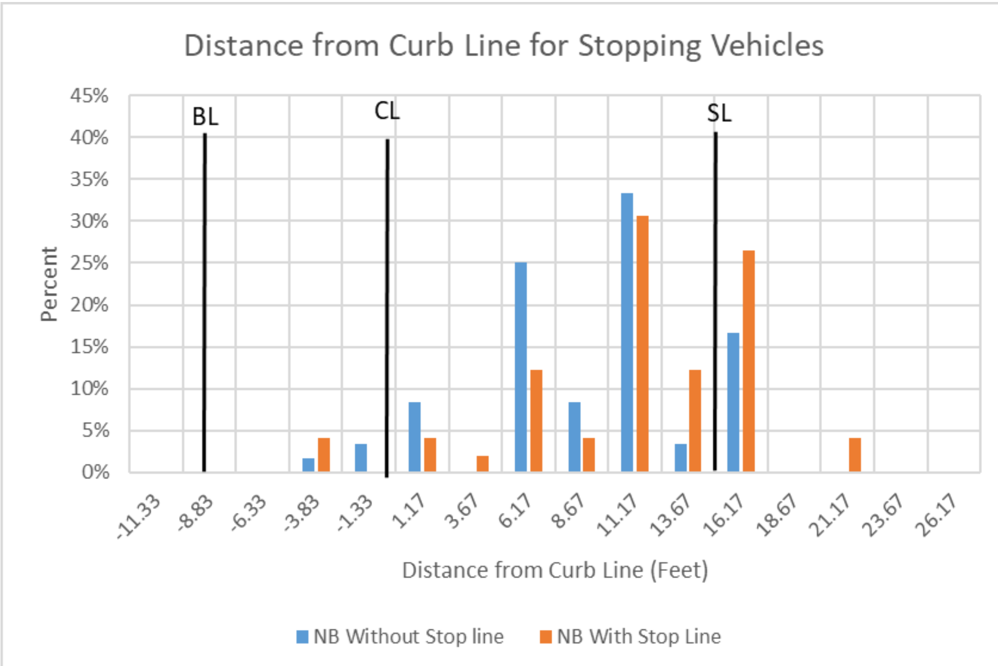

Figure 3.36 Woodhill Dr and Civic Center Dr Distribution of Stopping Distance During Stop Events

At Woodhill Dr, the stop line had a small effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.37, the average time to travel 30 feet increased by about 1 second after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down a little more as they pass through the intersection. This is a very small change to be significant.

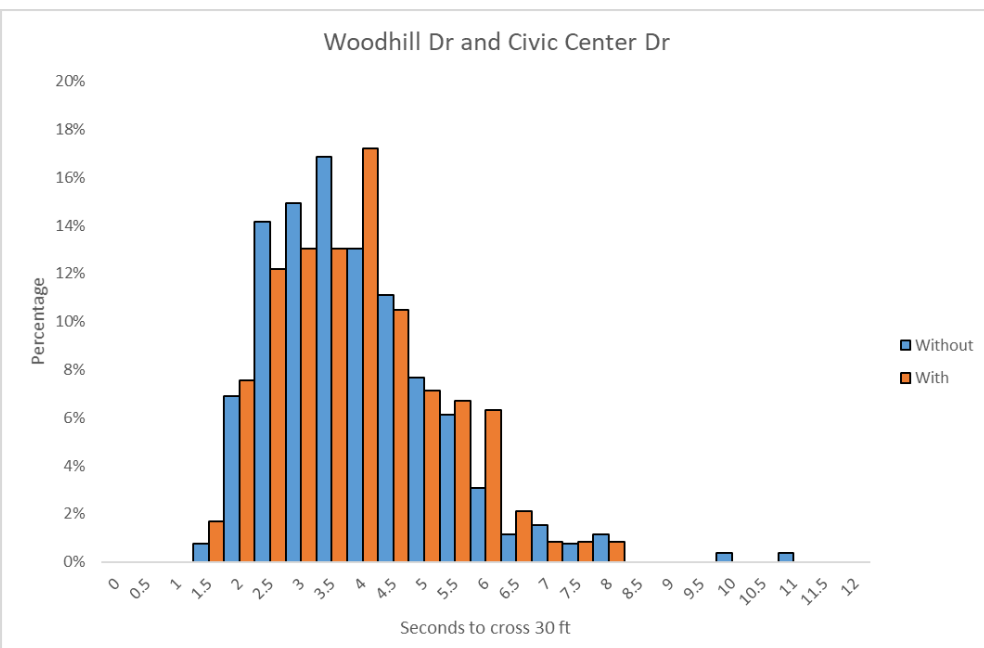

Figure 3.37 Woodhill Dr and Civic Center Dr Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.5 S089A – Dale St N and Iona Ln

The intersection of Dale St North and Iona Lane is located in Roseville. Although the intersection is four-way, only the eastern approach was studied as the western approach is a short residential stretch with expected low traffic. The intersection did not have crosswalks or stop lines prior to the project. The site was selected because of standard four-way geometry and inadequate sight distances from the stop sign. The major road has an AADT of 2250, and the minor road has an AADT of over 500 vehicles. The sight distance to both the left and the right was deemed inadequate by the research team and is shown in Figure 3.40. An aerial view of the site is shown in Figure 3.38.

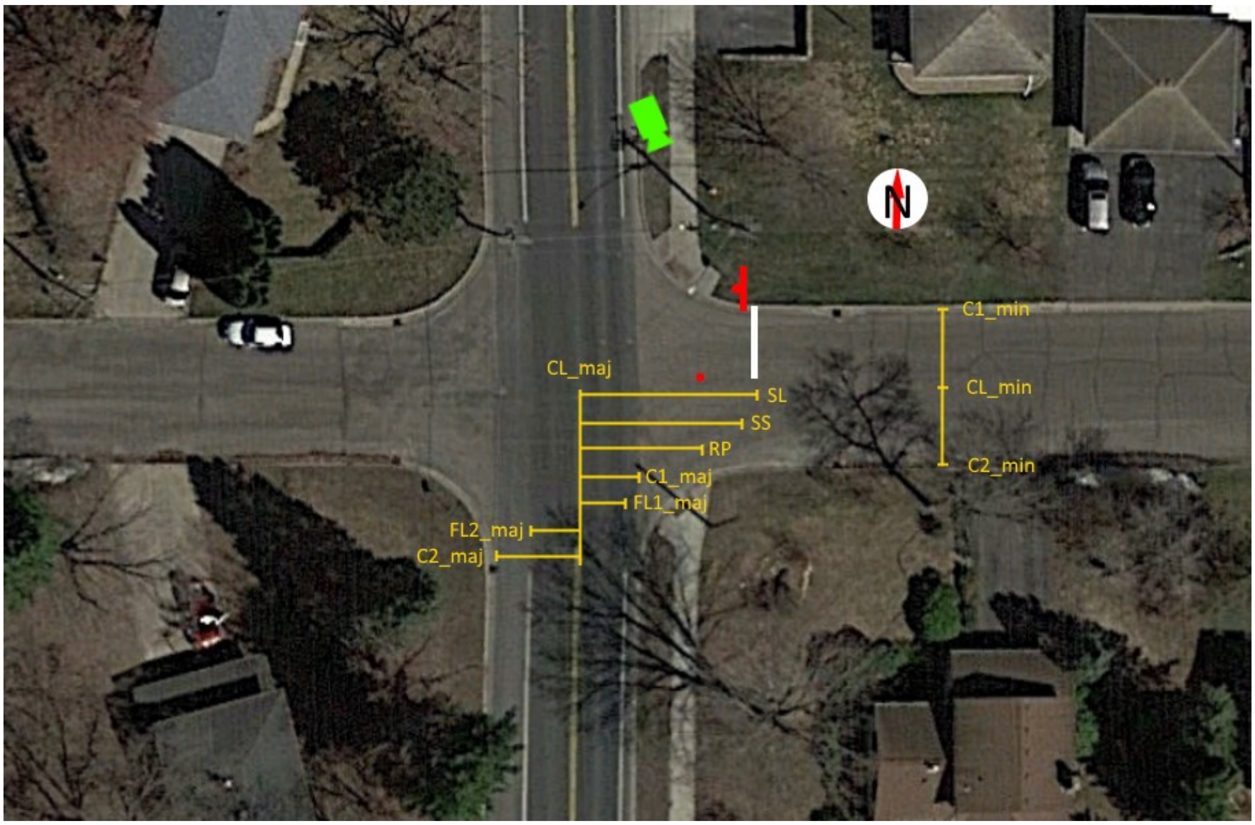

Figure 3.38 Aerial view of the intersection of Dale St N and Iona Ln with measurements marked

Measurements noted on Figure 3.38 are listed in Table 3.15.

Table 3.15 Relevant measurements at Dale St in feet

From CL_maj to...	SL	SS	RP	C1_maj	FL1_maj	FL2_maj	C2_maj
	37.83	36.83	28.50	17.25	12.92	9.08	18.08
From CL_min to...	**C1_min**	**C2_min**					
	17.92	17.92					

A camera view with overlay lines marked is shown in Figure 3.39.

Figure 3.39 Camera view of the intersection of Dale St N and Iona Ln with 5-ft overlay lines marked

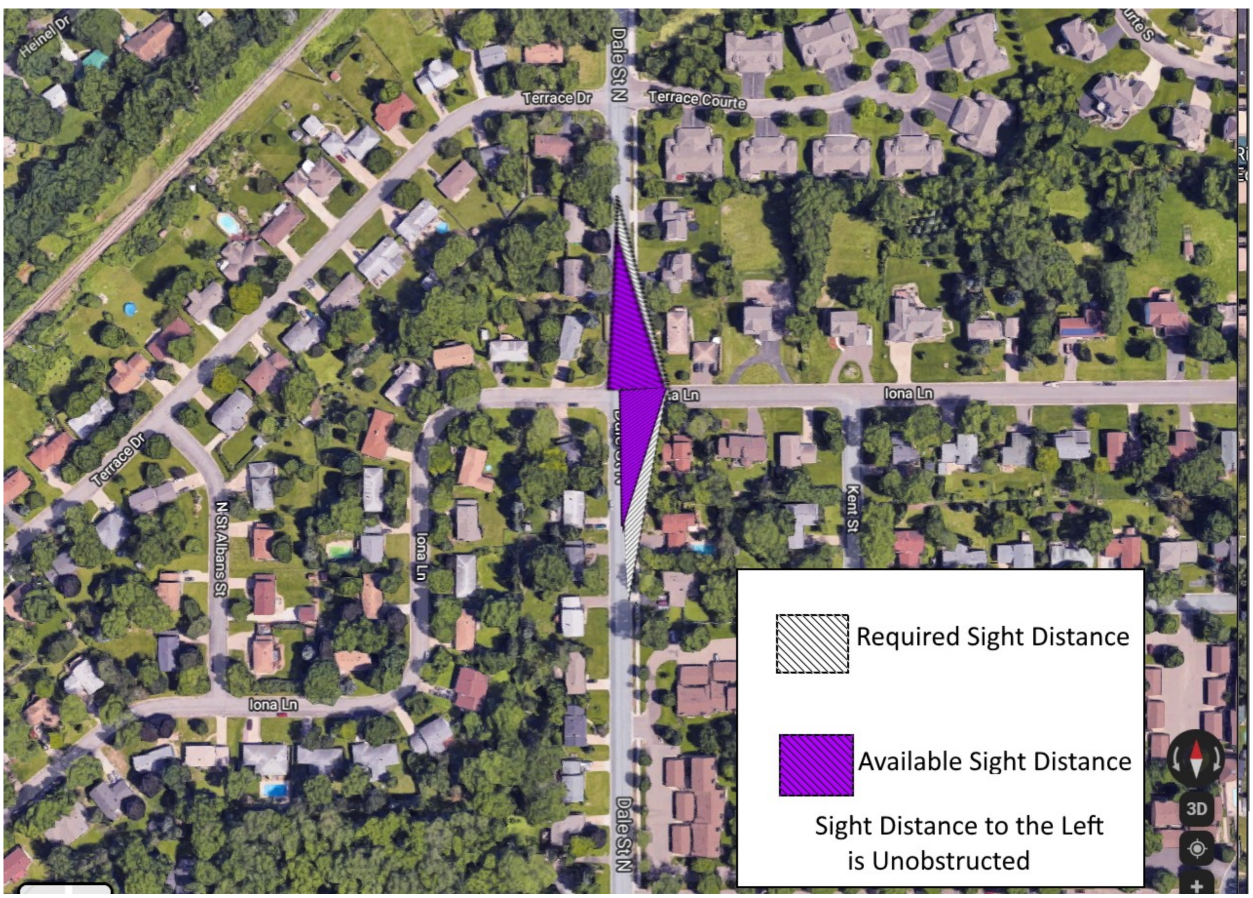

Figure 3.40 Available sight distance and required sight distance at Dale St N and Iona Ln

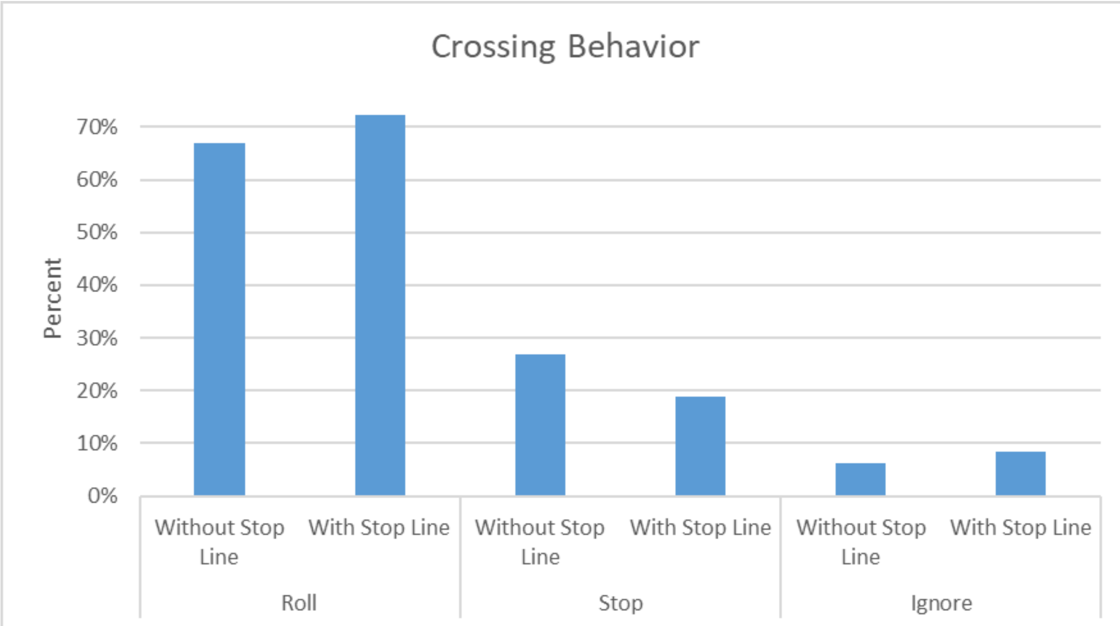

Figure 3.41 Iona Ln distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

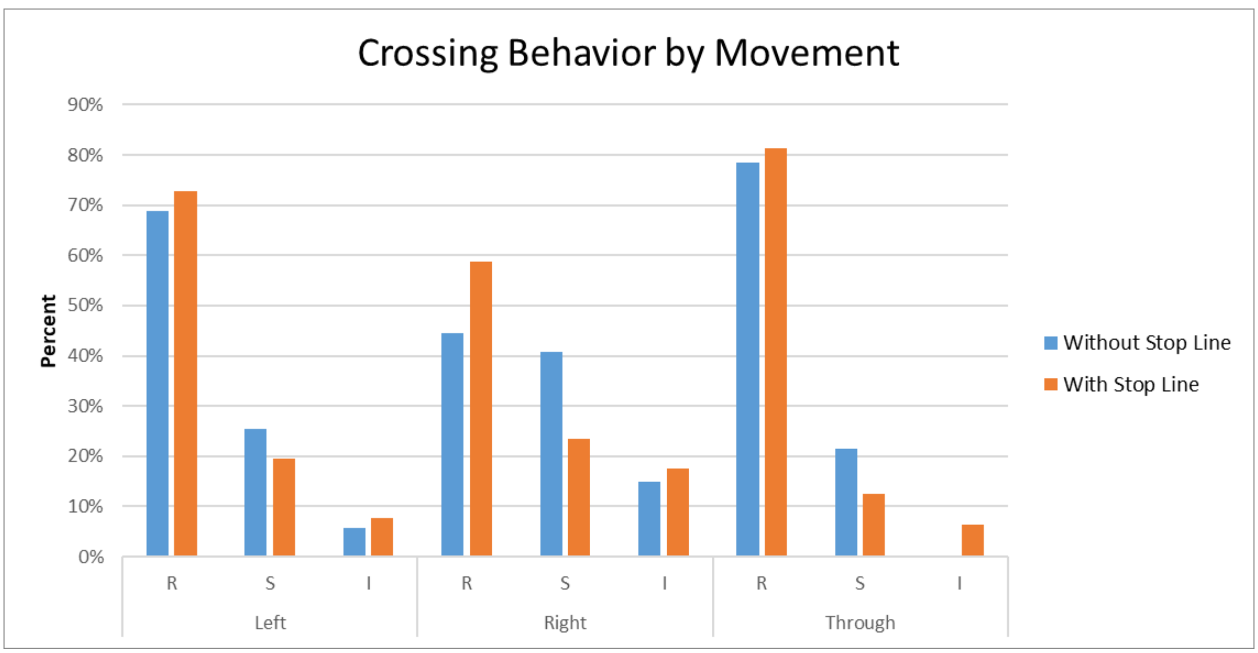

Figure 3.42 Iona Ln distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

The Dale St N intersection overall, experienced small increases in roll and ignore events, and a decrease in stop events, shown in Figure 3.41. Ignore events are at normal levels for a site of this type. In the more detailed Figure 3.42, we see that, specifically for the right turning movement, there was an approximate 12% shift towards rolls along with a 17% reduction in stops. This is a consistent observation with all the previous sites, suggesting that the stop line encourages drivers to not stop when they are turning right. That said, from Figure 3.44 we see that, although less drivers stop when the stop line is present, they are also slow down considerably more during the roll. One hypothesis explaining this is, that the drivers, aided by the more prominent visual queue of the stop line, are paying closer attention to the left side view and turn without stopping. Naturally, it is very difficult to support such hypothesis without observing the drivers themselves.

The sight distance is challenging at this site (Figure 3.40); the distribution of stops between the curb and the stop line is shifted entirely downstream of the stop line. The stop line appears to have resulted in a pushback of a few feet in stop location, shown in Figure 3.43. Given the sight distance limitations particularly over the hill to the left and busy environment, there is a small effect of vehicles leaving greater distance to the edge of the road when stopping, but no ultimate difference in stopping behavior (as it pertains to violating the stop line).

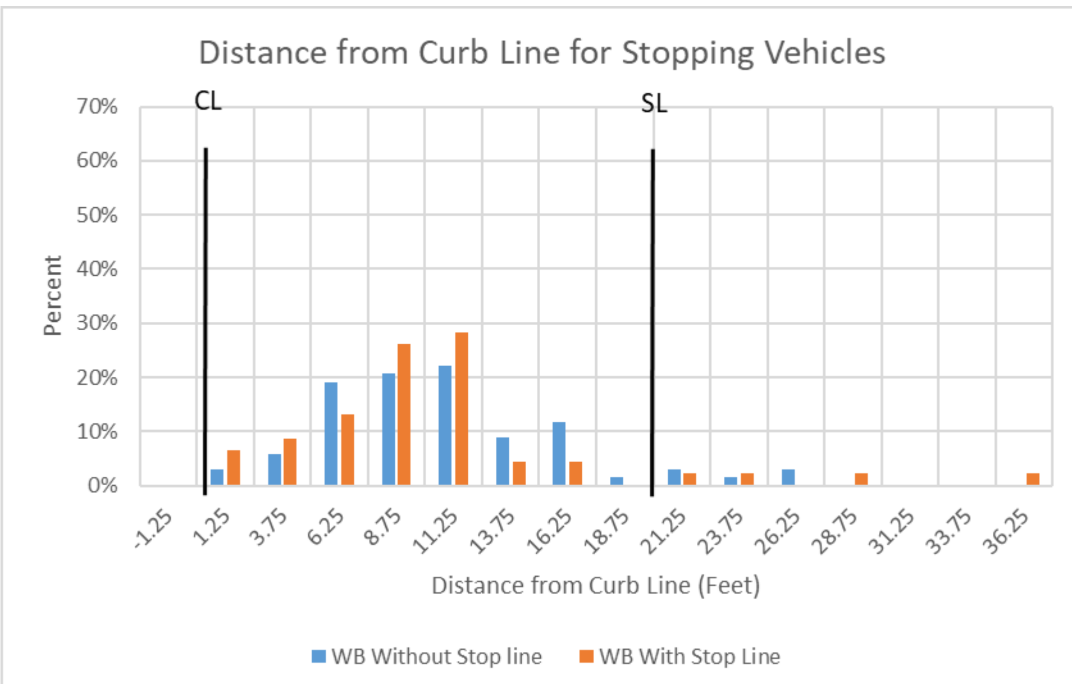

Figure 3.43 Dale St N and Iona Ln Distribution of Stopping Distance During Stop Events

At this site, no one is pushing past the curb line to the fog line, where the point of collision would be. They are moving forward enough to gain a clear line of sight. The stop line (and stop sign) are not appropriately placed to allow actual line of sight of the oncoming traffic. Drivers are not going farther than necessary to gain a good line of sight. As discussed, earlier Figure 3.44 shows evidence that drivers took at least 1.5 seconds longer to perform the roll. This suggests that the stop line had an effect, although maybe not the desired one.

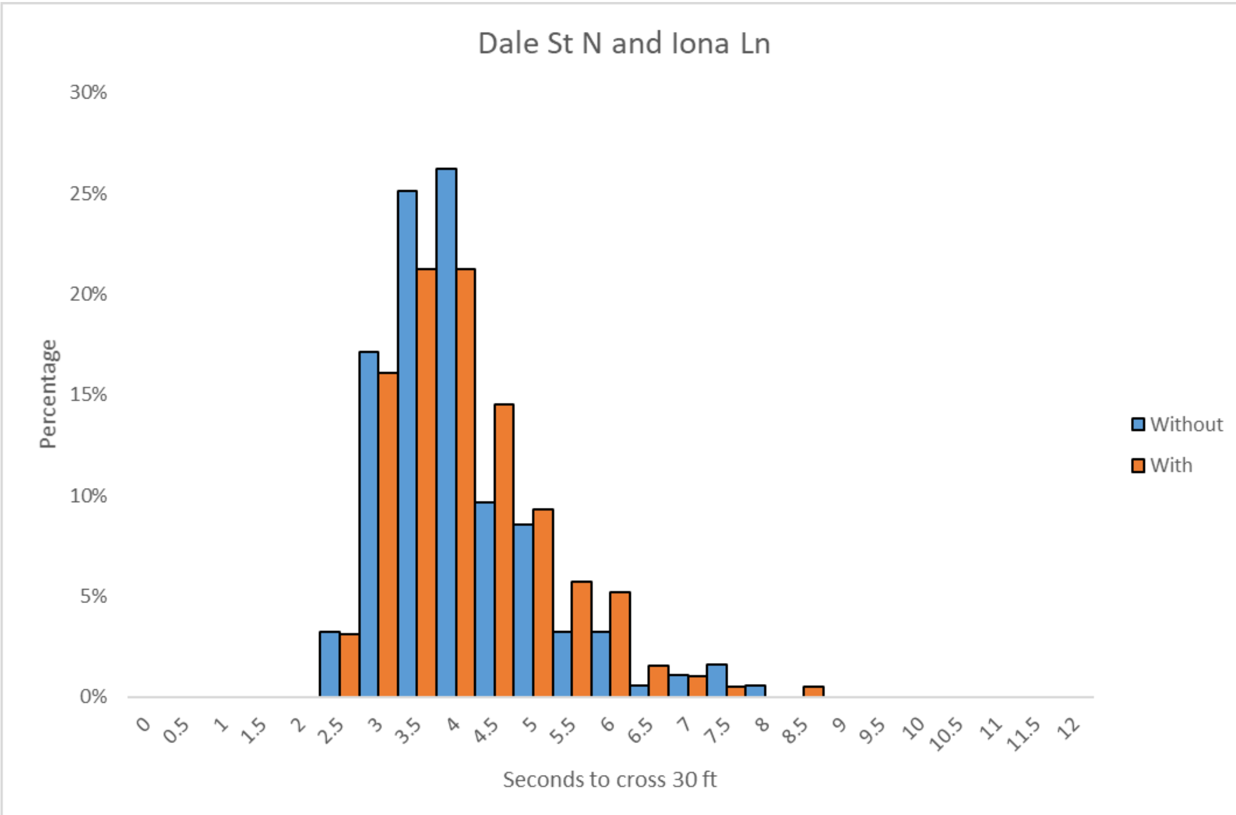

Figure 3.44 Dale St N and Iona Ln Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.6 S094A – Lincoln Dr and Lydia Ave W

Lincoln Dr and Lydia Ave W is located near University of Northwestern, in Roseville. This site was chosen due to its crosswalks, and the unique geometry of the two-lane approach to the stop line. The sight distance to the left and the right was deemed inadequate by the research team due to obstructions on both the left and right side of the approaches (Figure 3.47). The ADT of both the major and minor roads are unknown but are estimated to be low based on project counts. This site experiences more pedestrians than others in the observational study but examining pedestrian-only events did not differ from mixed pedestrian and non-pedestrian events, so non-pedestrian-only results are omitted.

An aerial view of the site is presented in Figure 3.45. Notice the skewed line when the two different pavements meet after the crosswalk. It has been clear in this study that drivers are greatly influenced by this type of visual cue and, in this case, the numbers highlight it.

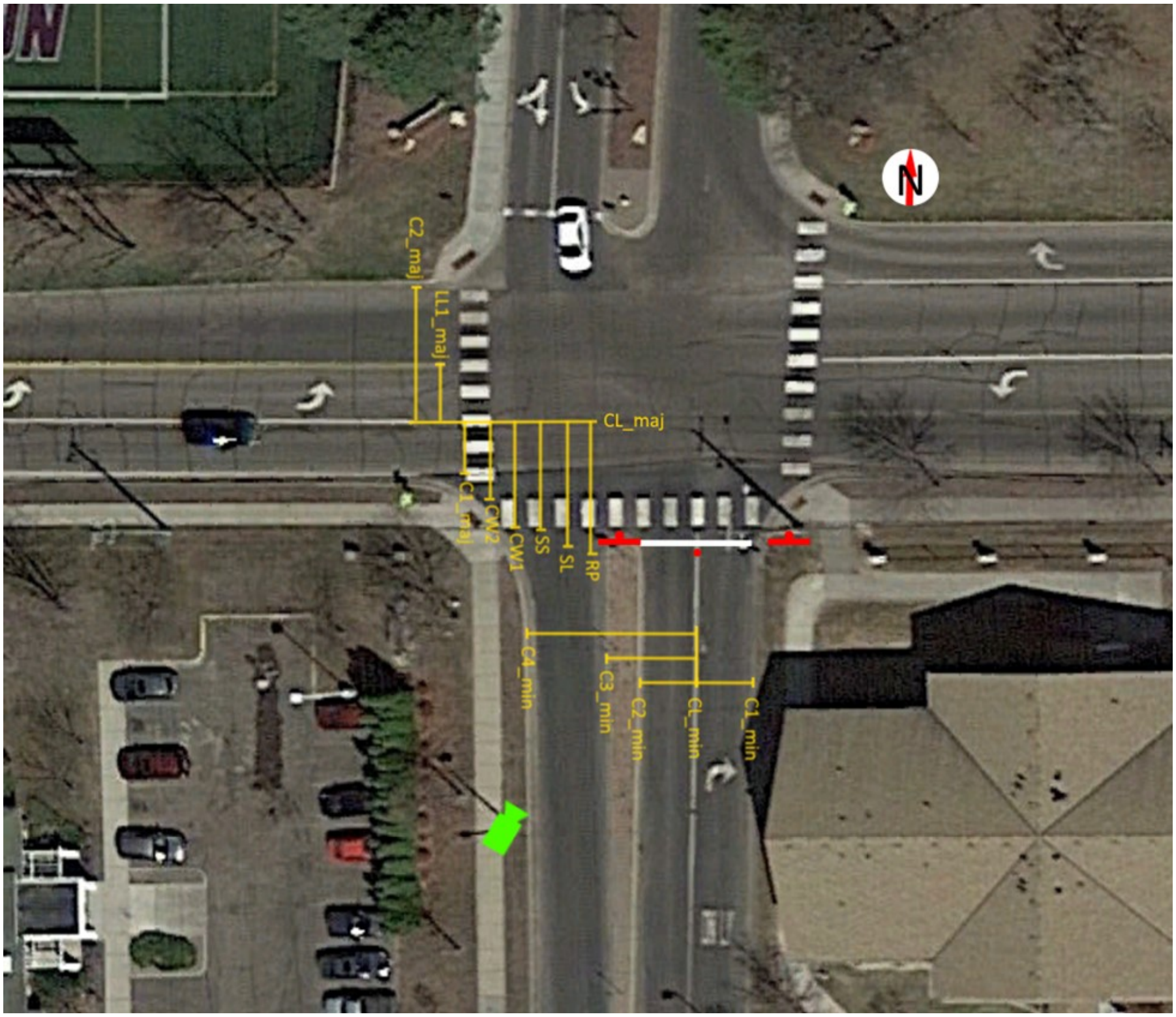

Figure 3.45 Aerial view of the intersection of Lincoln Dr and Lydia Ave W with measurements marked

Measurements noted on Figure 3.45 are listed in Table 3.16.

Table 3.16 Relevant measurements at Lincoln Dr in feet

From CL_maj to...	RP	SL	SS	CW1	CW2	C1_maj	
	35.00	34.00	32.50	29.75	23.75	14.00	
From CL_maj to...	**LL1_maj**	**C2_maj**					
	12.50	18.00					
From CL_min to...	**C1_min**	**C2_min**	**C3_min**	**C4_min**			
	14.00	11.84	19.84	37.09			

A camera view of the site with overlay lines marked is presented in Figure 3.46.

Figure 3.46 Camera view of the intersection of Lincoln Dr and Lydia Ave W with 5-ft overlay lines marked

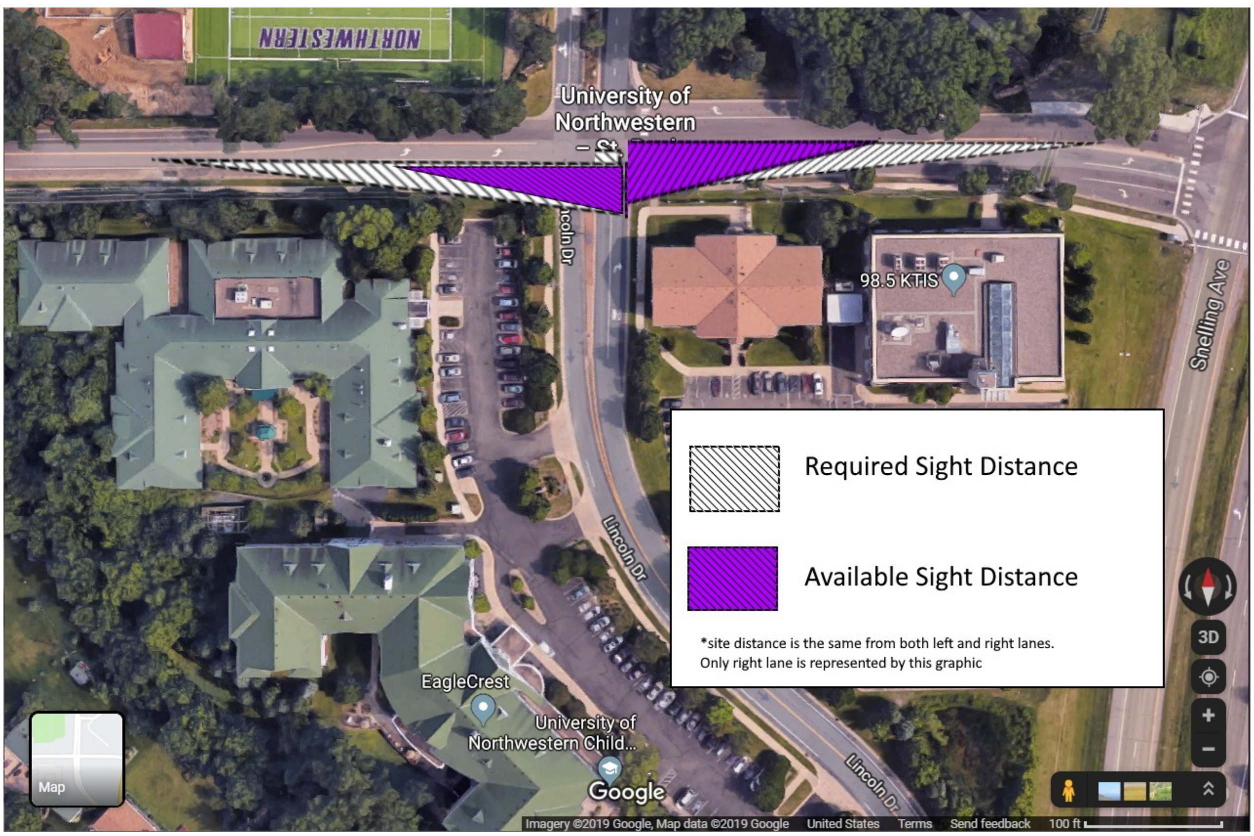

Figure 3.47 Available sight distance and required sight distance at Lincoln Dr and Lydia Ave W, for both left and right lane

As this site has two distinct approaches allowing for different driver movements (albeit with similar bad sight distance at each approach), the results for this site are broken down by left lane (3.4.6.1) and right lane (3.4.6.2).

3.4.6.1 Lincoln Dr Left Lane

At Lincoln Dr's left lane, there was a change of greater than 10% in both roll and stop events after placement of the stop line, as seen in Figure 3.48. Drivers decreased their roll behavior and increased their stopping behavior. Ignores were lower than anticipated, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.51 and discussed below.

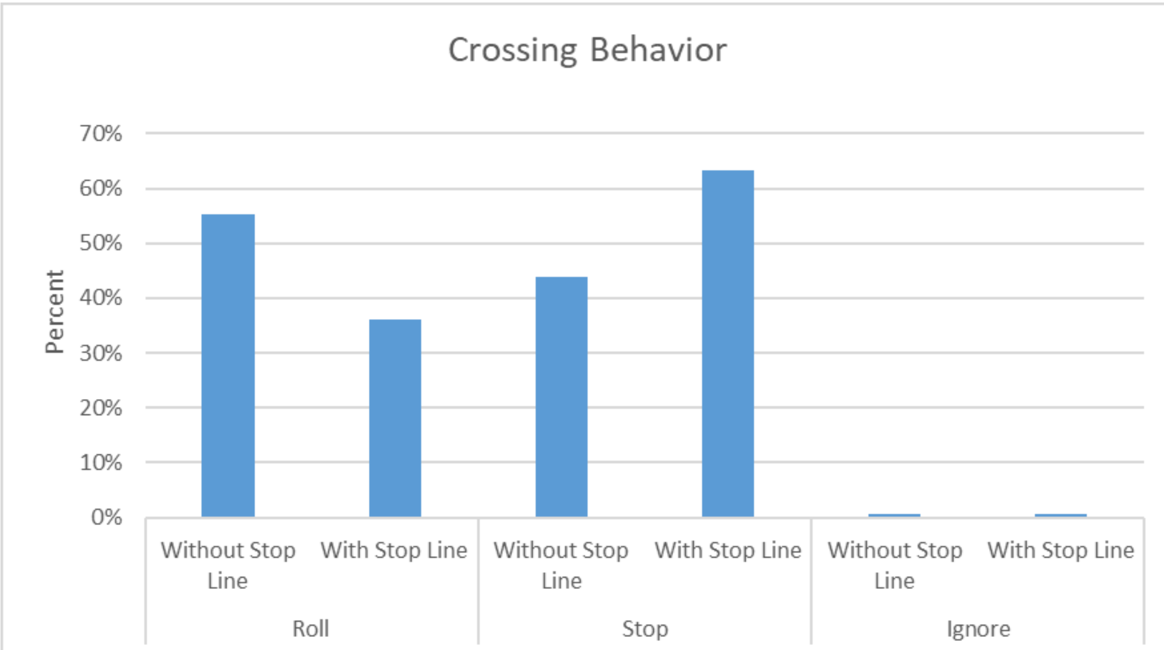

Figure 3.48 Lincoln Dr Left Lane distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

Turning movement behavior is presented in Figure 3.49 but given the separation by lane it only covers left turns and through movements. There is an observably large shift towards stops, especially on the through movements but also one of the largest observed on the left turns also. This is consistent with the observations on other sites, where we see left turns being influenced towards stopping. Note the left-hand sight distance is especially challenging on this location.

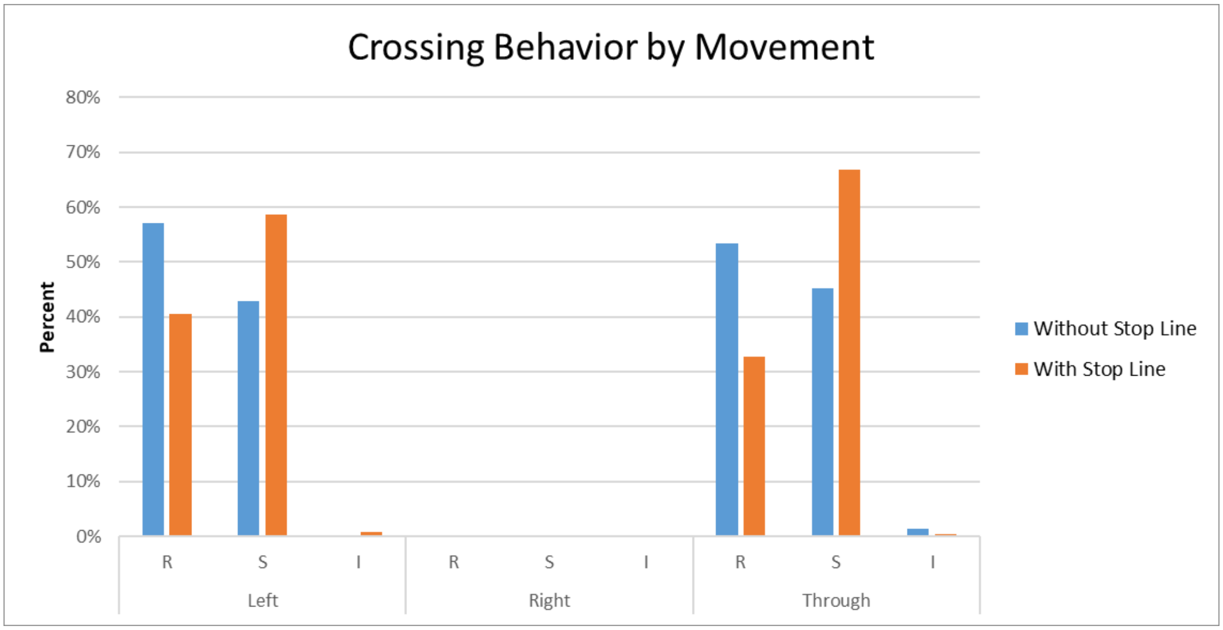

Figure 3.49 Lincoln Dr Left Lane distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

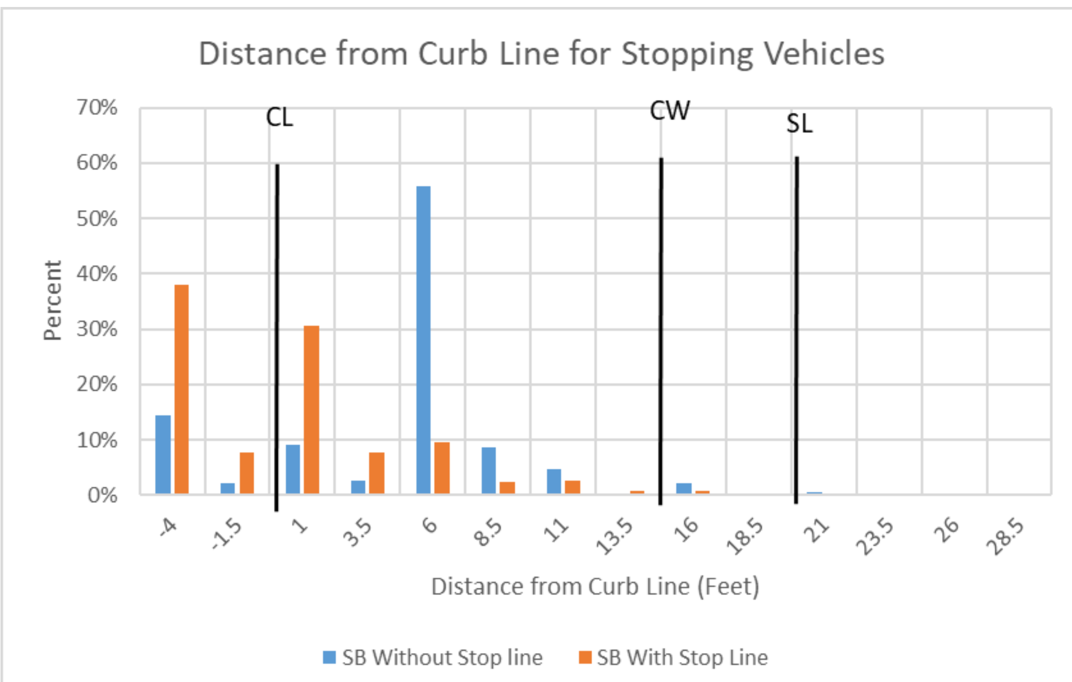

Figure 3.50 Lincoln Dr Left Lane and Lydia Ave W Distribution of Stopping Distance During Stop Events

Although the aforementioned results regarding crossing behavior are encouraging, when, from Figure 3.50 observe the distribution of driver's stop location during stop events, we see that both without and with the stop line, drivers are stopping between the back of crosswalk and curb line as well as spilling over the curb line closer to the center line. Prior to the stop line's placement, most drivers were stopping six feet upstream of the curb line. After the stop line's placement, that shifted by five to ten feet forward, with roughly 30% of drivers stopping just short of the curb line and 38% stopping four feet after the curb line, closer to the center line of the roadway. The latter is an artifact of created by the way the research team measured distances. As can be seen in the aerial photo of this site, the reference point was on the left side of the minor road. The measurement on the above graph assume a perpendicular line curb to curb while the pavement seam, as mentioned earlier, is skewed. This generates an additional 3 to 4 feet of implied space in front of the approach lanes. This is not a space designed for drivers to use, but it is implied by the change in pavement color and conditions.

The forward shift in vehicles' stop location can be explained the same way as discussed on the earlier site of 72nd and Lyndale. The stop line, in addition to the crosswalk, provides for better orientation allowing drivers to more boldly infringe forward in search of a better sight distance. In addition, given that this is the first of the two sites observed that have a crosswalk, we cannot ignore the fact that regardless of the presence of the stop line, drivers are stopping the closest to the curb line. The presence of a bike lane is the only other characteristic so far that shows similar influence but in that case the infringement is a much safer (for vehicles) affair.

At Lincoln Dr's left lane, the stop line did appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.51, the average time to travel 30 feet increased by more than 1 second after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down more as they pass through the intersection.

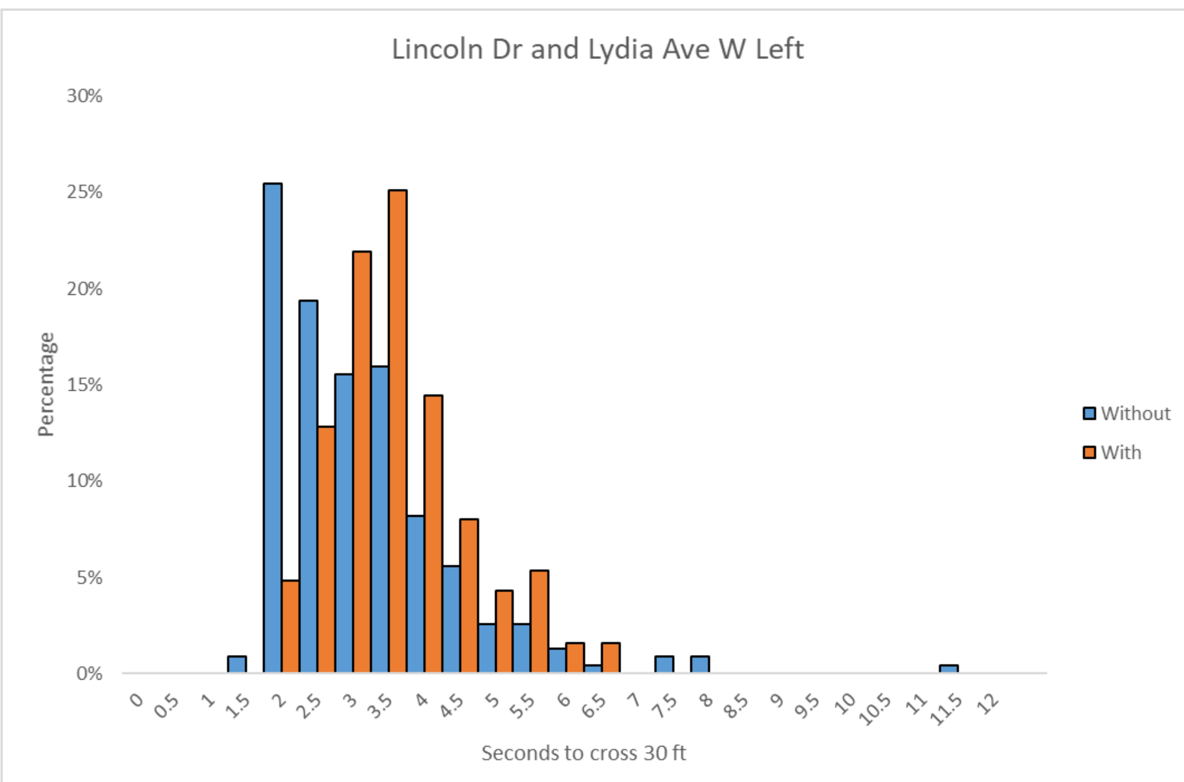

Figure 3.51 Lincoln Dr Left Lane Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.6.2 Lincoln Dr. Right lane

At Lincoln Dr's right lane, the absolute percentage of drivers that rolled decreased by 30% and stops increased by 25%; ignores were low, within expected tolerances. This is shown in Figure 3.52. Of all events recorded at this site, about 6% of vehicles illegally used this lane to go straight; these events are excluded from analysis.

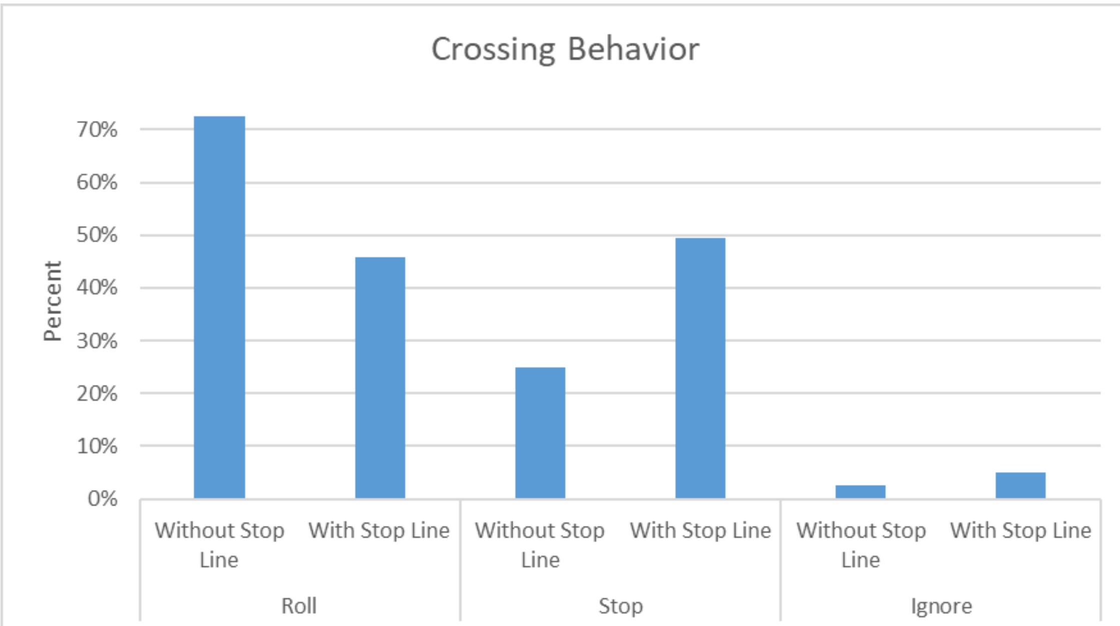

Figure 3.52 Lincoln Dr Right Lane distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

No detailed breakdown of driver movement is necessary at this site as right turns are the only driver movement permitted.

Figure 3.53 presents the distribution of driver's stop location during stop events, which indicates that both without and with the stop line, right turning drivers are stopping between the crosswalk and curb line as well as spilling over the curb line closer to the center line. Prior to the stop line's placement, most drivers were stopping six feet upstream of the curb line. After the stop line's placement, that shifted between five and ten feet forward, with roughly 25% of drivers stopping just short of the curb line and 30% stopping four feet after the perpendicular curb line, closer to the center line of the roadway. This is the same behavior as in the left lane, showing an influence from the crosswalk. Further discussion on this trend is presented in the conclusion of this report.

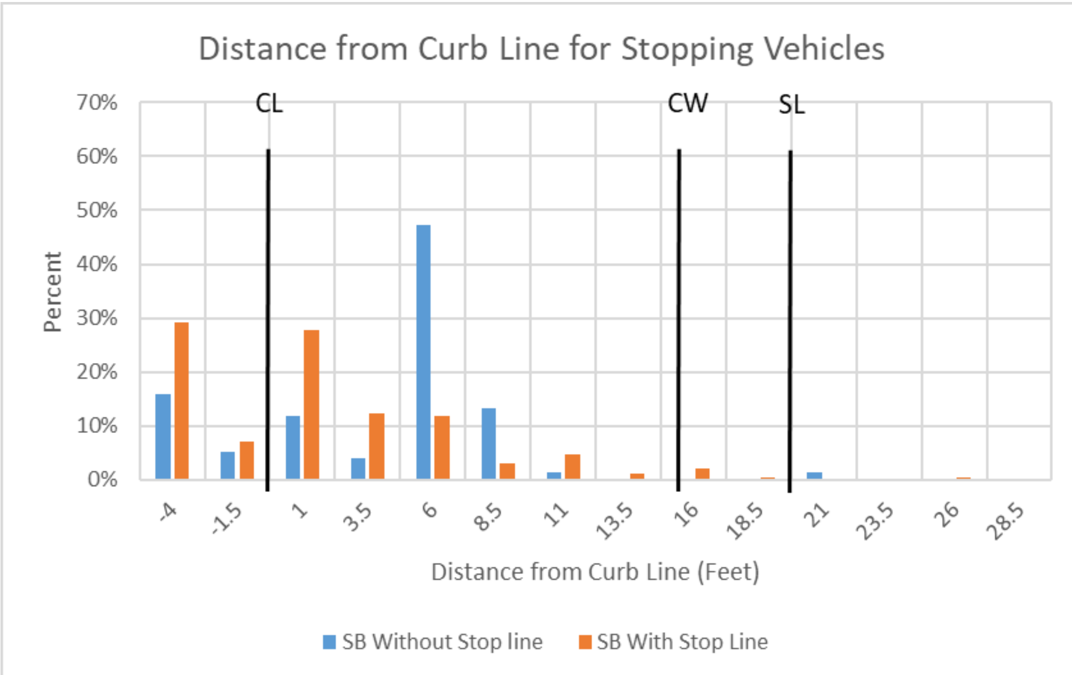

Figure 3.53 Lincoln Dr Right Lane and Lydia Ave W Distribution of Stopping Distance During Stop Events

Similar to the left lane, at Lincoln Dr's right lane, the stop line did appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.54, the average time to travel 30 feet increased by almost 2 seconds after the placement of the stop line, meaning although drivers continued to roll through or ignore the stop line, they did slow down more as they passed through the intersection.

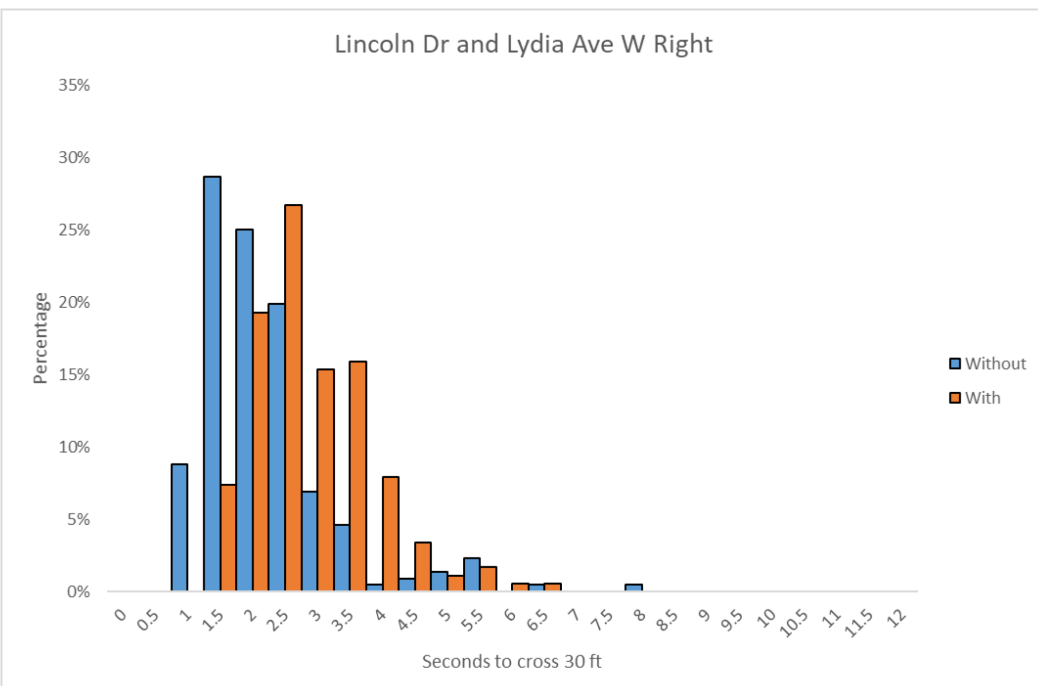

Figure 3.54 Lincoln Dr Right Lane Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.7 S179O – 50th St W and Eden Ave

50th St W and Eden Ave is located in Edina, near Highway 100 and Edina City Hall. The major ADT is 18000 vehicles per day, and the minor ADT is unknown but low based on observational counts. This site again was chosen for its crosswalks, the ADT of the major road, and the geometry of the major road with multiple lanes, a turn lane and a median. Sight distance is unobstructed in both directions. This site was chosen in part because the City of Edina presented it to the MTO as an intersection of concern. An aerial view of the site is shown in Figure 3.55. Sight distances are presented in Figure 3.57.

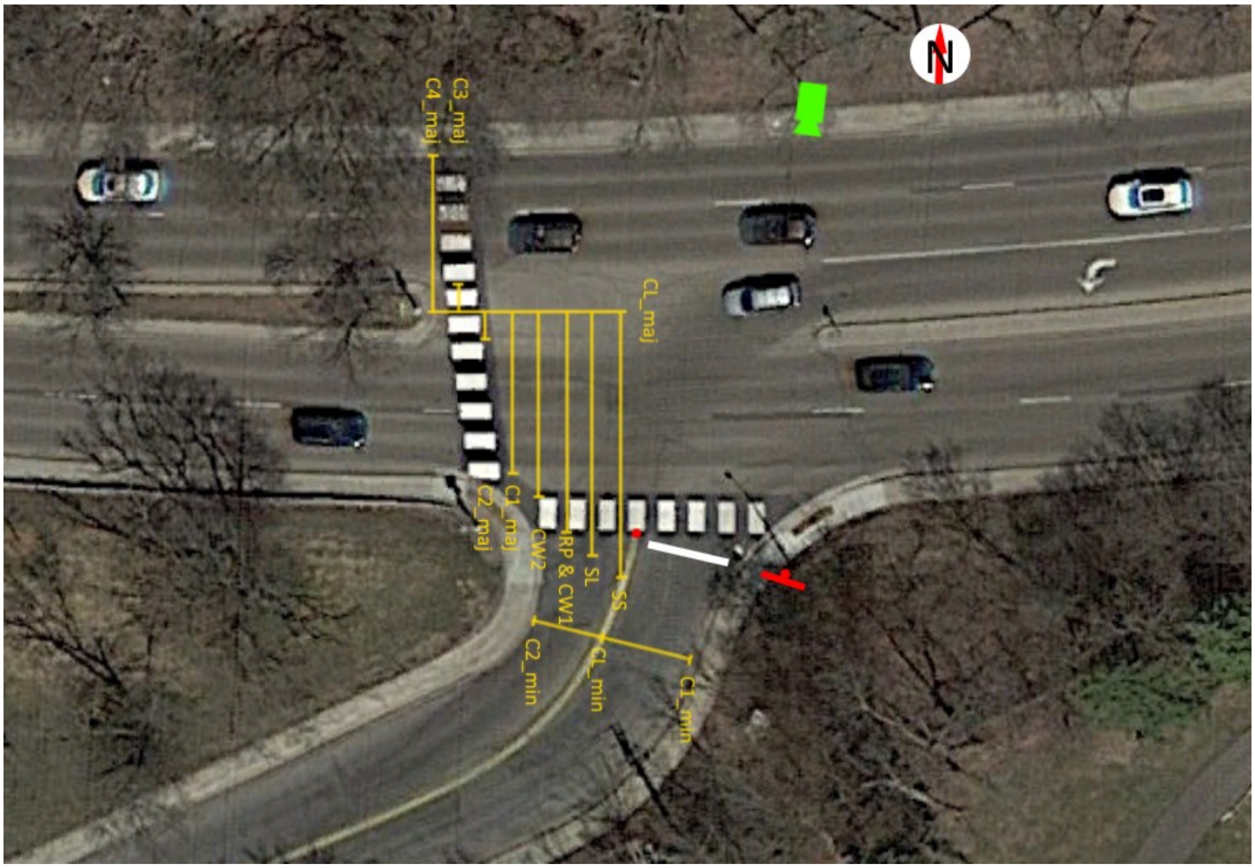

Figure 3.55 Aerial view of the intersection of 50th St W and Eden Ave with measurements marked

Measurements noted on Figure 3.55 are listed in Table 3.17.

Table 3.17 Relevant measurements at 50th St W in feet

From CL_maj to...	**SS**	**SL**	**RP & CW1**	**CW2**	**C1_maj**	**C2_maj**	
	57.25	54.96	45.33	39.33	35.58	6.58	
From CL_maj to...	**C3_maj**	**C4_maj**					
	3.67	32.75					
From CL_min to...	**C1_min**	**C2_min**					
	16.50	16.50					

A camera view of the site with overlay lines is presented in Figure 3.56.

Figure 3.56 Camera view of the intersection of 50th St W and Eden Ave with 5-ft overlay lines marked

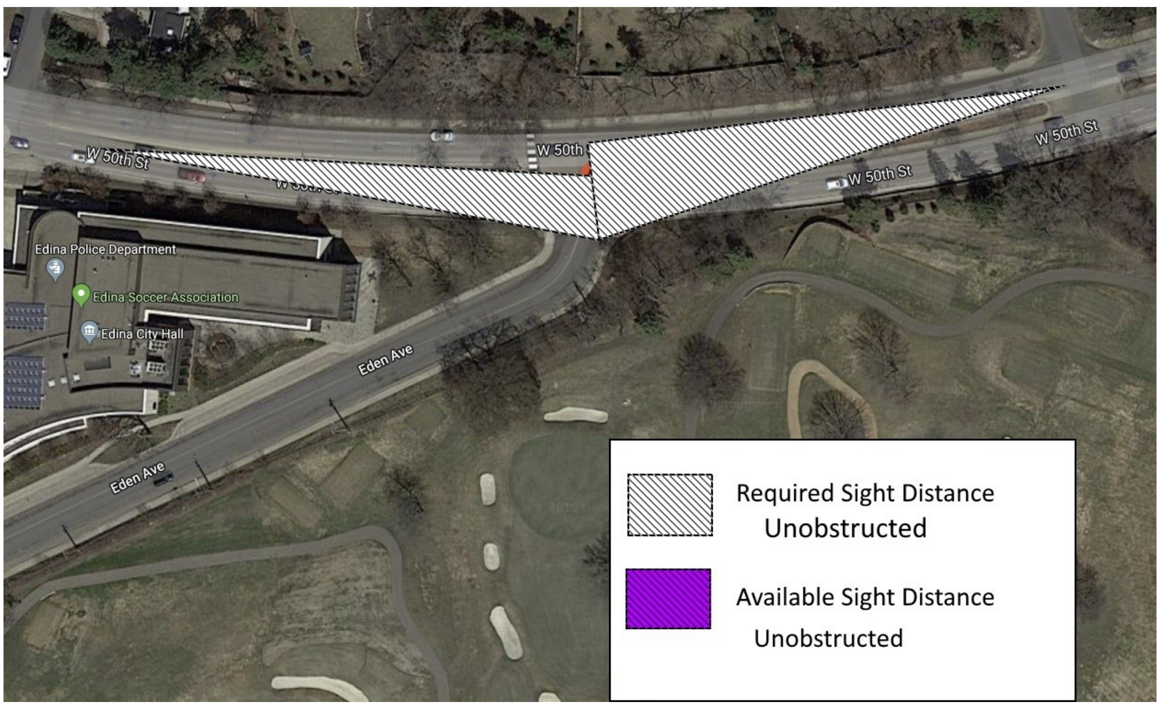

Figure 3.57 Available sight distance and required sight distance at 50th St W

This site did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.58) or broken down by turning movement (Figure 3.59). Ignores were very high, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.61 and discussed later in this section.

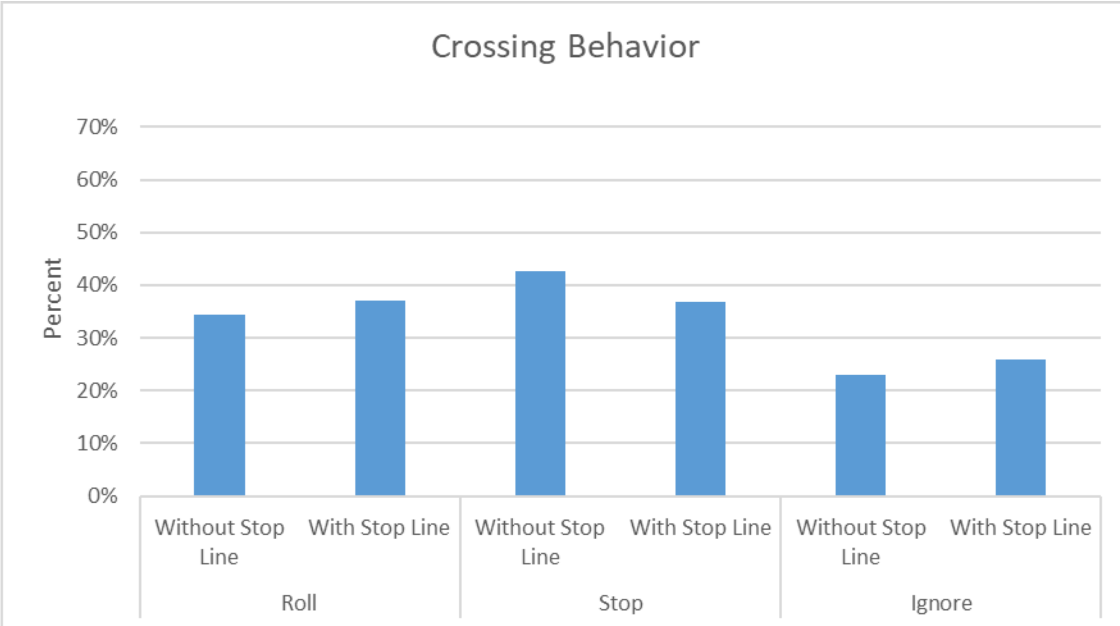

Figure 3.58 50th St W and Eden Ave distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

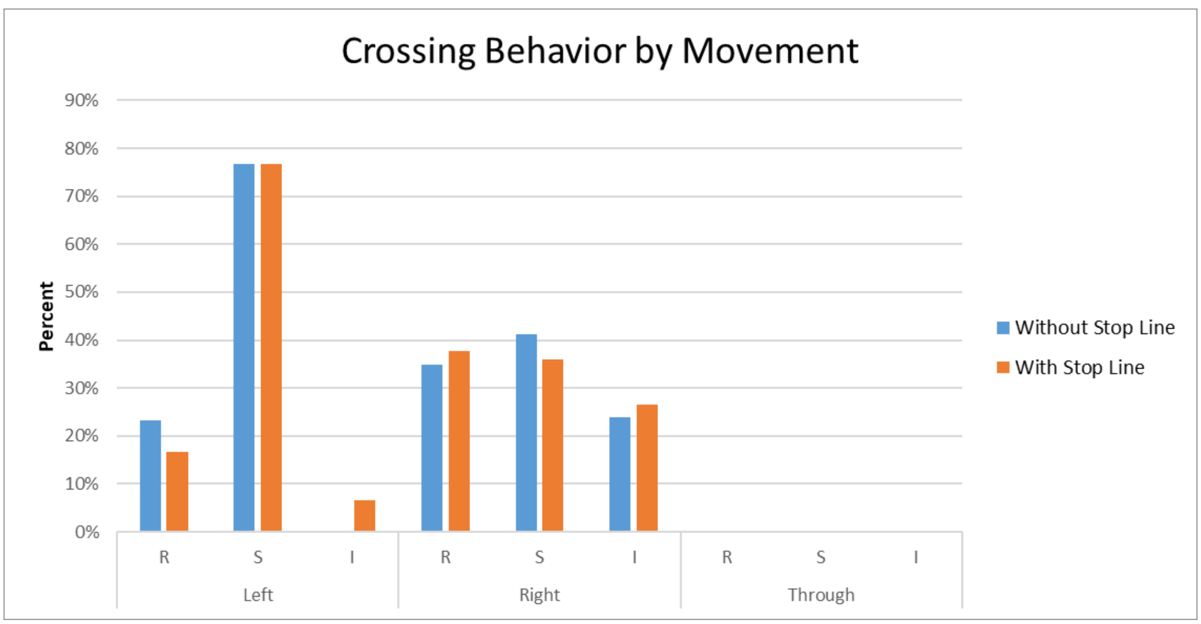

Figure 3.59 50th St W and Eden Ave distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

From Figure 3.60, it is observed that, like in the case of the Lincoln Dr, the other site with crosswalks, drivers, almost entriely stop way pass the stop line, into and over the crosswalk. This behavior was worsen with the addition of the stop line, fact concistent to earlier observations. This reinforces the fact that crosswalk seem to increase the drivers confidence in moving closer to the conflict point.

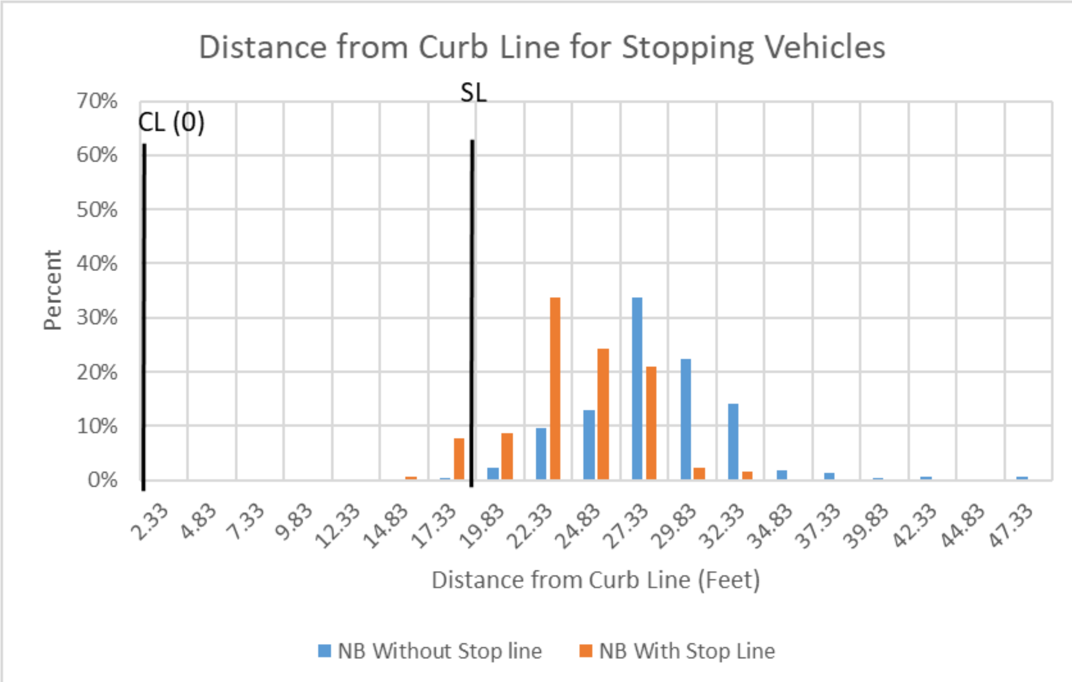

Figure 3.60 50th St W and Eden Ave Distribution of Stopping Distance During Stop Events

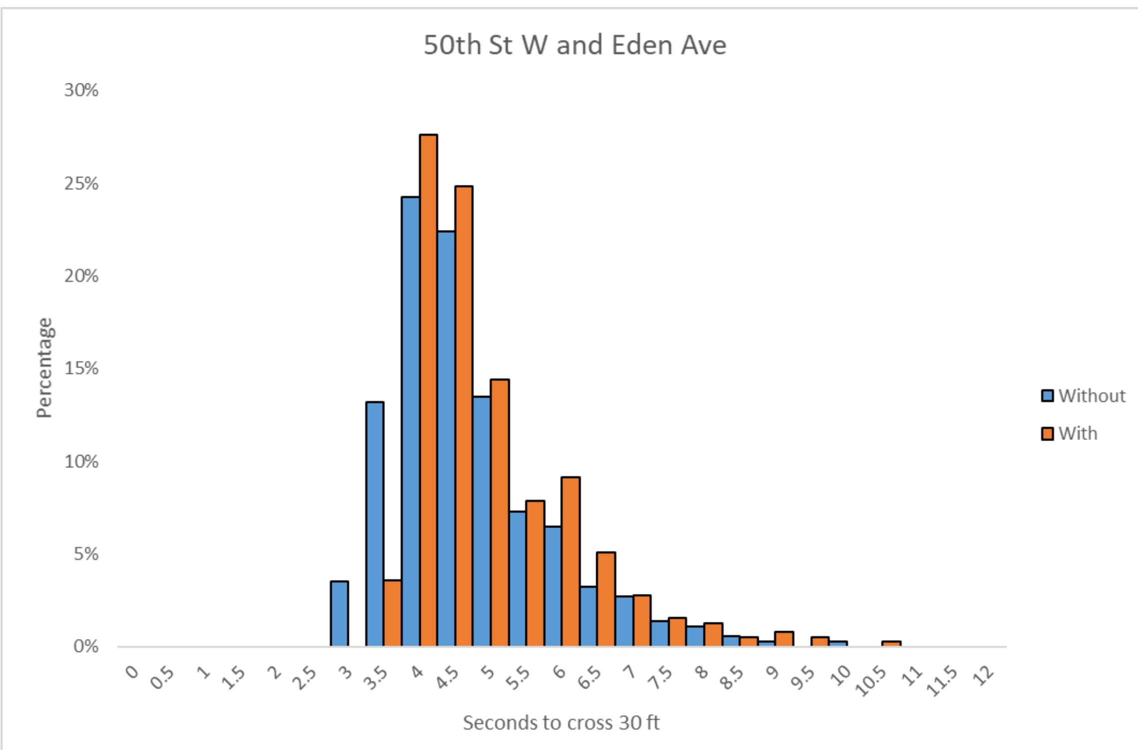

Figure 3.61 50th St W and Eden Ave Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

At 50th St W, the stop line did again appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.61, the average time to travel 30 feet increased by about 1.5 seconds after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down more as they pass through the intersection. Note that this one of the sites exhibiting the slowest rolls among the ones covered in this study, probably due to the skewness of the intersection.

3.4.8 S182O – Vernon Ave S and Arcadia Ave

Vernon Ave S and Arcadia Ave is located in Edina, to the west of Highway 100 and near several retail centers. The major road ADT is 18700 vehicles per day, and the minor ADT is unknown but low based on observational counts. This site was chosen as the City of Edina presented it to the MTO as an intersection of concern. Sight distance to the left was unobstructed (Figure 3.64); sight distance to the right was obstructed but as no traffic comes from that direction, should not affect driver behavior. An aerial view of the site is presented in Figure 3.62.

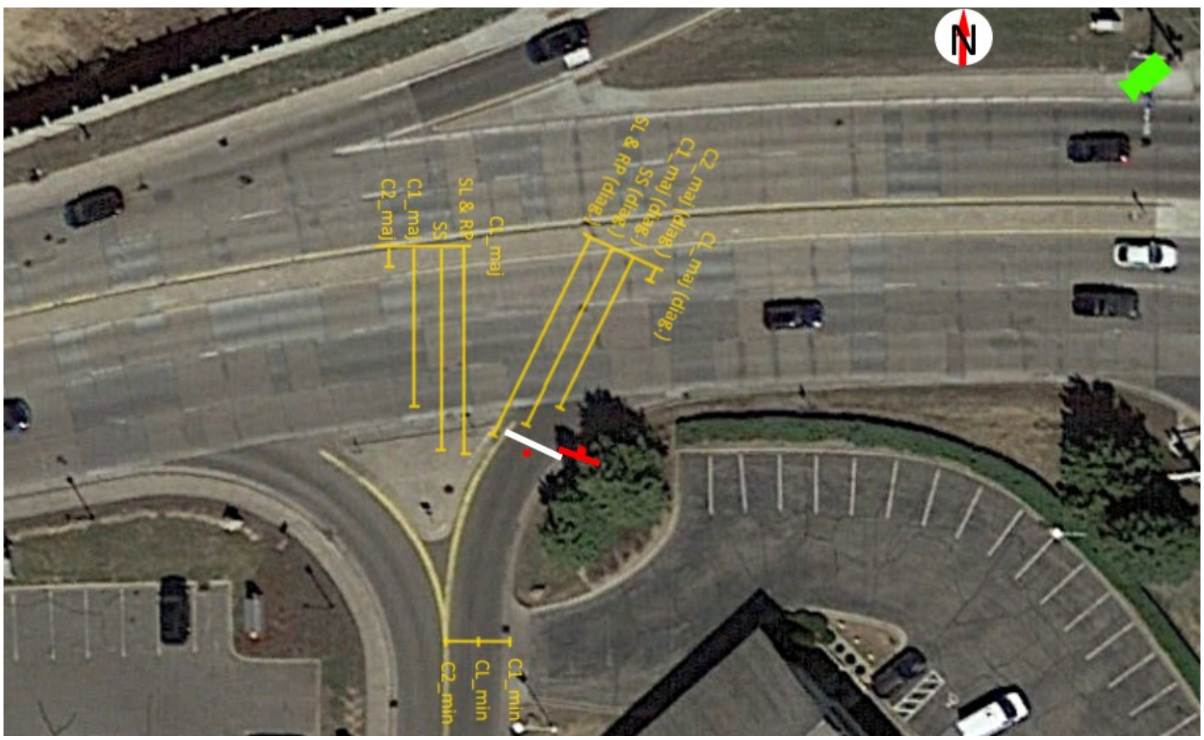

Figure 3.62 Aerial view of the intersection of Vernon Ave S and Arcadia Ave with measurements marked

Measurements noted on Figure 3.62 are listed in Table 3.18.

Table 3.18 Relevant measurements at Vernon Ave S in feet

From CL_maj to...	SL & RP	SS	C1_maj	C2_maj			
	52.33	50.14	43.75	3.00			
From CL_maj (diag.) to...	SL & RP (diag.)	SS (diag.)	C1_maj (diag.)	C2_maj (diag.)			
	71.67	68.67	10.50	4.11			
From CL_min to...	C1_min	C2_min					
	8.84	8.84					

A camera view with overlay lines marked is shown in Figure 3.63.

Figure 3.63 Camera view of the intersection of Vernon Ave S and Arcadia Ave with 5-ft overlay lines marked

Figure 3.64 Available sight distance and required sight distance at Vernon Ave S and Arcadia Ave

This site did not see a change in either the absolute percentage or ratio of driver behavior turning right (Figure 3.65). No detailed breakdown of driver movement is necessary at this site as right turns are the only driver movement permitted. Ignores were higher than anticipated, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.67. As discussed later in this section, after taking in consideration the shape of the crossing travel times in Figure 3.67, the probability of subjective error during the video reduction process is high. This means that most ignores are actually rolls. This brings the ratio between rolls and stops to levels consistent to the rest of the sites.

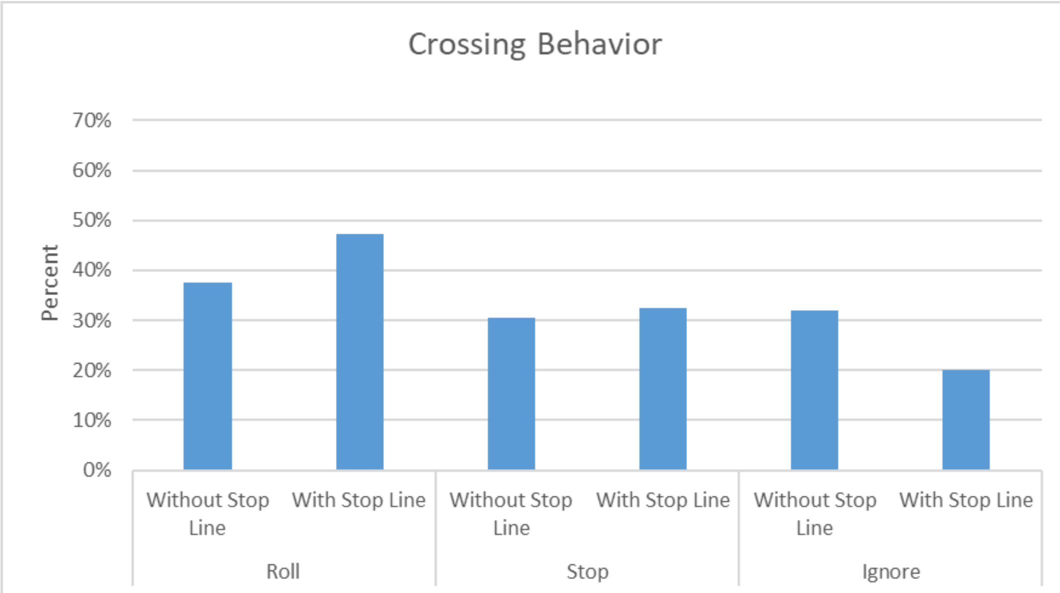

Figure 3.65 Vernon Ave S and Arcadia Ave distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

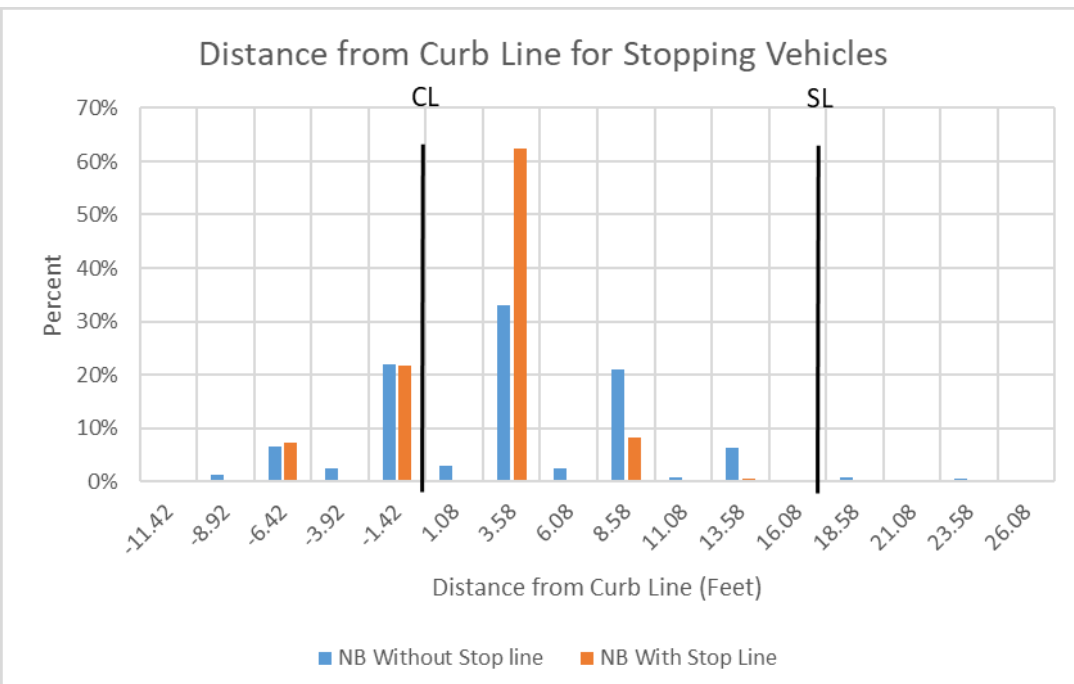

Figure 3.66 Vernon Ave S and Arcadia Ave Distribution of Stopping Distance During Stop Events

As seen in Figure 3.66, without the stop line there was a normal shaped distribution with a peak at just over 3.5 feet upstream of the curb line. This distribution shifted left after the stop line was added, with the peak remaining at the same location but with nearly double the number of drivers stopping there. Both without and with the stop line, 25-30% of drivers stopped downstream of the curb of the major road. The skewedness of the road alignment can explain some of this behavior as well as the fact that, on the main road the rightmost lane was introduced only about 1000 feet upstream of the intersection probably resulting in much lower traffic; essentially acting as a partial shoulder lane.

That been said, the addition of the stop line, along with the much highlighted boundary between pavements, seem to encourage more people to pull closer to the curb line. This observation is consistent to the rest of the studied sites with similar characteristics.

At Vernon Ave, the stop line did appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.67, the average time to travel 30 feet increased by more than 1 second after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down more as they pass through the intersection. The reduction is even more evident on the left side of the graph where the higher crossing speeds are. It seems that the stop line increases the confidence of the drivers to go closer to the curb line but slower, possibly looking longer for conflicting traffic.

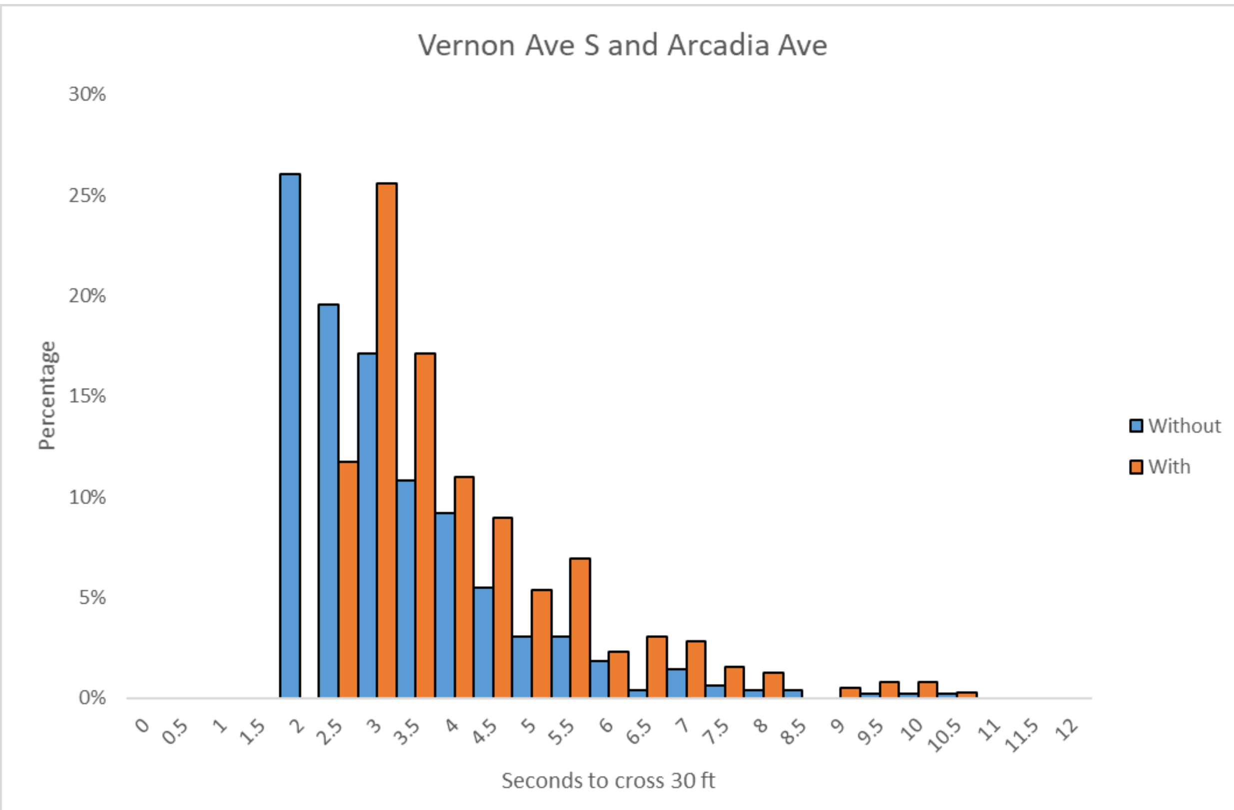

Figure 3.67 Vernon Ave S and Arcadia Ave Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.9 S190C – Portland Ave and E 73rd St

Portland Ave and E 73rd St is located in Richfield. This site was chosen due to the opportunity to paint and study both approaches of the minor road, the crosswalks on the main road, the ADT of Portland Ave, and the unique geometry of Portland Ave, with two lanes, a median, a turning lane in both directions, and a bike lane closer to the eastbound minor approach. Note that the bike lane, made out of concrete, presents a highly visible boundary between pavements. The major ADT is 11200 vehicles per day. Additionally, this site has a bus stops on the major road. Sight distances for the eastbound approach are unobstructed (Figure 3.70), and sight distances for the westbound approach are obstructed to the left (Figure 3.76). An aerial view is presented in Figure 3.68.

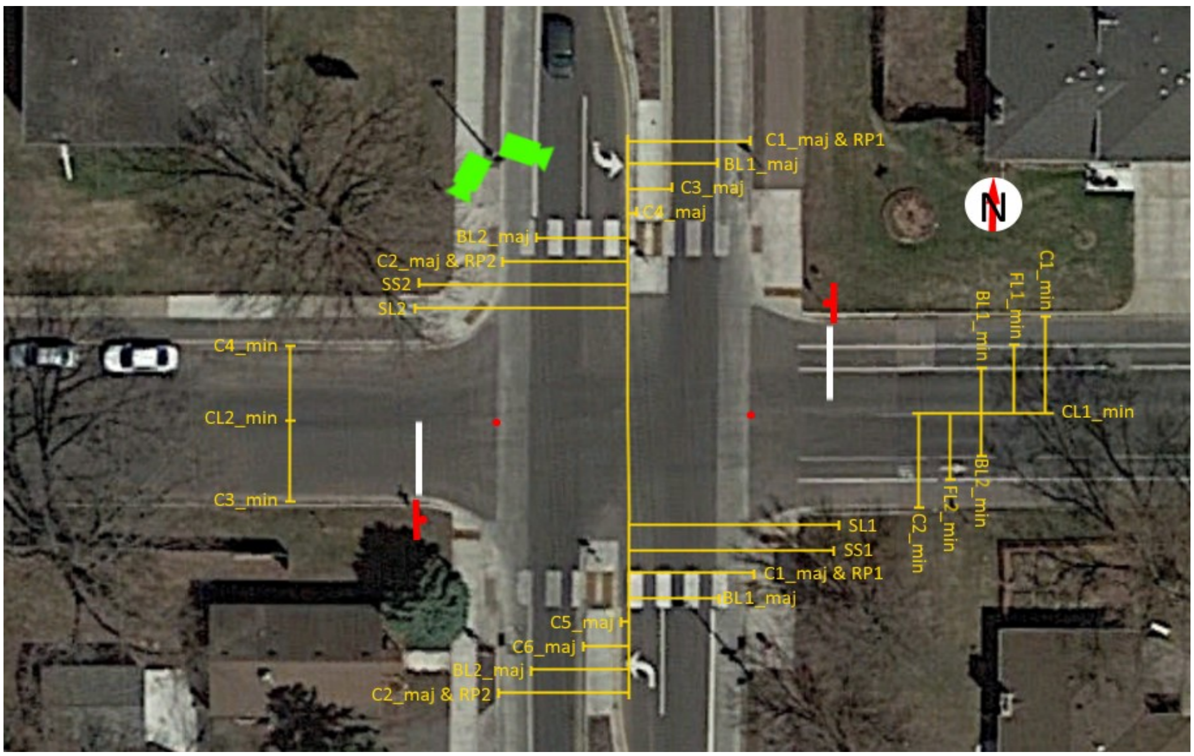

Figure 3.68 Aerial view of the intersection of Portland Ave and E 73rd St with measurements marked

Measurements noted on Figure 3.69 are listed in Table 3.19.

Table 3.19 Relevant measurements at Portland Ave (EB and WB) in feet

From CL_maj to...	SL1	SS1	C1_maj	RP1	BL1_maj	C3_maj	C4_maj
	44.62	42.12	26.42	26.42	19.75	8.75	1.75
From CL_maj to...	SL2	SS2	C2_maj	RP2	BL2_maj	C6_maj	C5_maj
	38.08	35.92	26.42	26.42	19.75	8.75	1.75
From CL1_min to...	C1_min	FL1_min	BL1_min	BL2_min	FL2_min	C2_min	
	21.92	15.42	10.42	10.25	15.25	21.75	

The geometry of this site prevented one camera from being able to capture both the eastbound and westbound approaches in the same view. Two cameras were deployed at the same time to capture both sites without and with the stop line. The camera views and analyses will be presented separately for approach.

3.4.9.1 S190B – Portland Ave and E 73rd St EB

A camera view of the eastbound Portland Ave and E 73rd St approach is shown in Figure 3.69. Sight distance in both directions is unobstructed as presented in Figure 3.70.

Figure 3.69 Camera view of the intersection of Portland Ave and E 73rd St with 5-ft overlay lines marked

Figure 3.70 Available sight distance and required sight distance at Portland Ave EB

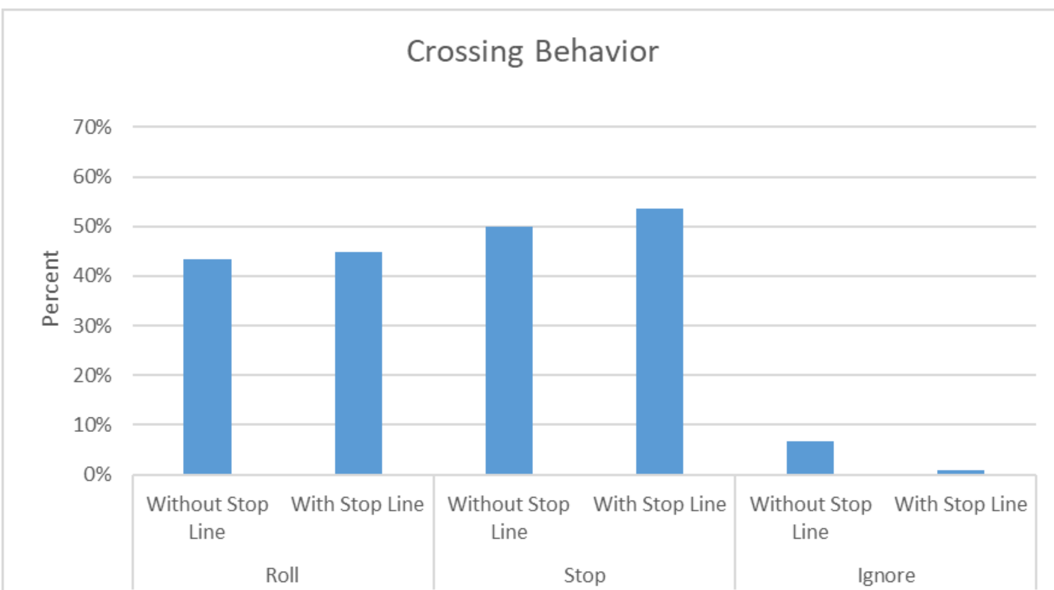

Figure 3.71 Portland Ave and 73rd St EB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

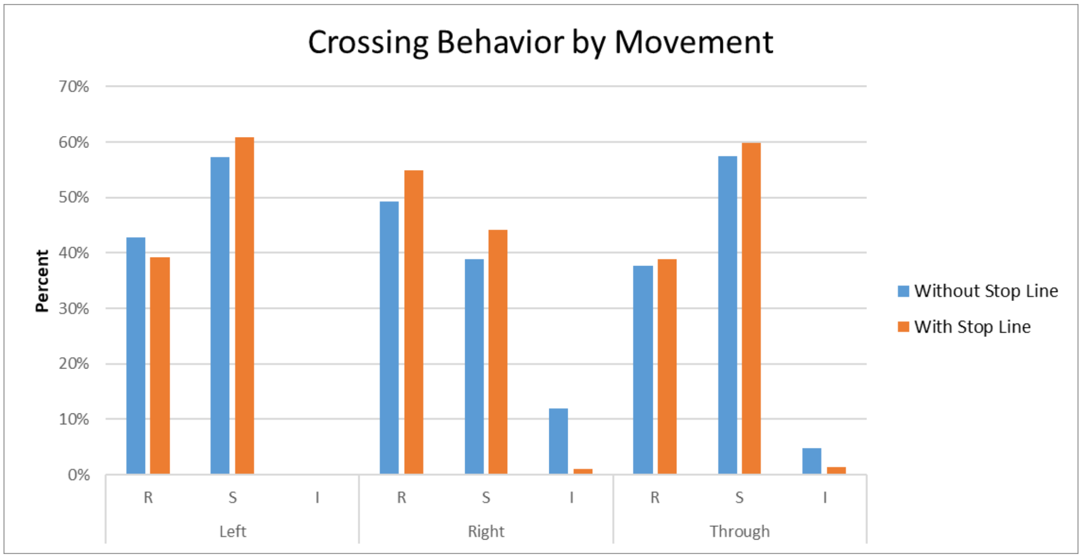

Figure 3.72 Portland Ave and 73rd St EB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

This site did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.71) or broken down by turning movement (Figure 3.72). Ignores were within an acceptable range.

Prior to the stop line's placement, drivers were stopping primarily between the stop line and the curb line with some spillover into the bike lane, as seen in Figure 3.73. After the stop line was painted, drivers appear to have been pushed forward 2.5-5 feet, with a little more spillover into the bike lane and further. This stop line influence seems consistent on all sites where there is a perceived safety buffer for vehicles to encroach in.

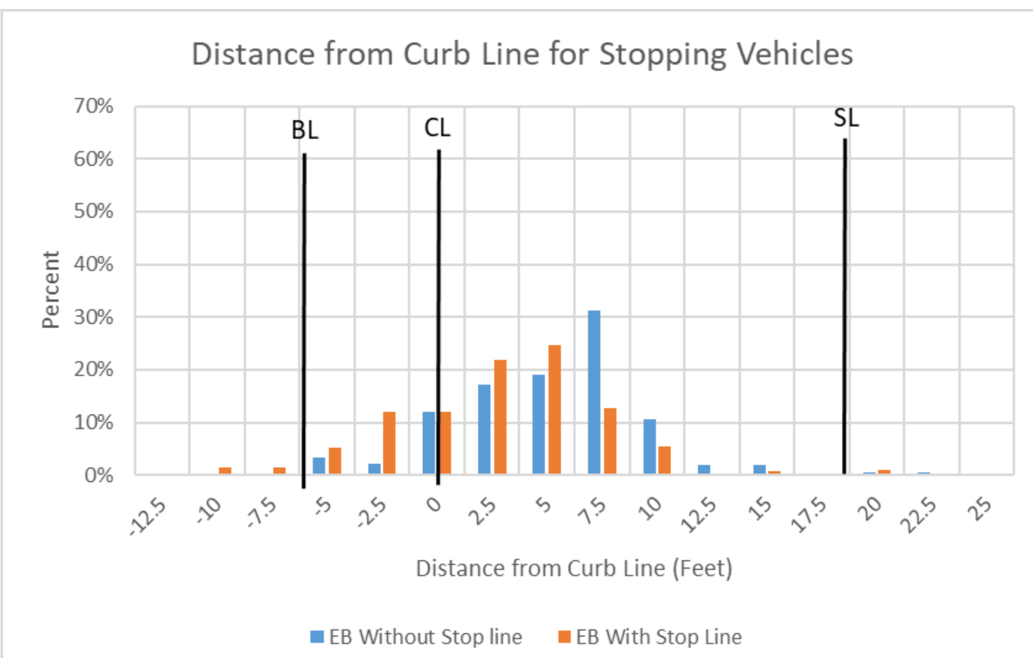

Figure 3.73 Portland Ave and E 73rd St EB Distribution of Stopping Distance During Stop Events

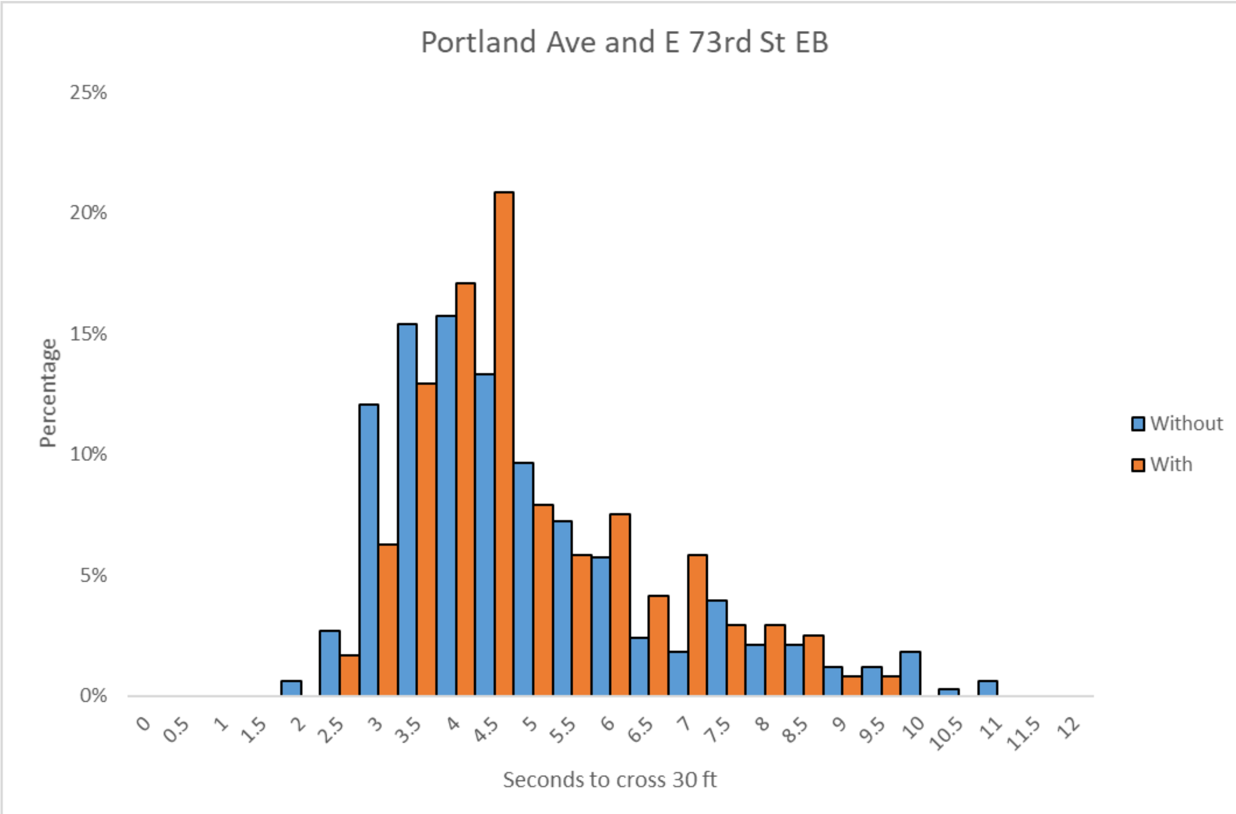

Figure 3.74 Portland Ave and E 73rd St EB Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

At this approach, the stop line appears to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.74, the average time to travel 30 feet increased by about 1.5 seconds after the placement of the stop line, meaning although drivers are continuing to roll through or ignore the stop line, they are slowing down more as they pass through the intersection.

3.4.9.2 S190B – Portland Ave and E 73rd St WB

A camera view of the westbound Portland Ave and E 73rd St approach is shown in Figure 3.75. Sight distance to the left was obstructed, as shown in Figure 3.76.

Figure 3.75 Camera view of the intersection of Portland Ave and E 73rd St WB with 5-ft overlay lines marked

Figure 3.76 Available sight distance and required sight distance at Portland Ave and E 73rd St WB

This approach again did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.77) or broken down by turning movement (Figure 3.78). Ignores were within an expected range.

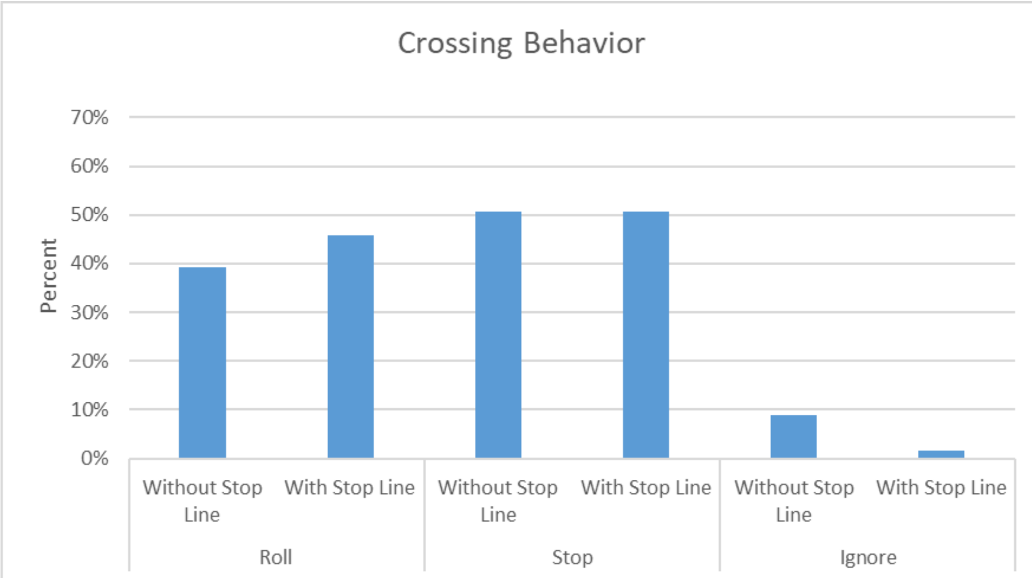

Figure 3.77 Portland Ave and 73rd St WB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

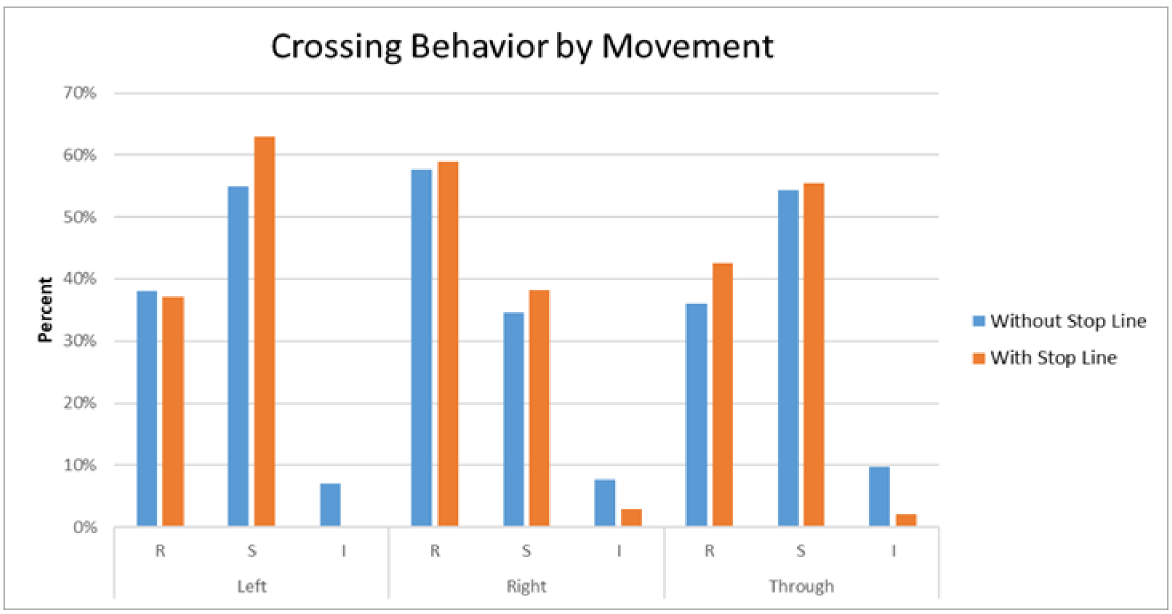

Figure 3.78 Portland Ave and 73rd St WB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

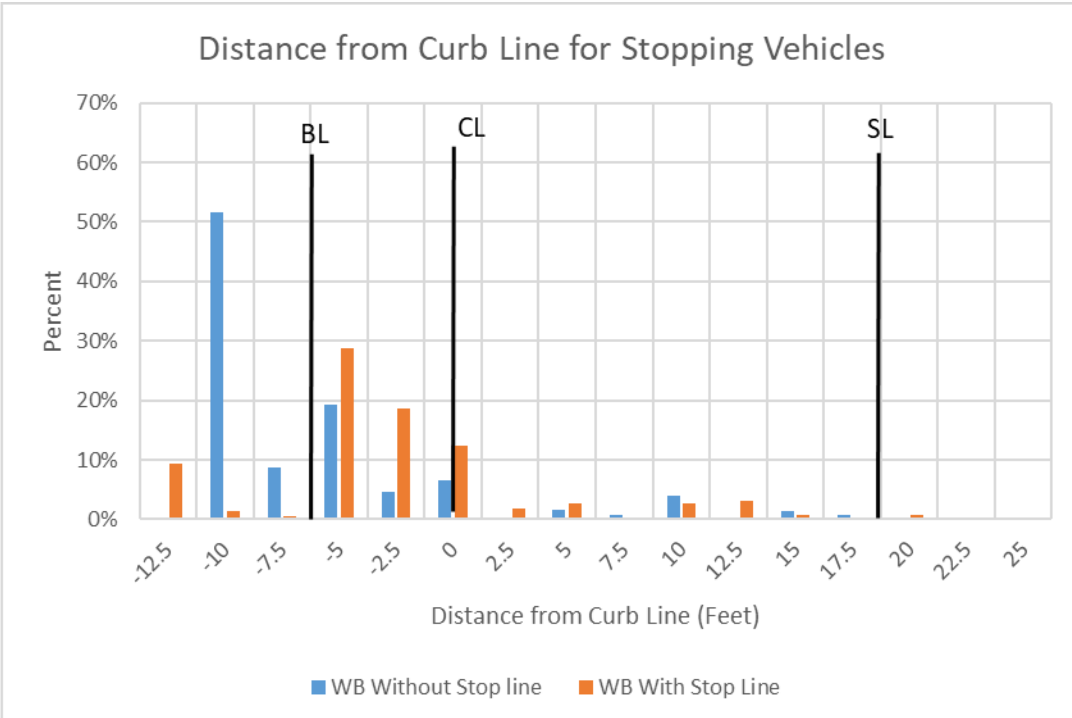

Figure 3.79 Portland Ave and E 73rd St WB Distribution of Stopping Distance During Stop Events

As seen in Figure 3.79, drivers were stopping right at the curb line (51%) before the stop line was painted, with some distribution of stops toward the stop line. No drivers encroached into the bike lane or further. After the stop line was added, drivers appear to be stopping in two different ways (bi-modal distribution) with one group of drivers safely stopping between 5-10 feet back from the curb line, and another group, nearly 25%, now encroaching into the bike lane or even past it, into the main road. This suggests, given the reduced left sight distance, that some, but not all drivers will use the stop line as a reference point and venture forward more. Still, it also means that a sizable group of drivers is influenced by the stop line in a positive way and stops farther away from the "edge".

At this site, the stop line did not appear to have a noticeable effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.80, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop line at the same pace as before the stop line was painted. Comparatively speaking, the roll times on the WB approach, before the stop line were comparable to the roll times on the EB approach after the stop line was introduced. This implies that drivers were already spending more time rolling so the stop line did not introduce a change. This implies that there is a limit to the roll speed, under which the stop line is ineffectual in that regard.

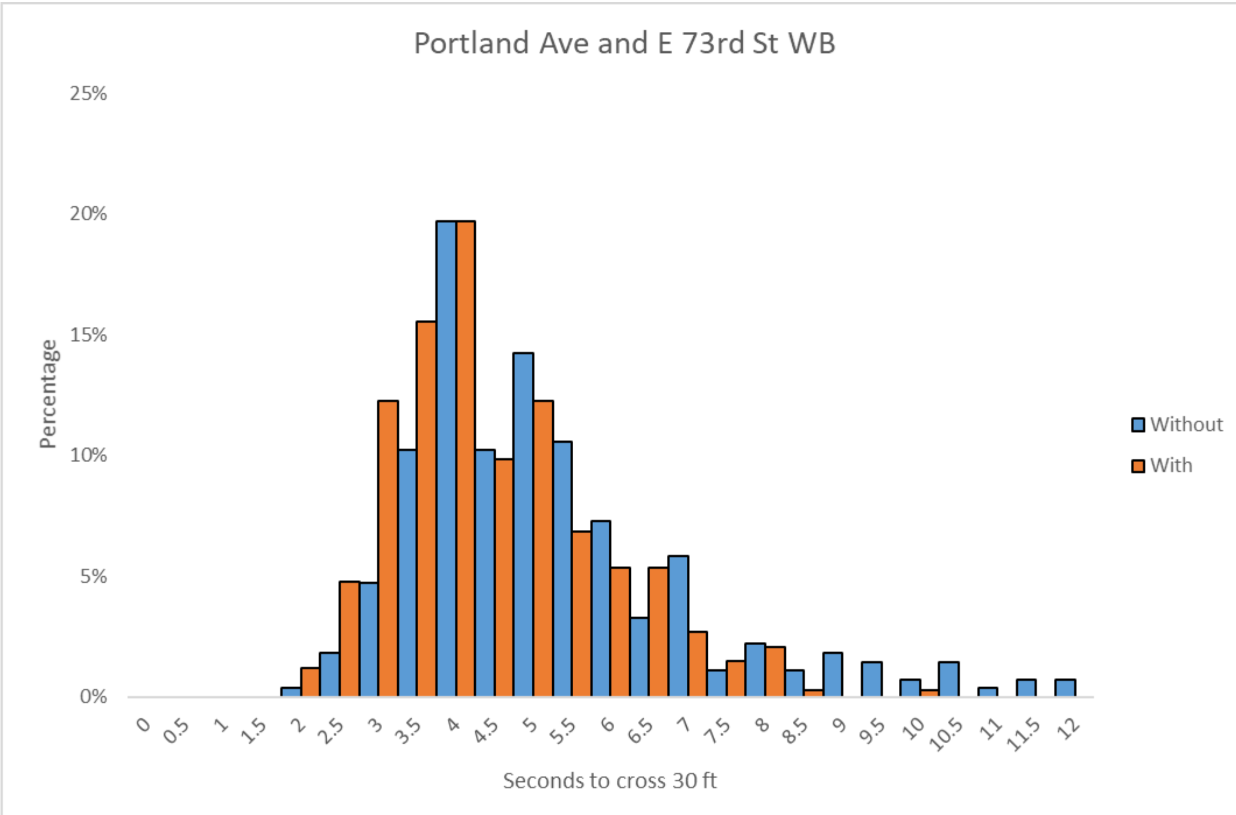

Figure 3.80 Portland Ave and E 73rd St WB Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.10 S221O – Warner Rd and Fish Hatchery Rd N

Warner Rd and Fish Hatchery Rd N is located in St. Paul, near the Minnesota DNR Region 3 Headquarters. Warner Rd has an ADT of 7000 vehicles, and at 50 mph had the highest speed limit of any major road studied. Fish Hatchery Rd N is a small road that connects to a nearby fish hatchery and then dead-ends. Also of note is that Warner Rd has such a high ADT that it is often very difficult to make a left turn onto Fish Hatchery Rd, or left or right onto Warner Rd. Fish Hatchery Rd also sees a large number of semis going to and from the nearby rail yard and vehicle transfer lot. There is also a bike trail running along Warner Rd, which jogs down parallel to Fish Hatchery Rd N before veering eastward. Available sight distance is the highest at this intersection of all sites studied; however, unobstructed in both directions (Figure 3.83). An aerial view of the site is presented in Figure 3.81. Some other unique characteristics on this site are the location of the stop sign in regards to the location the stop line was painted. In all other cases the line was painted at the location of the stop sign. At this site, the stop sign was located between the entrance to the bike trail and the major road. This made siting the stop line difficult because it required that the stop line painted nearly 13 feet upstream of the sign to avoid directing vehicles to stop in front of the entrance to the trail.

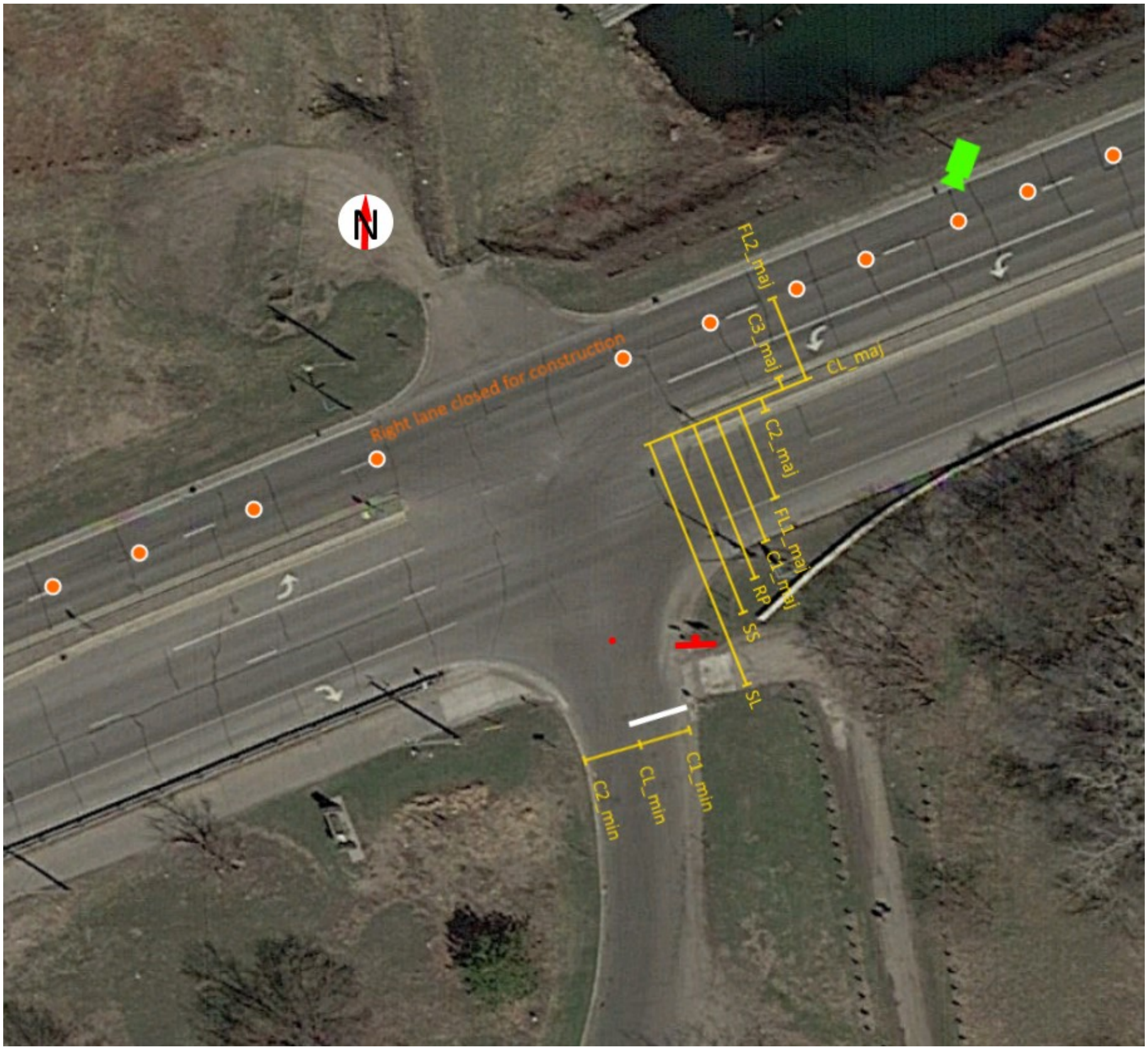

Figure 3.81 Aerial view of the intersection of Warner Rd and Fish Hatchery Rd N with measurements marked

Measurements noted on Figure 3.81 are listed in Table 3.20.

Table 3.20 Relevant measurements at Warner Rd in feet

SL	**SS**	**RP**	**C1_maj**	**FL1_maj**	**C2_maj**	
69.00	56.25	45.00	36.00	25.67	2.50	
C3_maj	**FL2_maj**					
2.50	26.16					
C1_min	**C2_min**					
17.58	17.58					

A camera view with overlay lines marked is shown in Figure 3.82.

Figure 3.82 Camera view of the intersection of Warner Rd and Fish Hatchery Rd N with 5-ft overlay lines marked

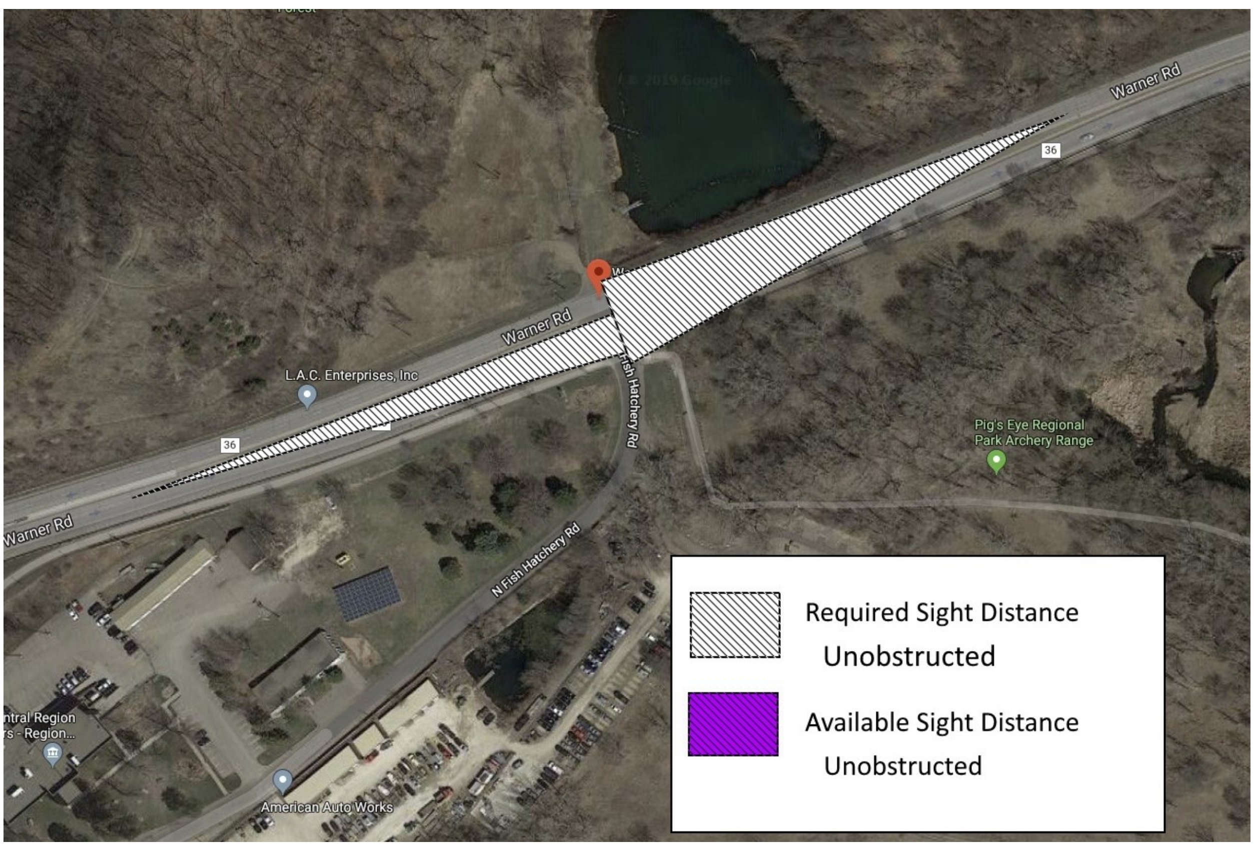

Figure 3.83 Available sight distance and required sight distance at Warner Rd and Fish Hatchery Rd N

This site did not see any noticable change in either the absolute percentage or ratio of driver behavior overall (Figure 3.84) or broken down by turning movement (Figure 3.85). Ignores were higher than anticipated, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.87 and discussed there.

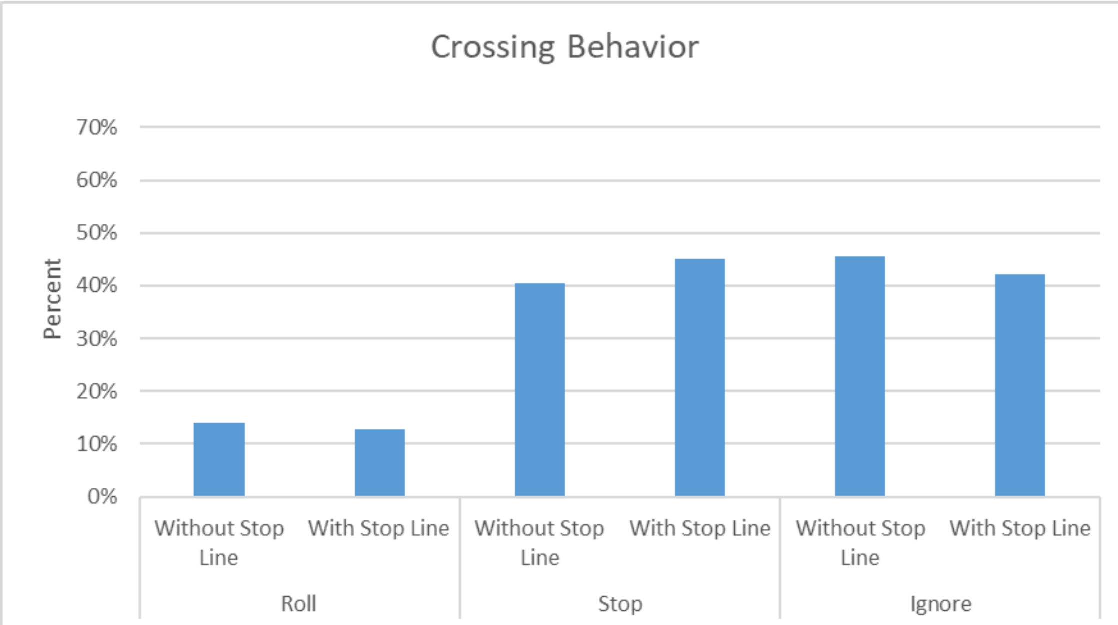

Figure 3.84 Warner Rd and Fish Hatchery Rd N distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

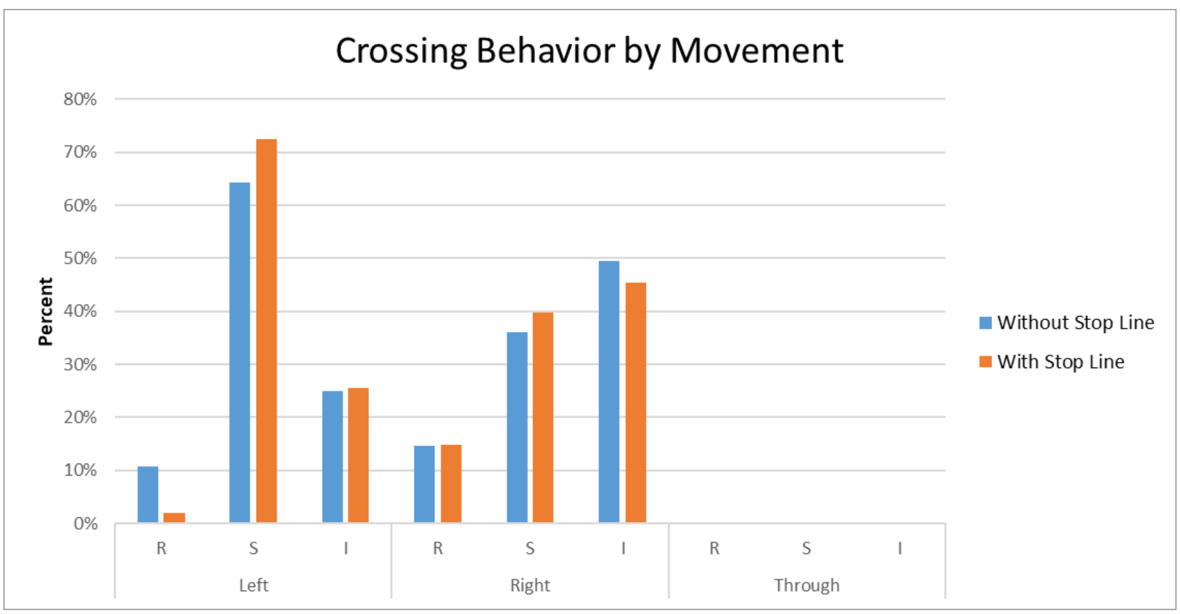

Figure 3.85 Warner Rd and Fish Hatchery Rd N distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

At this site, the majority (>80%) of drivers both without and with the stop line stopped between the stop line and the curb line, as seen in Figure 3.86. Roughly an additional 15% of drivers stopped between the curb line and the fog line. The later, being a turn only lane upstream of the intersection, results in a sizable shoulder lane rather than a curb. Drivers seem to use every bit of space available, regardless of the quality of the sight distance. There was not a significant shift in the overall distribution of stop location without or with the stop line.

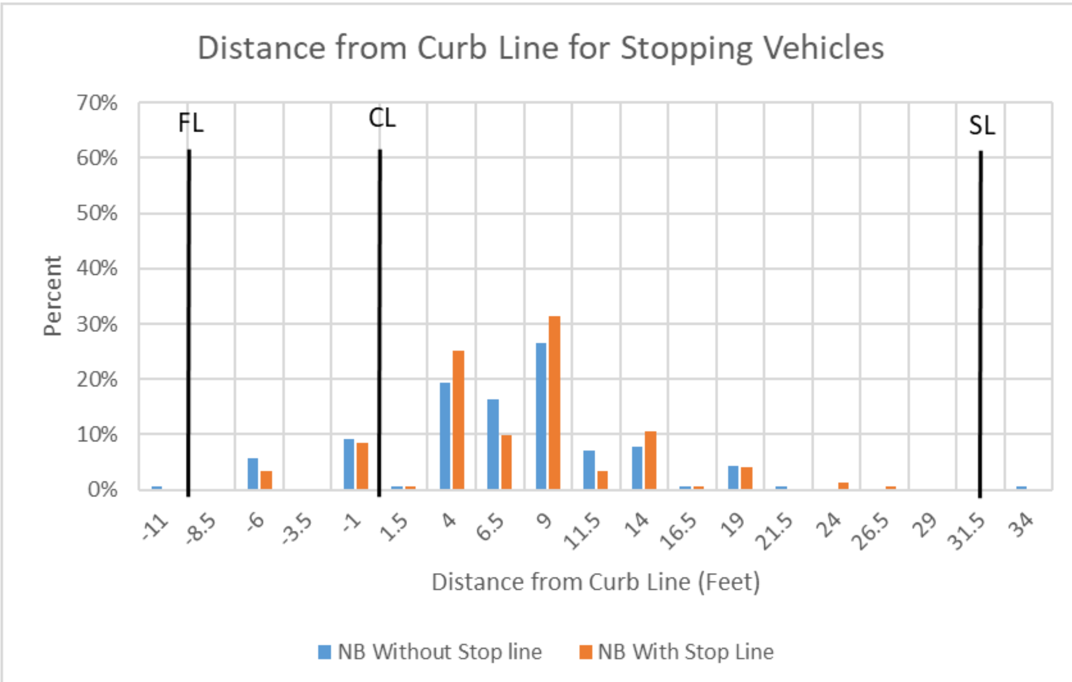

Figure 3.86 Warner Rd and Fish Hatchery Rd N Distribution of Stopping Distance during Stop Events

At Warner Rd, the stop line did not appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.87, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop sign at the same rate without or with the stop line.

Overall, it is clear that having the stop line so far from the edge of the approach, renders it completely ineffectual, practically invisible to the drivers.

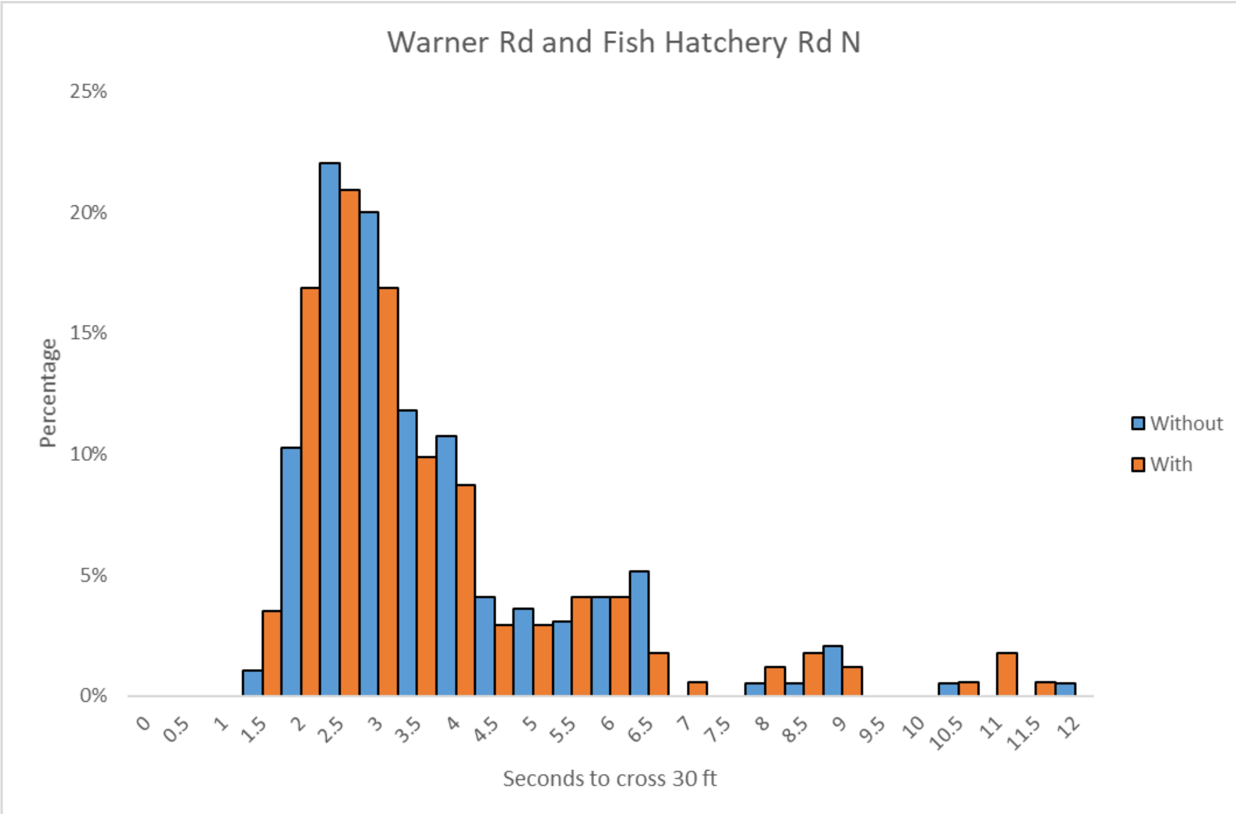

Figure 3.87 Warner Rd and Fish Hatchery Rd N Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.11 S227O – W Territorial Rd and Cromwell Ave

W Territorial Rd and Cromwell Ave is located in St. Paul, near Highway 280. This site was chosen due to its unique two-lane approach on the minor road, its proximity to Highway 280, and the freight-heavy makeup of traffic as compared to more residential or retail-based intersections studied. W Territorial Rd has an estimated ADT of 5000 vehicles based on project counts. Sight distances in both directions are adequate (Figure 3.90). An aerial view of the site is shown in Figure 3.88.

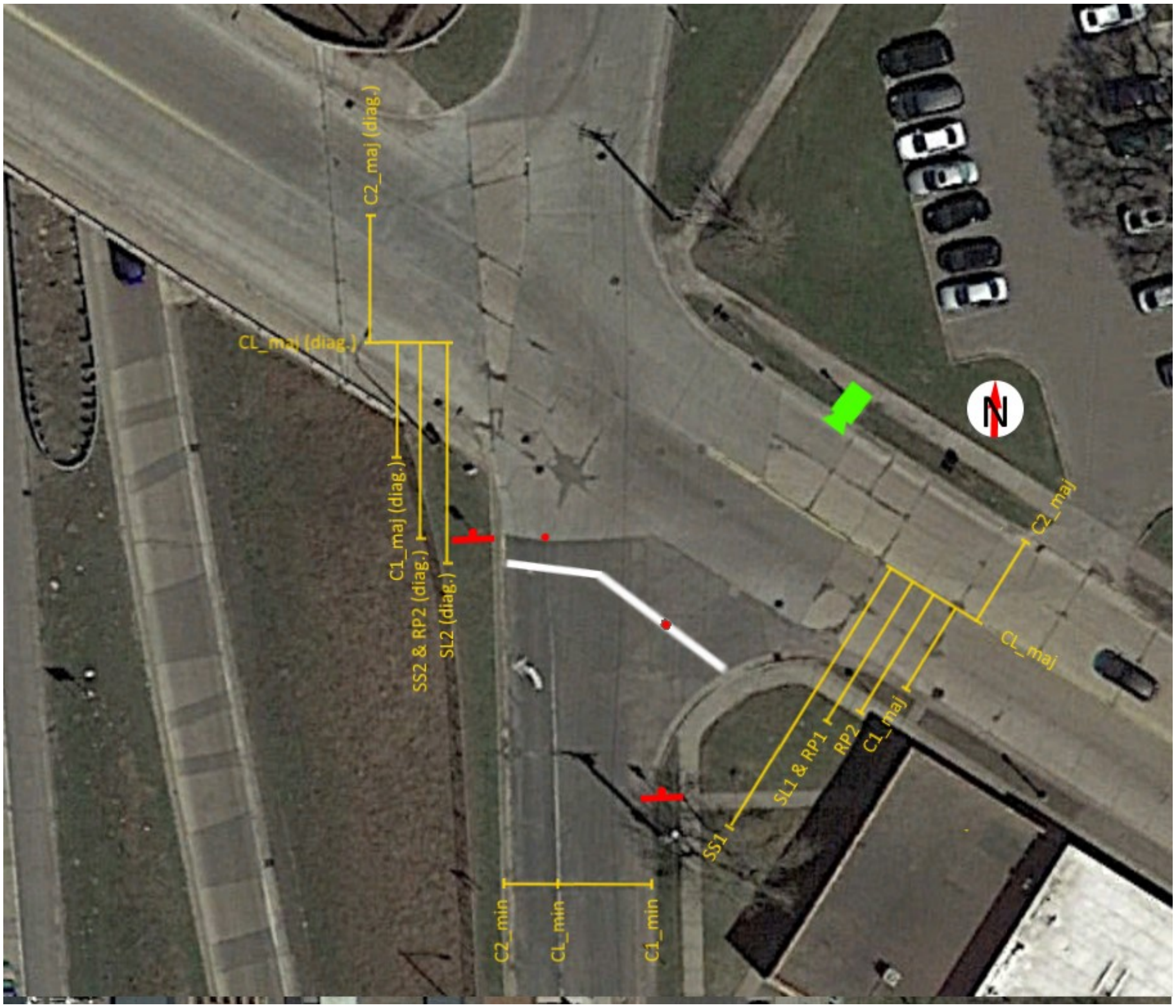

Figure 3.88 Aerial view of the intersection of W Territorial Rd and Cromwell Ave with measurements marked

Measurements noted on Figure 3.88 are listed in Table 3.21.

Table 3.21 Relevant measurements at W Territorial Rd in feet

From CL_maj to...	**SS1**	**SL1 & RP1**	**RP2**	**C1_maj**	**C2_maj**		
	69.83	43.33	34.83	22.50	22.50		
From CL_maj (diag.) to...	**SL2 (diag.)**	**SS2 (diag.)**	**RP2 (diag.)**	**C1_maj (diag.)**	**C2_maj (diag.)**		
	34.83	42.75	42.75	27.50	27.50		
From CL_min to...	**C1_min**	**C2_min**					
	21.58	12.42					

A camera view showing both approaches is presented in Figure 3.89.

Figure 3.89 Camera view of the intersection of W Territorial Rd and Cromwell Ave with 5-ft overlay lines marked

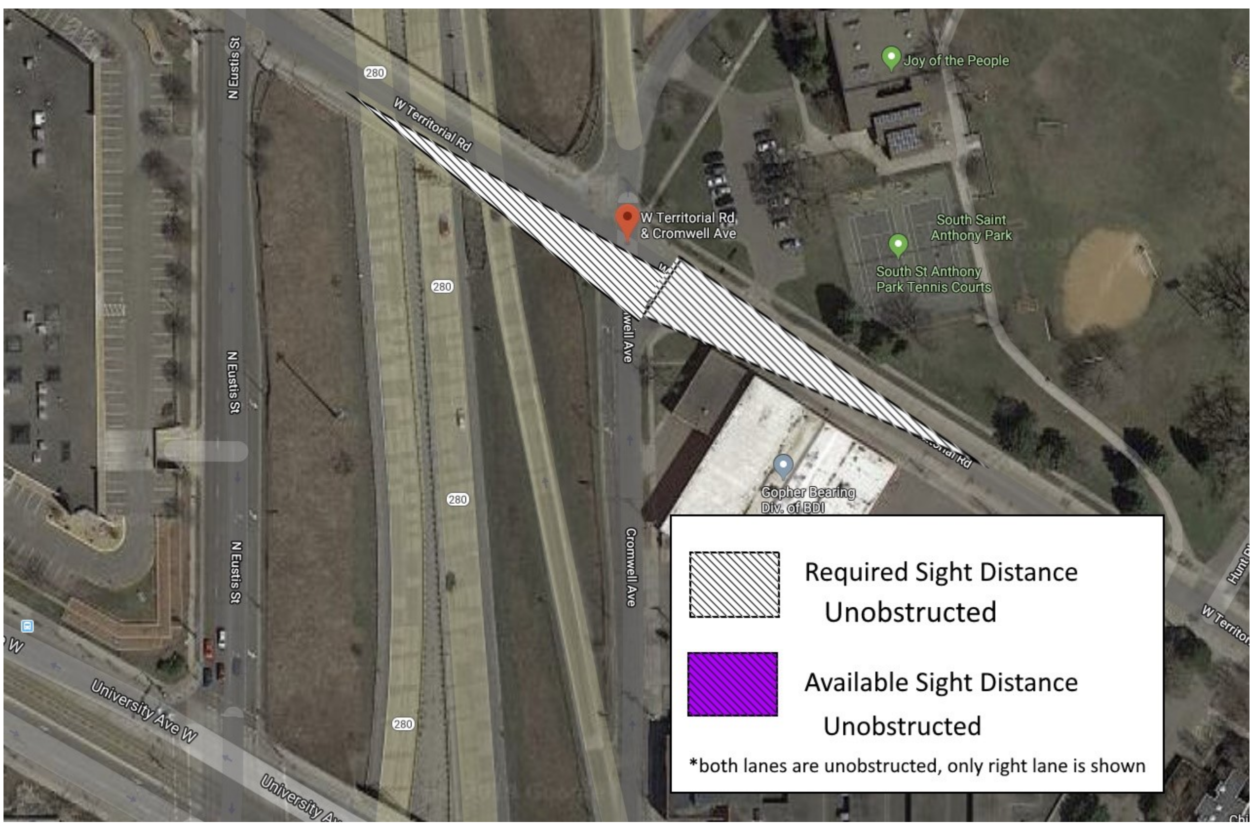

Figure 3.90 Available sight distance and required sight distance at W Territorial Rd and Cromwell Ave

Similarly to the Lincoln Dr site, the two lanes will be analyzed separately in sections below.

3.4.11.1 W Territorial Rd and Cromwell Ave: Right Lane

W Territorial Rd's right lane did not see a change in the ratio of driver behavior overall (Figure 3.91). Note that, only right turns are performed from this lane. Ignores during the without stop line period were lower than after the stop line installation but in such low samples the margin of error is high.

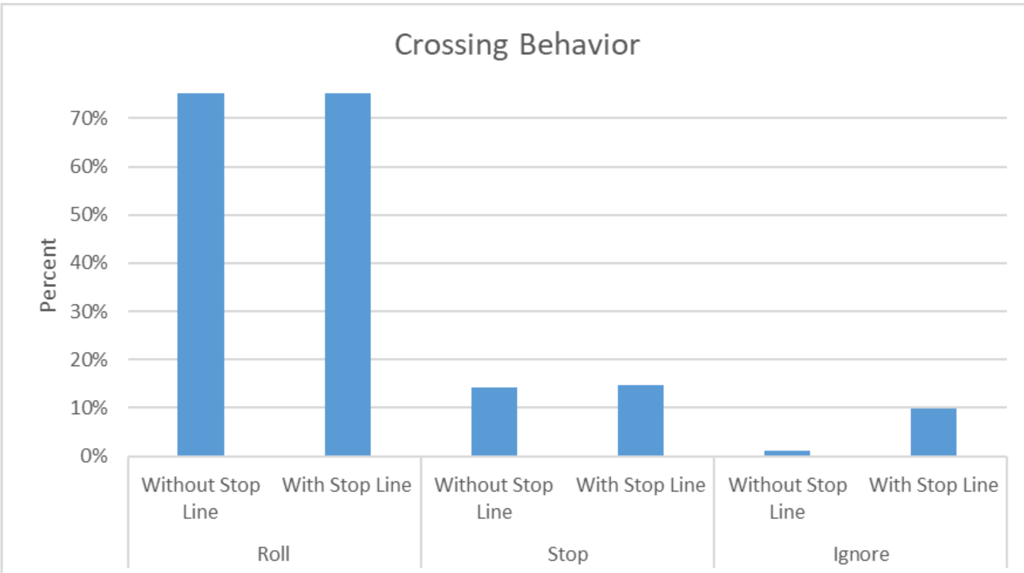

Figure 3.91 W Territorial Rd and Cromwell Ave (Right) distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

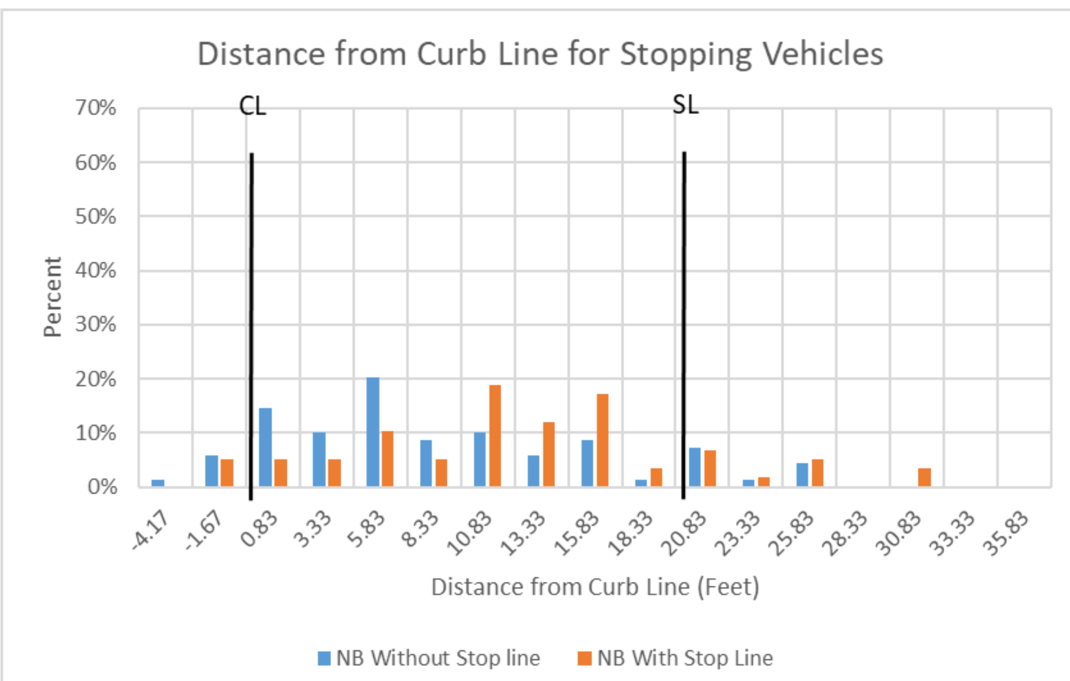

Figure 3.92 W Territorial Rd and Cromwell Ave N (Right) Distribution of Stopping Distance During Stop Events

As seen in Figure 3.92, >90% of drivers stopped before the curb line, both without and with the stop line in place. Only about 5% of drivers stopped after the curb line. The distribution of stop locations both without and with the stop line appears normal, with roughly a five foot shift away from the edge after the stop line was put into place. This is again consistent to the rest of the observed sites.

At this site, the stop line did not appear to have any effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.93, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop line at the same speed they did prior to its placement. Given the times presented in this graph, it is reasonable to assume that the ignores shown in the earlier figure are an artifact of the reduction process rather than a legitimate change.

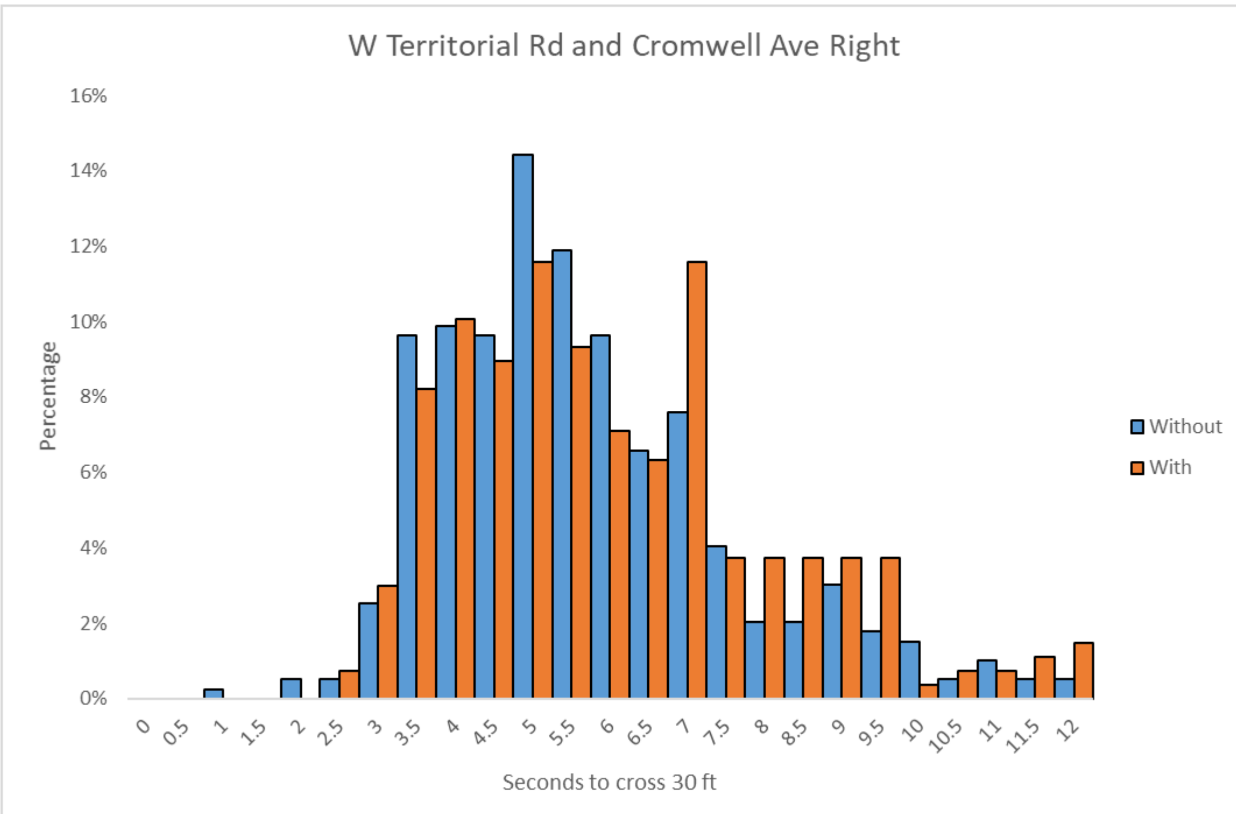

Figure 3.93 W Territorial Rd and Cromwell Ave N (right) Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

3.4.11.2 W Territorial Rd and Cromwell Ave Left/Through Lane

W Territorial Rd's left/through lane did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.94) or broken down by turning movement (Figure 3.95). Ignores during the without stop line period were lower than anticipated, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.97 and discussed below.

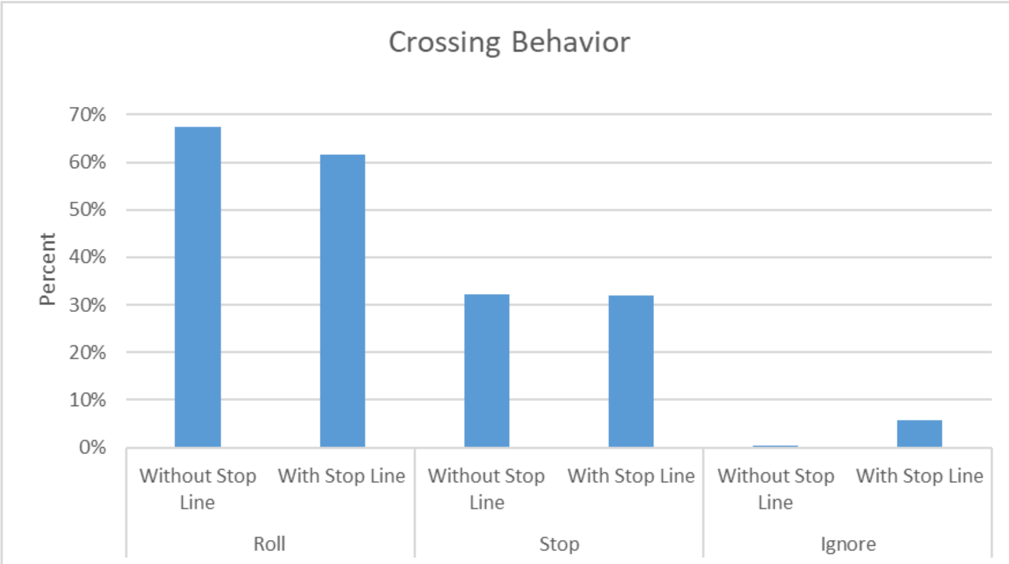

Figure 3.94 W Territorial Rd and Cromwell Ave N (through) distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

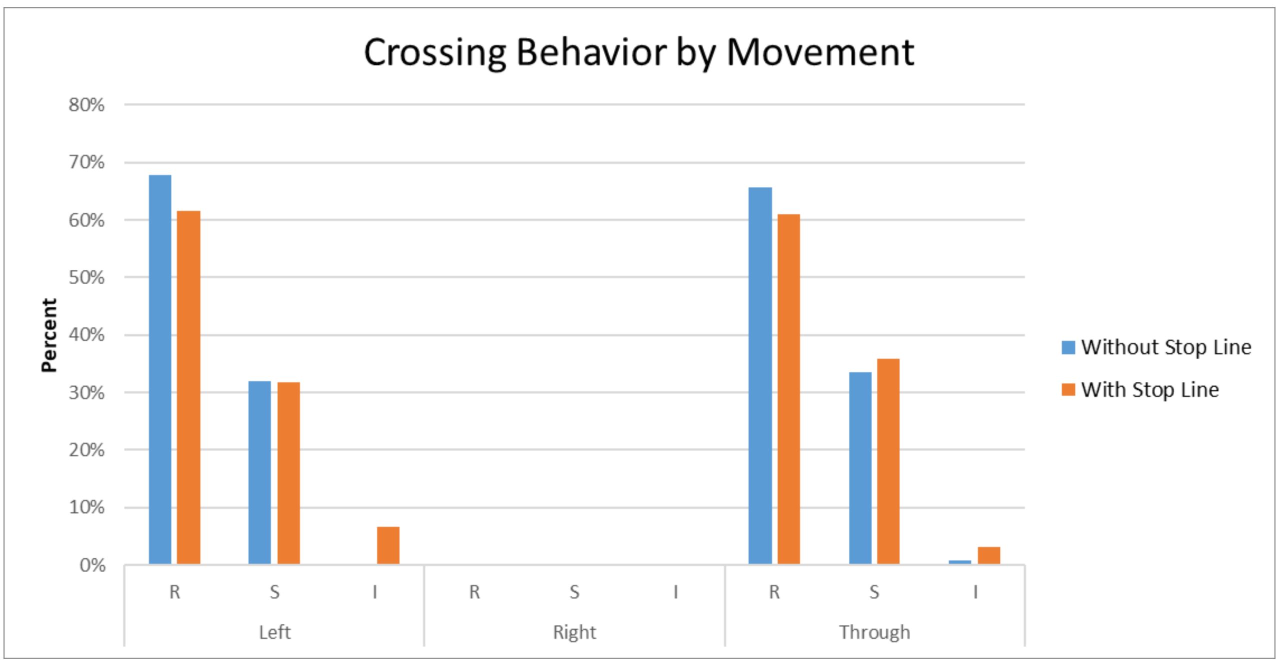

Figure 3.95 W Territorial Rd and Cromwell Ave N (through) distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

As seen in Figure 3.96, 85% of drivers stopped before the curb line without the stop line, and 95% stopped before the curb line with the stop line in place. Before the stop line was painted, 15% of drivers stopped after the curb line, closer to the point of collision. This was reduced to <5% after the stop line was painted. In addition to the decrease in driver stopping with their front wheel in an unsafe place, drivers' stop location shifted roughly five feet away from the center line after the stop line was painted.

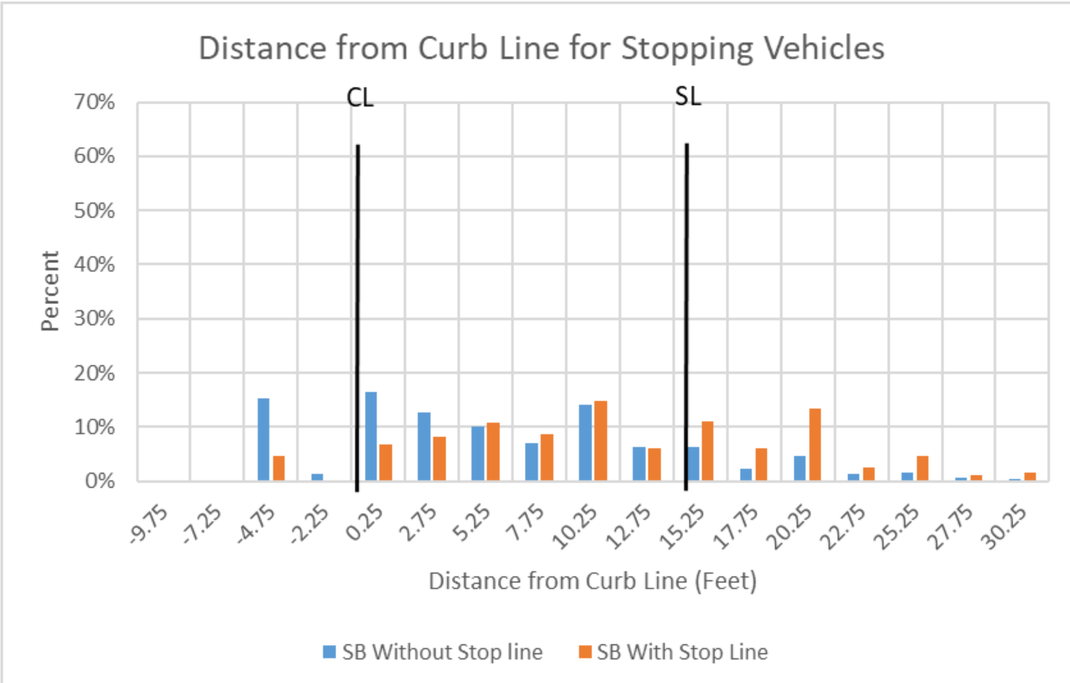

Figure 3.96 W Territorial Rd and Cromwell Ave N (through) Distribution of Stopping Distance During Stop Events

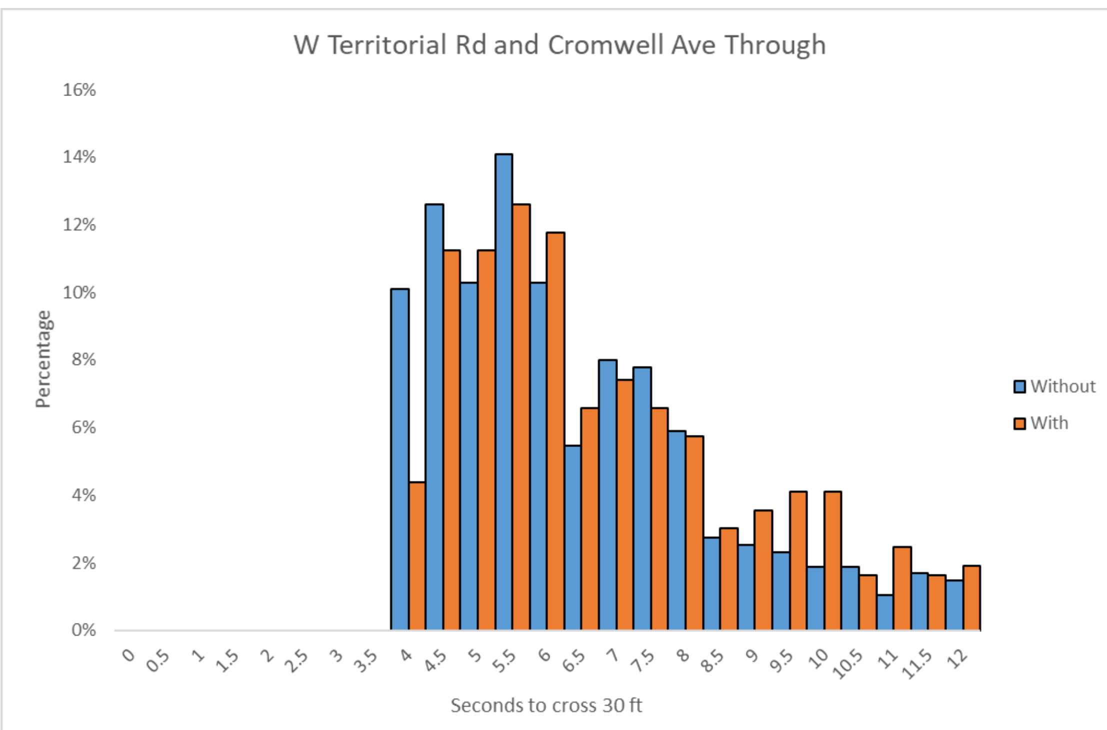

Figure 3.97 W Territorial Rd and Cromwell Ave N (through) Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

At this site, the stop line appears to have only marginal effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.97, the average time to travel 30 feet did not change after the placement of the stop line, although the very short times (higher speeds) were reduced to 1/3 of what they were before the installation of the stop line. This is a consistent observation, supporting the assumption that the stop line prompts drivers to spend more time looking if it is safe to cross.

3.4.12 S280C – Raleigh Ave and W 28th St

The intersection of Raleigh Ave and W 28th St is located in St. Louis Park. Like Portland Ave, Lincoln Dr, and W Territorial Rd, this site had two approaches at the same intersection. Both roads are mainly residential streets with very low ADTs, a major reason why this site was chosen. The actual ADTs of both the uncontrolled (major) and the stopped controlled (minor) approaches are unknown, but the major ADT is estimated at 1000 vehicles based on project counts and the minor ADT is even lower. Sight distance on both sides of the intersection at the stop line was deemed inadequate by the research team (Figure 3.100, Figure 3.105). An aerial view of the site is shown in Figure 3.98.

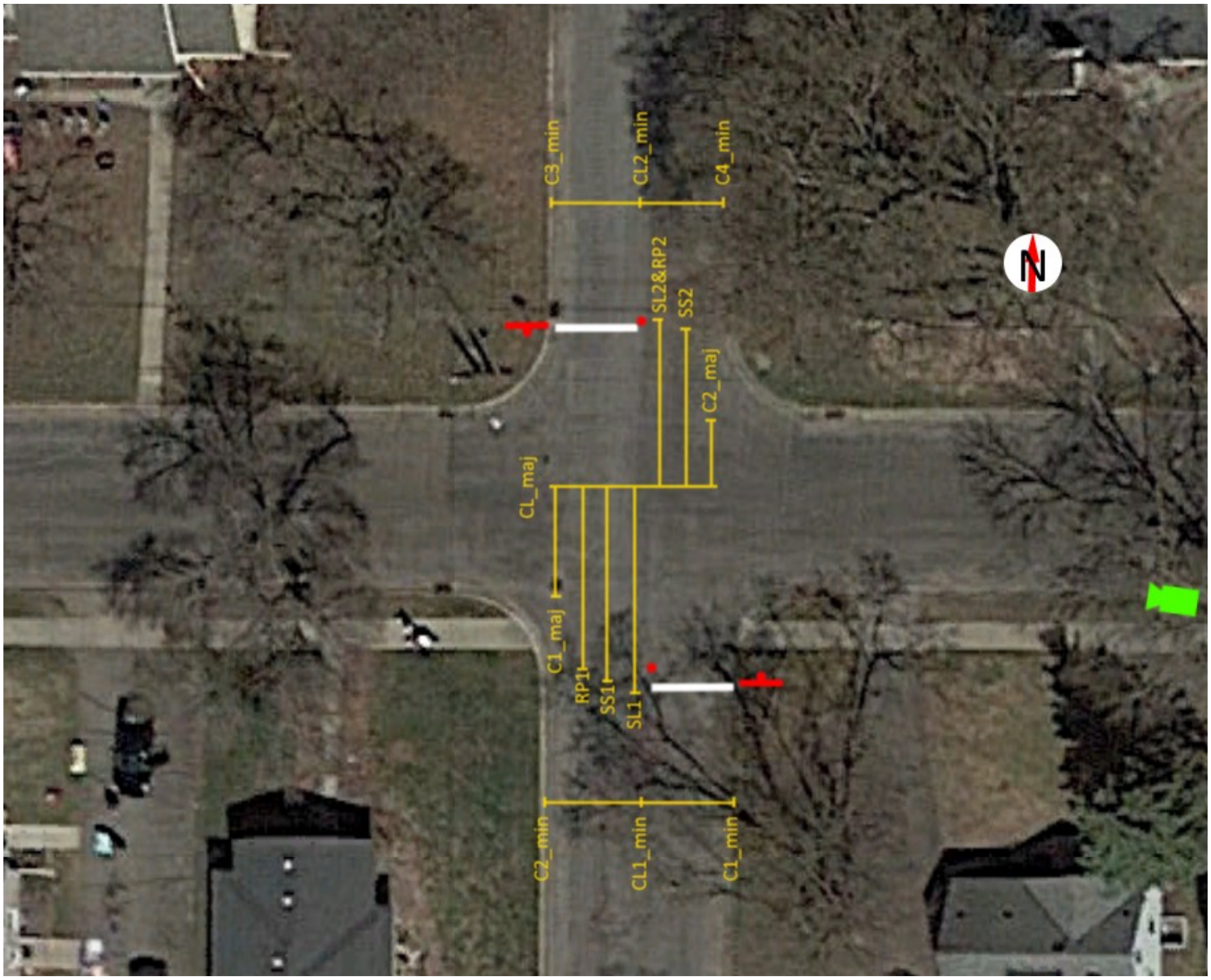

Figure 3.98 Aerial view of the intersection of Raleigh Ave and W 28th St with measurements marked

Measurements noted on Figure 3.98 are listed in Table 3.22.

Table 3.22 Measurements at Raleigh Ave NB and SB

From CL_maj to...	SL1	SS1	RP1	C1_maj	C2_maj	SS2	SL2 & RP2
	29.83	28.66	26.83	15.16	15.33	28.67	30.67
From CL1_min to...	C1_min	C2_min					
	14.42	14.42					
From CL2_min to...	C3_min	C4_min					
	15.00	15.00					

A camera view of both approaches with overlay lines marked is shown in Figure 3.99.

Figure 3.99 Camera view of the intersection of Raleigh Ave and W 28th St with 5-ft overlay lines marked

This site was one of the first to be reduced by UGRAs. On review of the initial results, the research team noted the number of ignore events at this site as abnormally and suspiciously high, which required further investigation. This led to the capture of arrival and departure frames during roll and ignore events at all sites in order to better understand driver behavior. Also, due to the low ADT on the minor road at this site, additional video beyond one day of event logging had to be reduced to not only investigate any potential bias in event logging but also to increase the initially low sample size. After an additional day of both without and with stop line event logging, the sample size was similar to other sites and the team felt comfortable including this intersection in the analysis. The minor approaches are analyzed separately in sections below.

Figure 3.100 Available sight distance and required sight distance at Raleigh Ave and W 28th St NB

3.4.12.1 S280A – Raleigh Ave and W 28th St NB

The sight distance for Raleigh Ave and W 28th St northbound is shown in Figure 3.100. Raleigh Ave northbound did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.101) or broken down by turning movement (Figure 3.102).

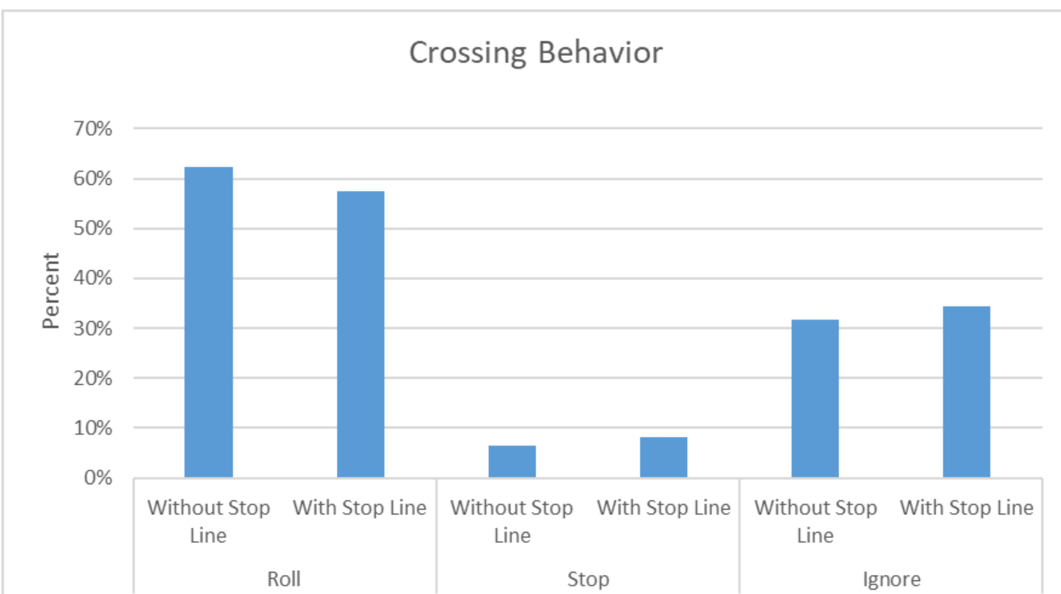

Figure 3.101 Raleigh Ave NB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

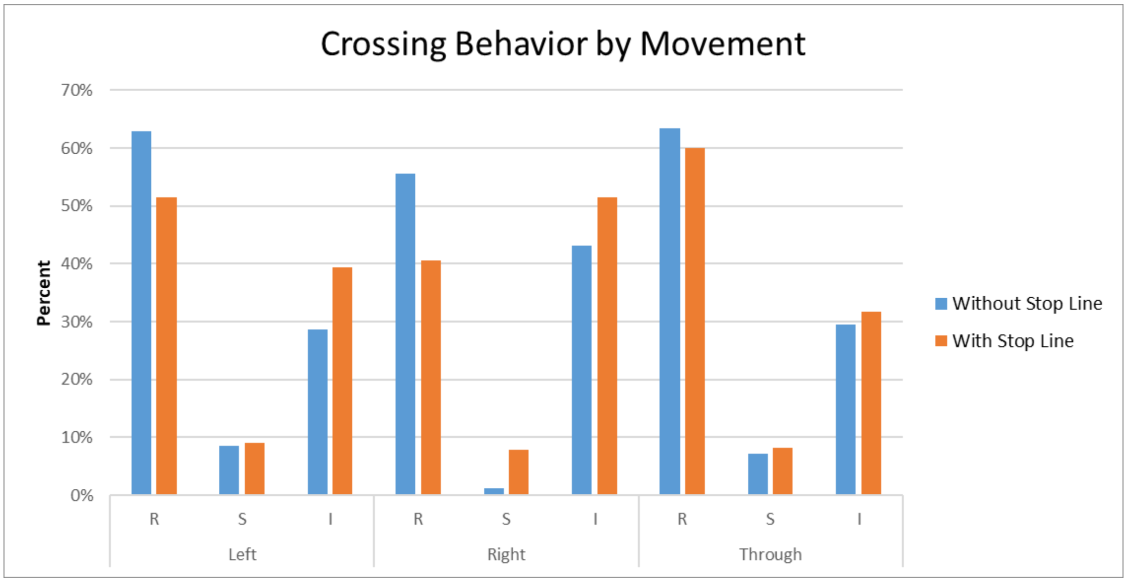

Figure 3.102 Raleigh Ave NB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

Regardless, of the correctness of the differentiation between rolls and ignores, it is evident that only a small fraction of drivers stopped before crossing. For the drivers who stopped, most of them stopped slightly downstream of the stop line or slightly farther into the intersection, as seen in Figure 3.103. The sight distances at the stop line at the NB approach are slightly better than the sight distances at the SB approach, so the stop line appears to be placed appropriately. There was roughly a 3-5 foot shift back in overall stop location after the stop line was added, and overall the distribution looked normal.

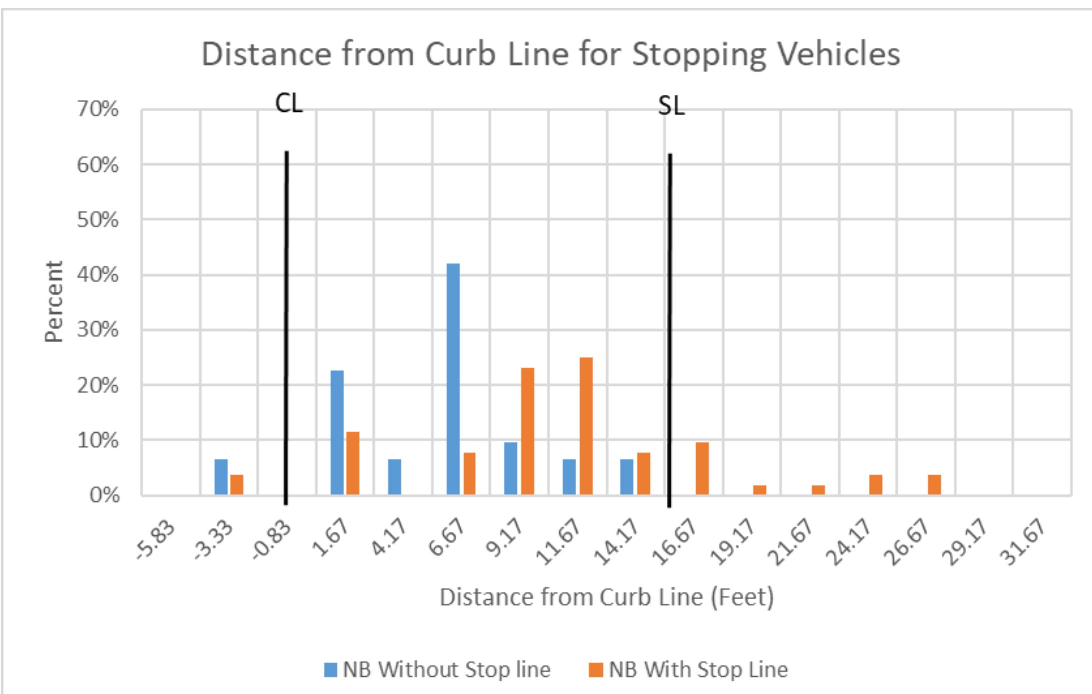

Figure 3.103 Raleigh Ave NB and W 28th St Distribution of Stopping Distance During Stop Events

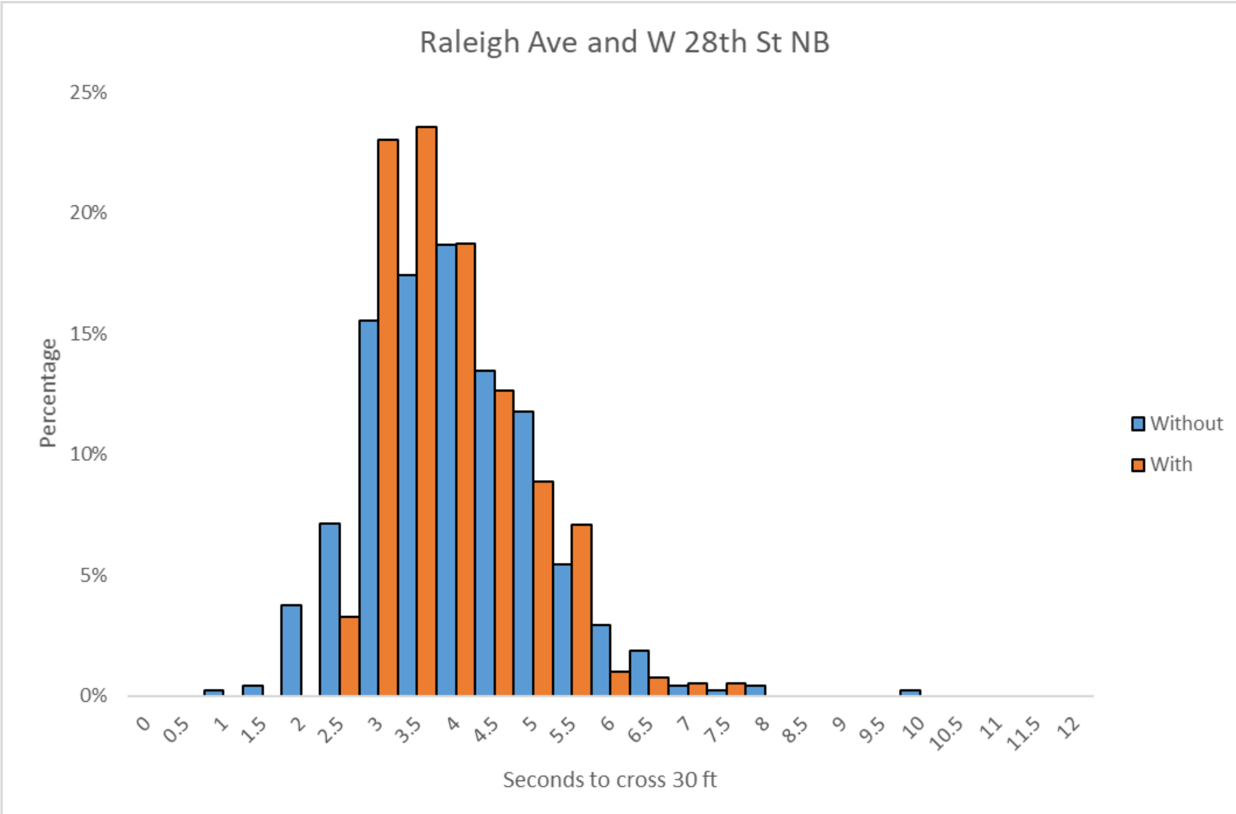

Figure 3.104 Raleigh Ave NB and W 28th St Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

At this intersection, the stop line did not appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.104, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop line at the same speeds as without it.

3.4.12.2 S280B – Raleigh Ave and W 28th St SB

The sight distance for Raleigh Ave and W 28th St southbound is shown in Figure 3.105.

Figure 3.105 Available sight distance and required sight distance at Raleigh Ave and W 28th St SB

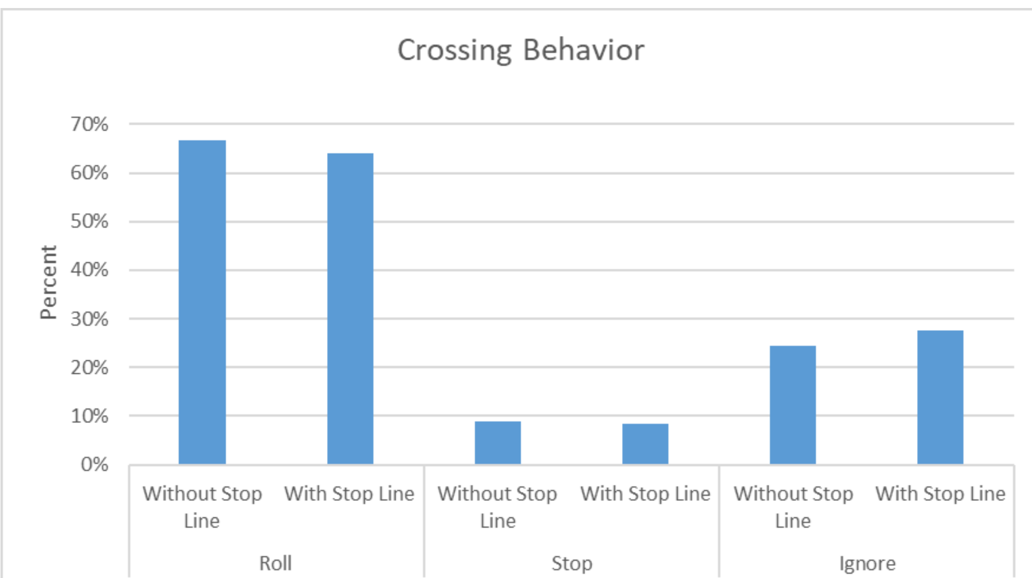

Figure 3.106 Raleigh Ave SB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

Raleigh Ave southbound did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.106) or broken down by turning movement (Figure 3.107). As mentioned previously, ignores were higher than anticipated, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.109 and discussed below.

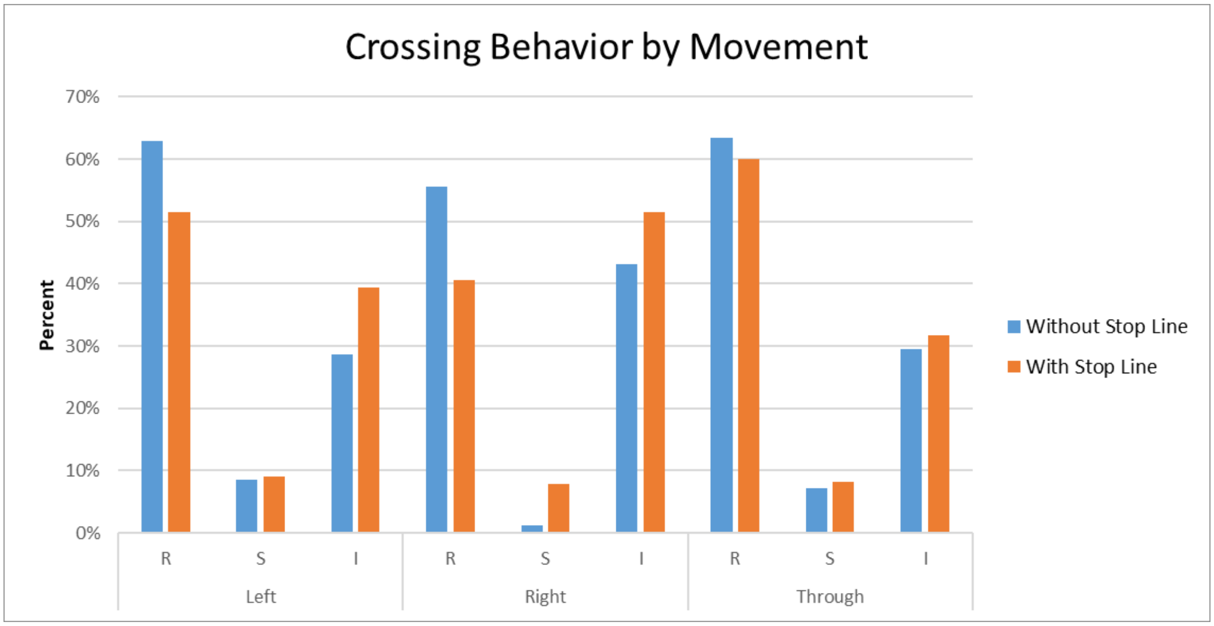

Figure 3.107 Raleigh Ave SB distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

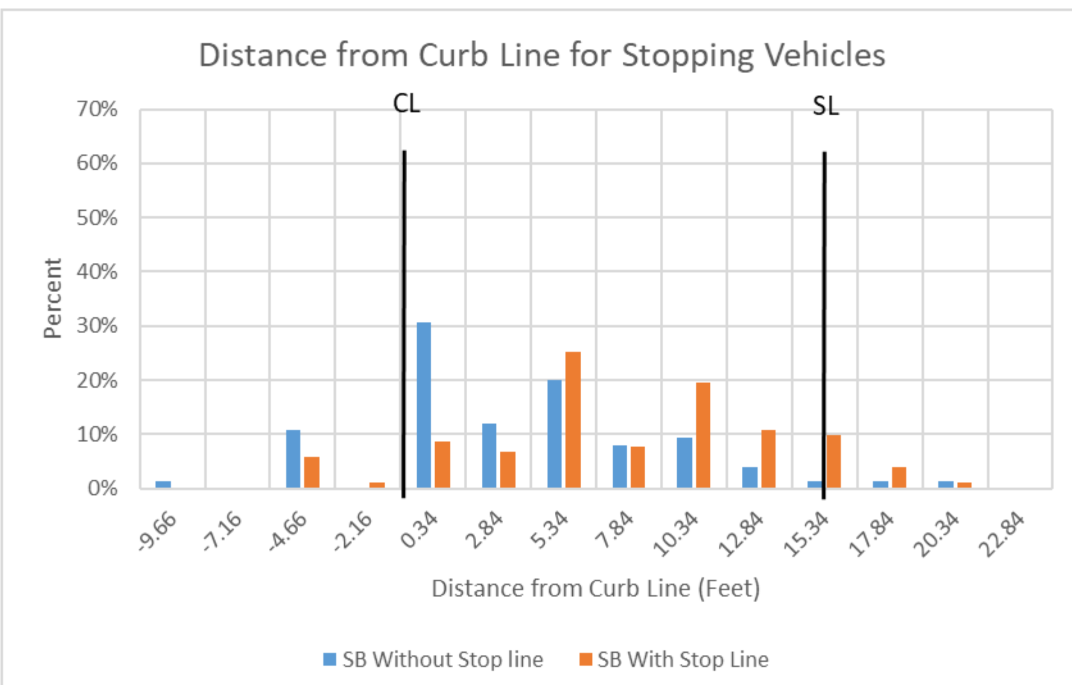

Figure 3.108 Raleigh Ave SB and W 28th St Distribution of Stopping Distance During Stop Events

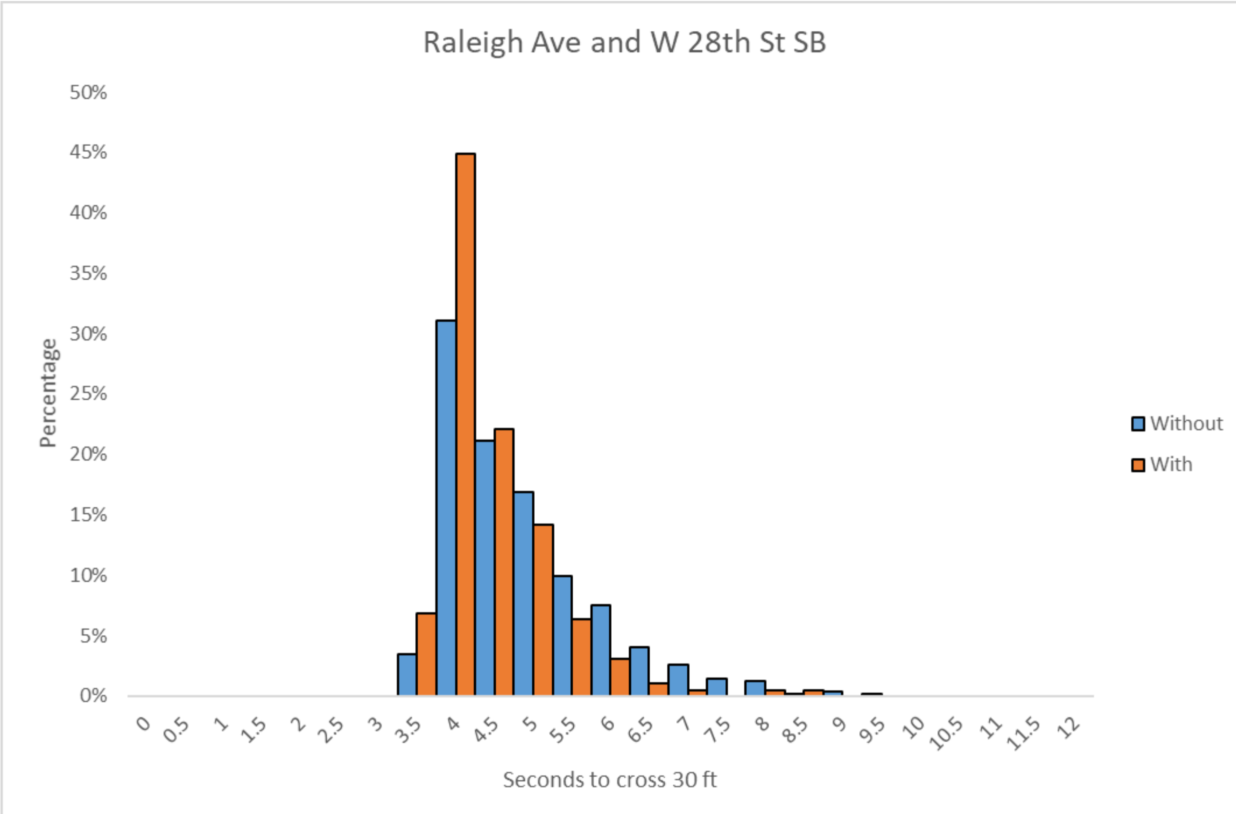

Figure 3.109 Raleigh Ave SB and W 28th St Histogram of Roll and Ignore behaviors, in seconds to travel 30 ft

Most drivers who stopped, stopped between the stop line and curb line, as seen in Figure 3.108. There does appear to be a five foot shift back, toward the stop line, after the stop line was added. The overall distribution of stopping distance remained normal.

At this intersection, the stop line did not appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.109, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop line at the same speeds as without it.

3.4.13 S282O – County Rd C W and Civic Center Dr

County Rd C W and Civic Center Dr is located in Roseville, near the Civic Center. The site was selected because the minor road has wide shoulders and adequate sight distances, the major road has an ADT of 10600 vehicles, two through lanes, two turning lanes, a median, and wide shoulders, and the stop sign and stop line are located over 30 feet from the fogline of the major road. Sight distance to the right is unobstructed, but sight distance to the left is obstructed due to signage (Figure 3.112). An aerial view of the site is shown in Figure 3.110.

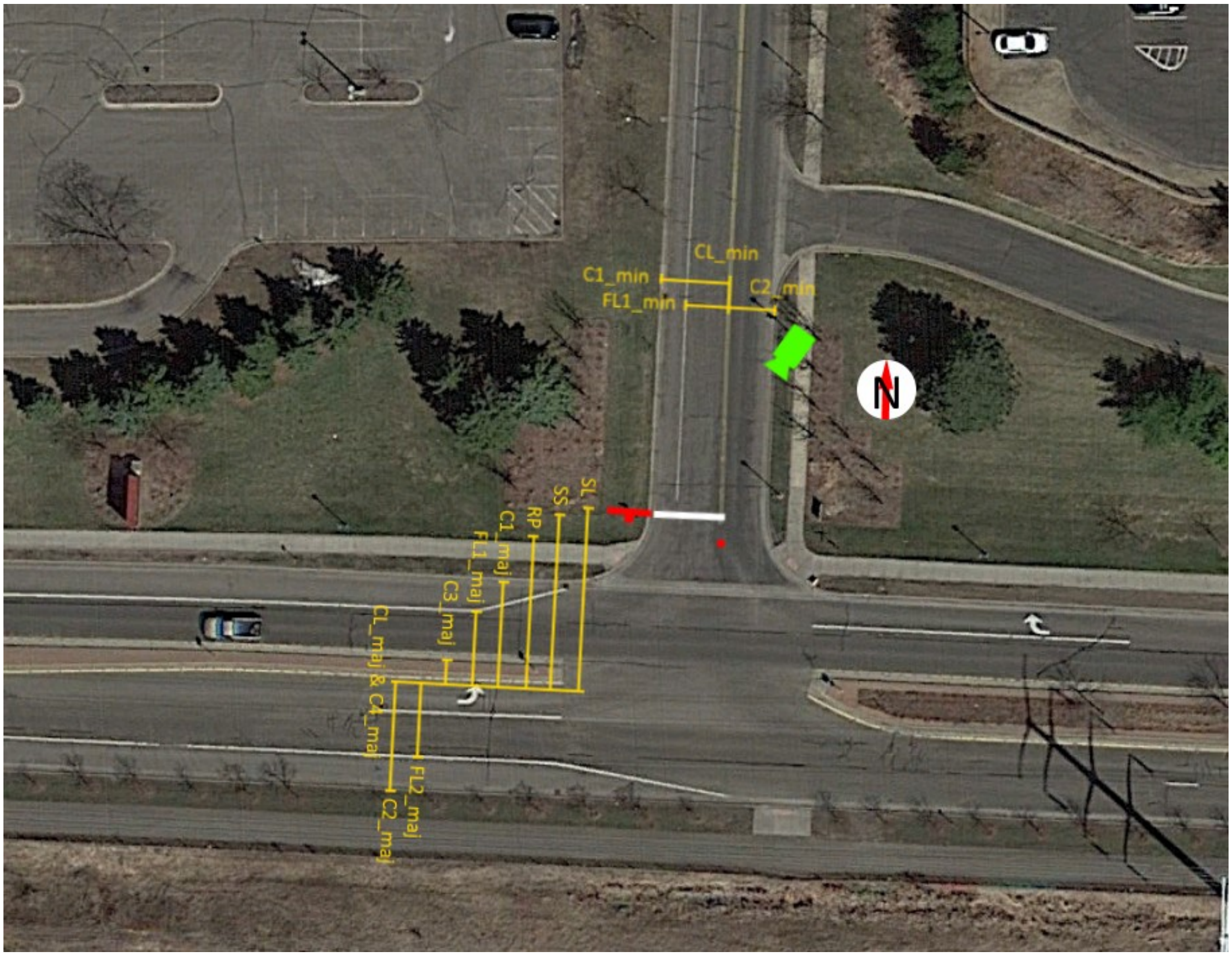

Figure 3.110 Aerial view of the intersection of County Rd C W and Civic Center Dr with measurements marked

Measurements marked in Figure 3.110 are shown in Table 3.23.

Table 3.23 Relevant measurements at County Rd C W in feet

From CL_maj to...	**SL**	**SS**	**RP**	**C1_maj**	**FL1_maj**	**C3_maj**	
	52.00	51.00	41.75	30.00	20.08	5.00	
From CL_maj to...	**C4_maj**	**FL2_maj**	**C2_maj**				
	0.00	25.08	36.25				
From CL_min to...	**C1_min**	**FL1_min**	**C2_min**				
	17.92	10.34	17.92				

A camera view with overlay lines marked is shown in Figure 3.111.

Figure 3.111 Camera view of the intersection of County Rd C W and Civic Center Dr with 5-ft overlay lines marked

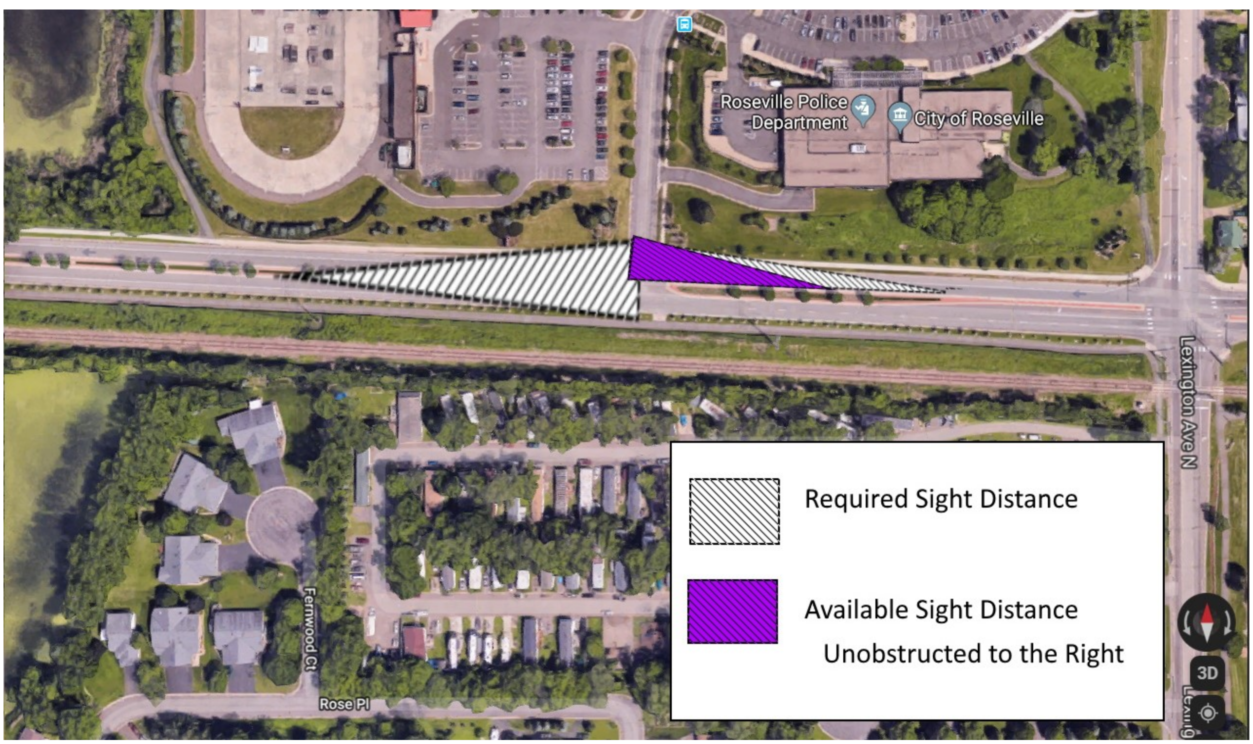

Figure 3.112 Available sight distance and required sight distance at County Rd C W and Civic Center Dr

County Rd C W did not see a change in either the absolute percentage or ratio of driver behavior overall (Figure 3.113) or broken down by turning movement (Figure 3.114). Ignores were lower than anticipated, which as with other sites led the research team to record and analyze arrival and departure frames, presented in Figure 3.116 and discussed below.

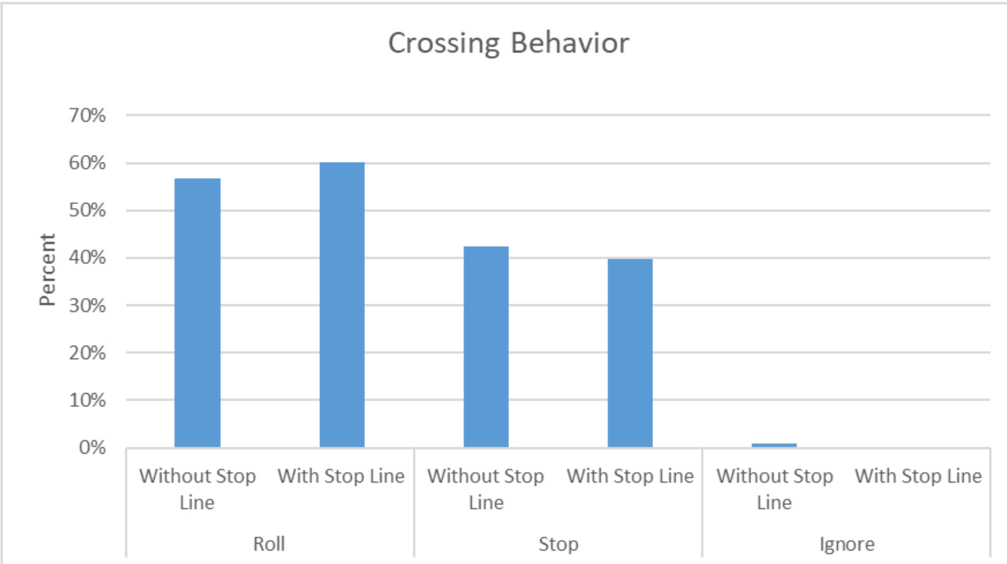

Figure 3.113 County Rd C W and Civic Center Dr distribution of driver crossing behavior as a percentage of all events without- vs with-stop line

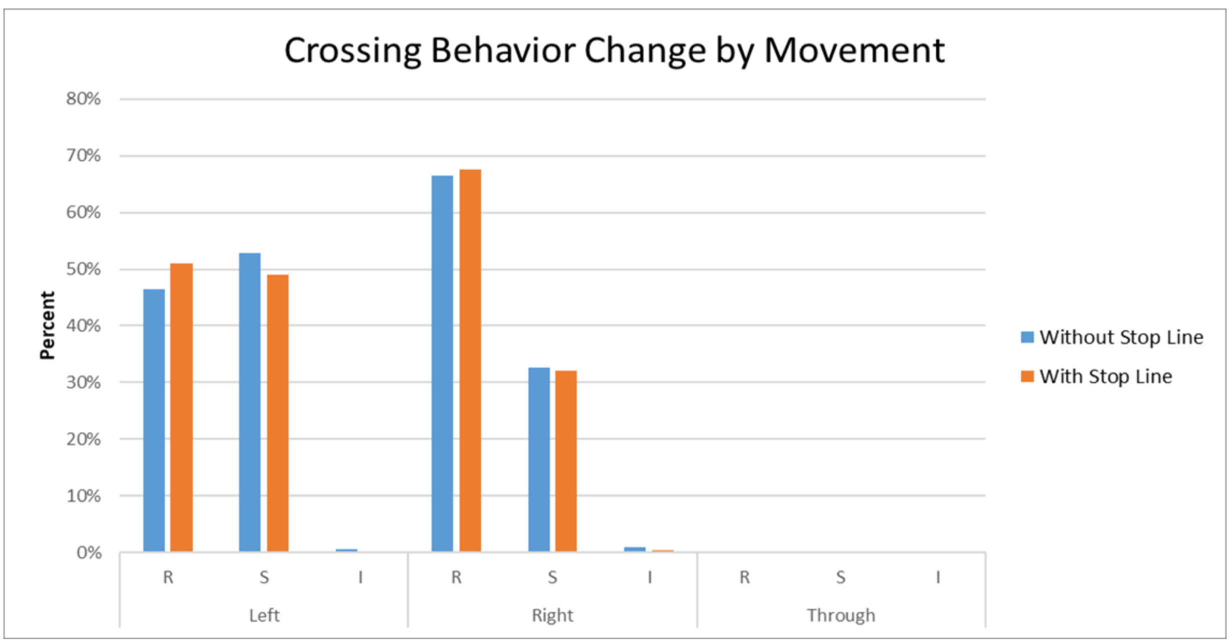

Figure 3.114 County Rd C W and Civic Center Dr distribution of driver crossing behavior as a percentage of all events without- vs with-stop line, by driver movement

At this site, all drivers stopped before the fog line, or point of collision, both without and with the stop line. The majority of drivers stopped between the stop line and the curb line. The distribution of stop locations both with and without the stop line appear normal with no significant shift, as seen in Figure 3.115.

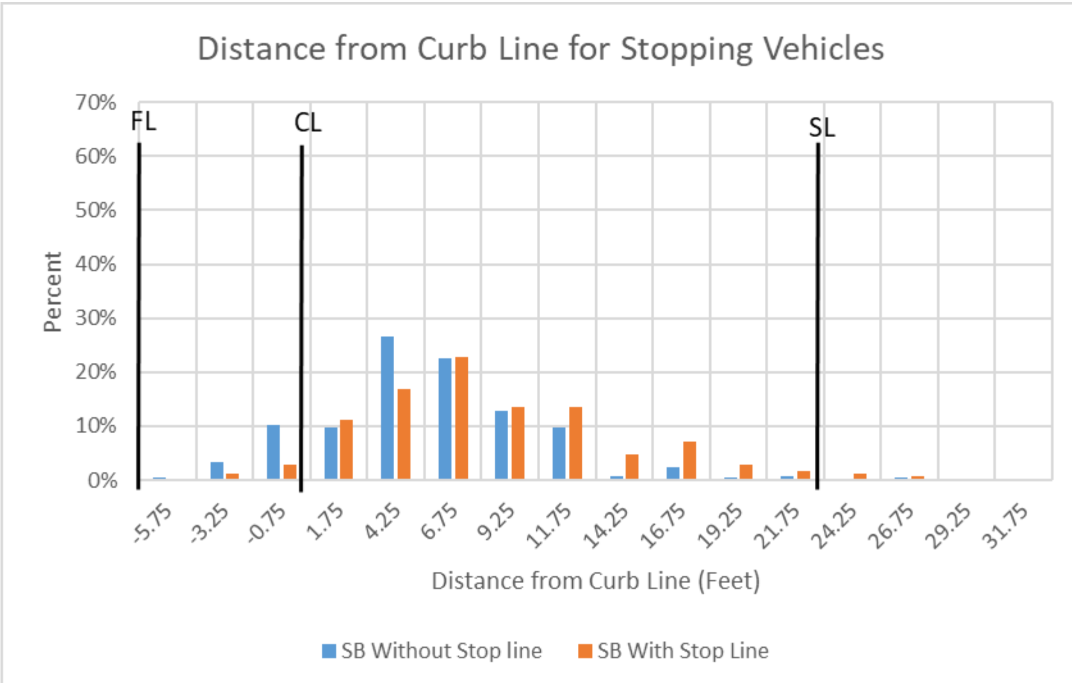

Figure 3.115 County Rd C W and Civic Center Dr Distribution of Stopping Distance during Stop Events

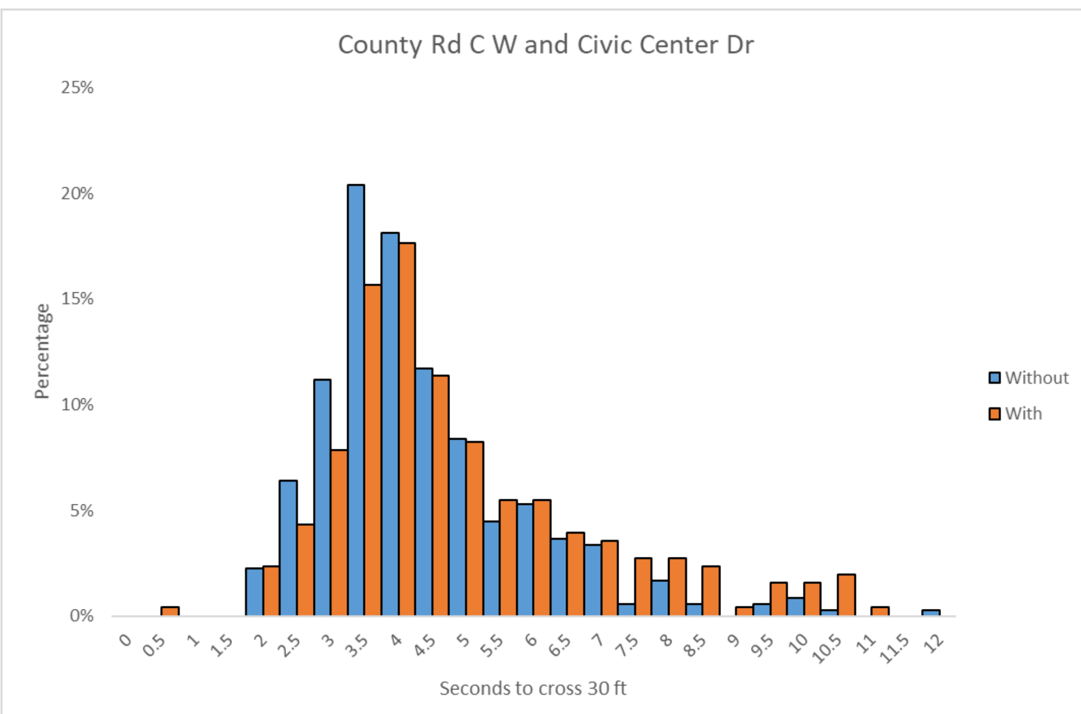

Figure 3.116 County Rd C W and Civic Center Dr Histogram of Roll and Ignore behaviors, (sec over 30ft)

At this intersection, the stop line did not appear to have an effect on drivers who rolled through or ignored the stop sign. As seen in Figure 3.109, the average time to travel 30 feet did not change after the placement of the stop line, meaning drivers are continuing to roll through or ignore the stop line at the same speeds as without it.

This site seems to support the assumption produced by the analysis of the observations from the intersection of Warner Rd and Fish Hatchery Rd; that when the distance of the stop line from the perceived edge of the conflicting driving lane is so large the stop line is irrelevant. Like on the previous site, upstream of the intersection, on the major approach we see a right only turn lane that generates an oversized shoulder lane downstream of the closest conflict point. Drivers see this obvious geometry that provides more than 15 feet of additional safety and completely ignore the stop line.

3.5 COMBINED OBSERVATIONS FROM ALL SITES

In this section figures summarizing the study observations overall on all sites are presented. Specifically, there are two types of graphs. The first set is comprised by two box-plot graphs of stop location distances from the curb line, separating sites between 4-leg (acting) interstions and T (acting) intersections. The box plot (a.k.a. box and whisker diagram) is a standardized way of displaying the distribution of data based on the five summary numbers: minimum, first quartile, median, third quartile, and maximum, with the dots marking outliers. The second set of graphs, combines all the overall, left, right, and through turning movement crossing behavior changes from all sites.

3.5.1 All Sites Stop Location Distances

Figure 3.117 and Figure 3.118 present the 4-way and T acting intersections. The graphs are oriented with the stop-controlled traffic moving from top to bottom, with the stop line (after install) marked with a solid horizontal black line. In most cases this is also the location of the stop sign. The bottom of the graph is towards the center of the major road.

A first, obvious observation is that, on all cases, both before and after the implementation of the stop lines, the drivers always stopped 10 feet or more after the line and/or sign. As mentioned earlier, the more space there is between the stop line and the edge of the conflicting driving lane, the more drivers ignore the stop line. Out of total 16 test sites, 7 exhibited a positive change, meaning that drivers started stopping closer to the stop line after it was installed. Still over it but less. At least three sites showed no significant change. From the remaining 6 sites on which the drivers exhibited a counter behavior, meaning they started to stop even farther than before, three had crosswalks, two had considerable distance between the stop line and the conflicting lane, and the remaining one (Lyndale Ave) has very bad sight distance to the right.

In the majority of cases, we can observe that the presence of the stop line resulted in fewer outliers, meaning the stop location of the drivers that did stop, reduced in variability. This observation is more evident on 4-way intersections on which it is also observed that the forward (closer to the edge) outliers were considerably reduced or eliminated. At T-intersections we observe the same but in a less pronounced way.

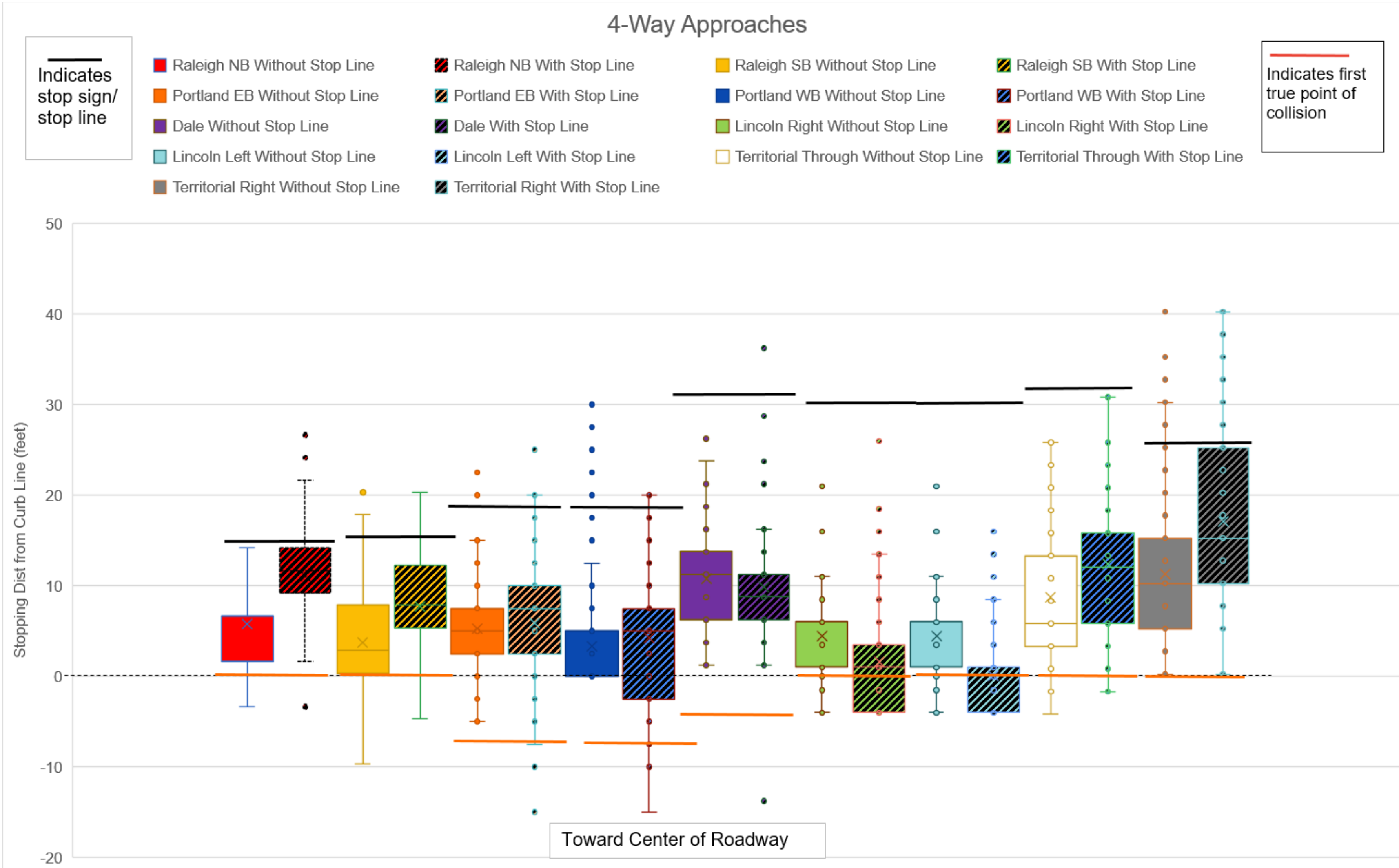

Figure 3.117 Overall Stop Location Distances on 4-way intersections

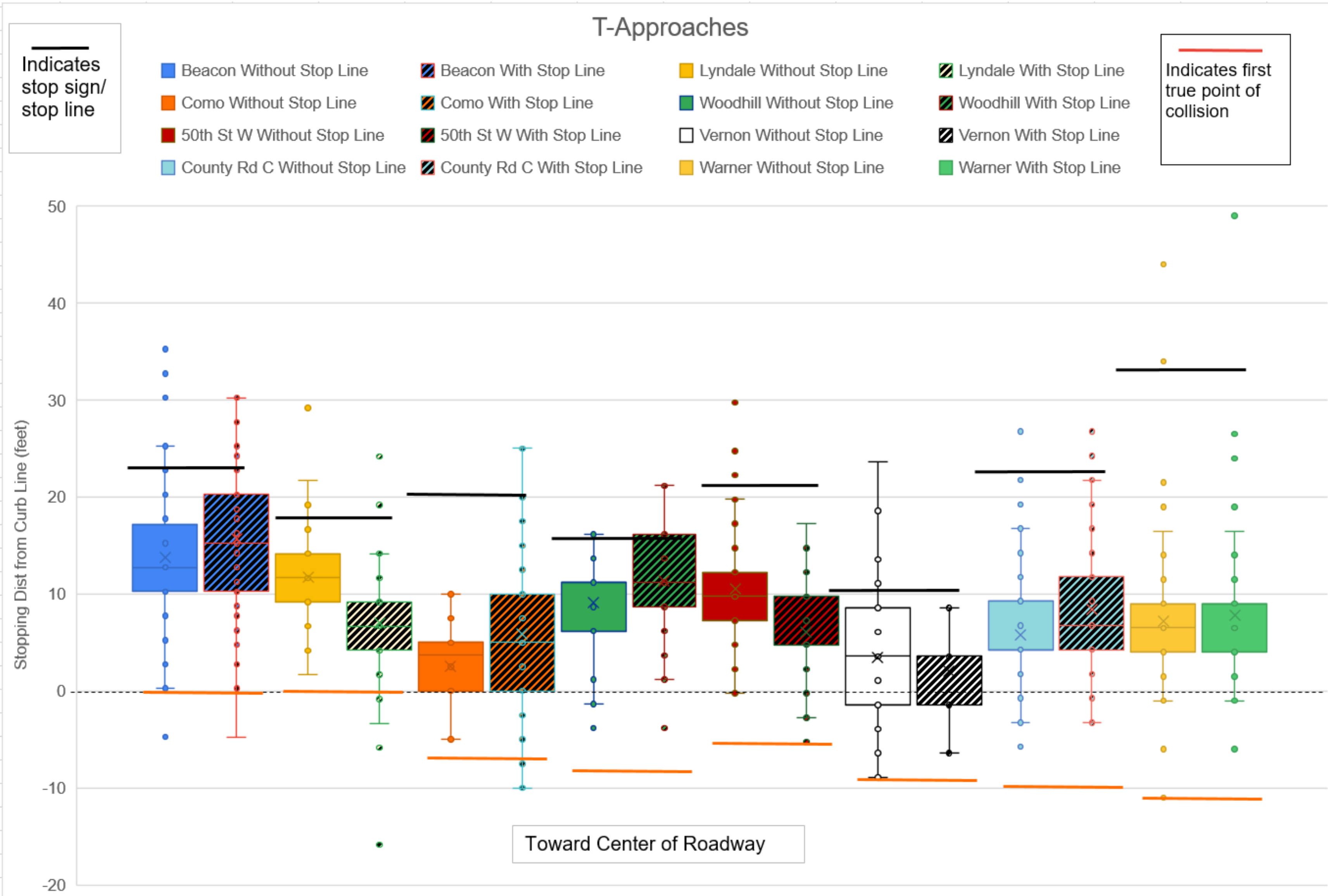

Figure 3.118 Overall Stop Location Distances on T intersections

3.5.2 Differences in Driver Behavior and Turning Movements

Figure 3.119 presents the crossing behavior of driver in terms of stop, roll, or ignore, on all sites overall. From this graph we see that, overall on most sites the implementation of the stop lines did not change the crossing behavior in a significant way. Exceptions to this are seen on the right end of the graph, where the two lanes of Lincoln Dr and Lydia Ave are shown. On that two-lane approach there seems to be a significant shift towards stopping instead of rolling. Note that, as mentioned in the previous section, this is also one of the intersections where the drivers started stopping farther away from the stop line or stop sign. It is clear that there is some strong interplay and influence between the crosswalk and the stop line. The second site with a crosswalk, 50th St and Eden on the overall graph doesn't exhibit significant change in behavior.

The remaining three figures, Figure 3.120, Figure 3.121, and Figure 3.122 each present the crossing behavior of driver on all sites separately on the Left, Right, and Through movements respectively. On the left-turning movements, most of the sites has unremarkable changes. Notable is the case of Como and Knapp where the stops increased by more than 10% as well as the Left lane of Lincoln Dr where we see an increase in stop behavior of approximately 20%**.** On the Right Turning movements, again most sites have changes of less than 10% with the exception of Dale and Iona where after the stop line was implemented, there was a shift towards rolls of more than 15% and on Lincoln Dr with an increase in stops of greater than 20%. As discussed earlier this could be the result of a combination of inadequate sight distances, more than a full vehicle length of safe space downstream of the stop line, and the low volume of Dale St drivers, with increased confidence, roll over the stop line looking for a better sight distance, encounter no conflicting traffic and keep rolling while without the stop line they were approaching the curb line with less confidence and stopped although there was no conflicting traffic. Further investigation that could separate the cases where there was conflicting traffic and look at them separately may resolve this mystery. The thru movements are generally unremarkable except for the left lane of Lincoln Dr where thru movements match in behavior the left and the right in improving crossing behavior by almost 20%.

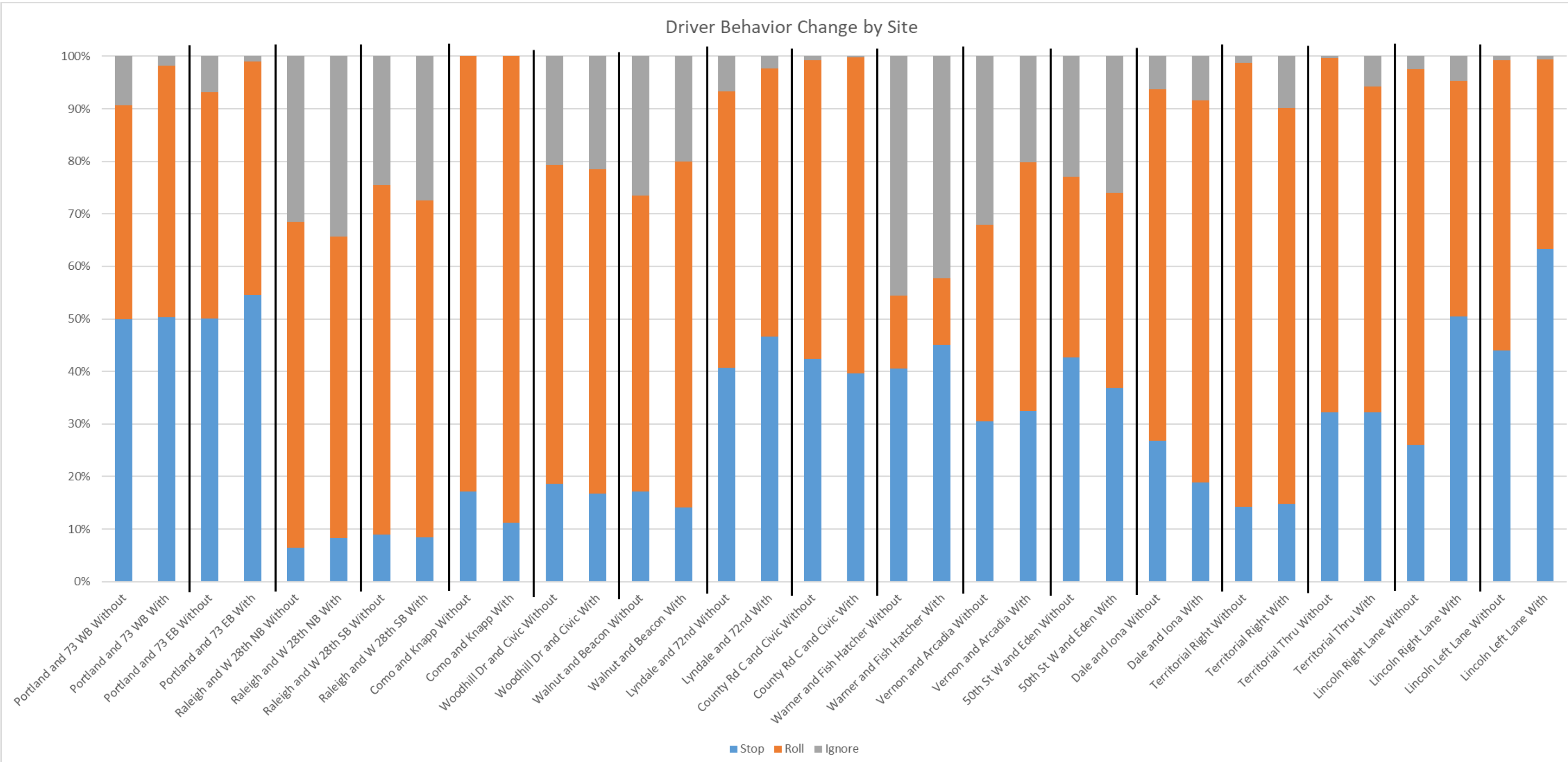

Figure 3.119 Overall Crossing Behaviors before and after the Stop Line installation

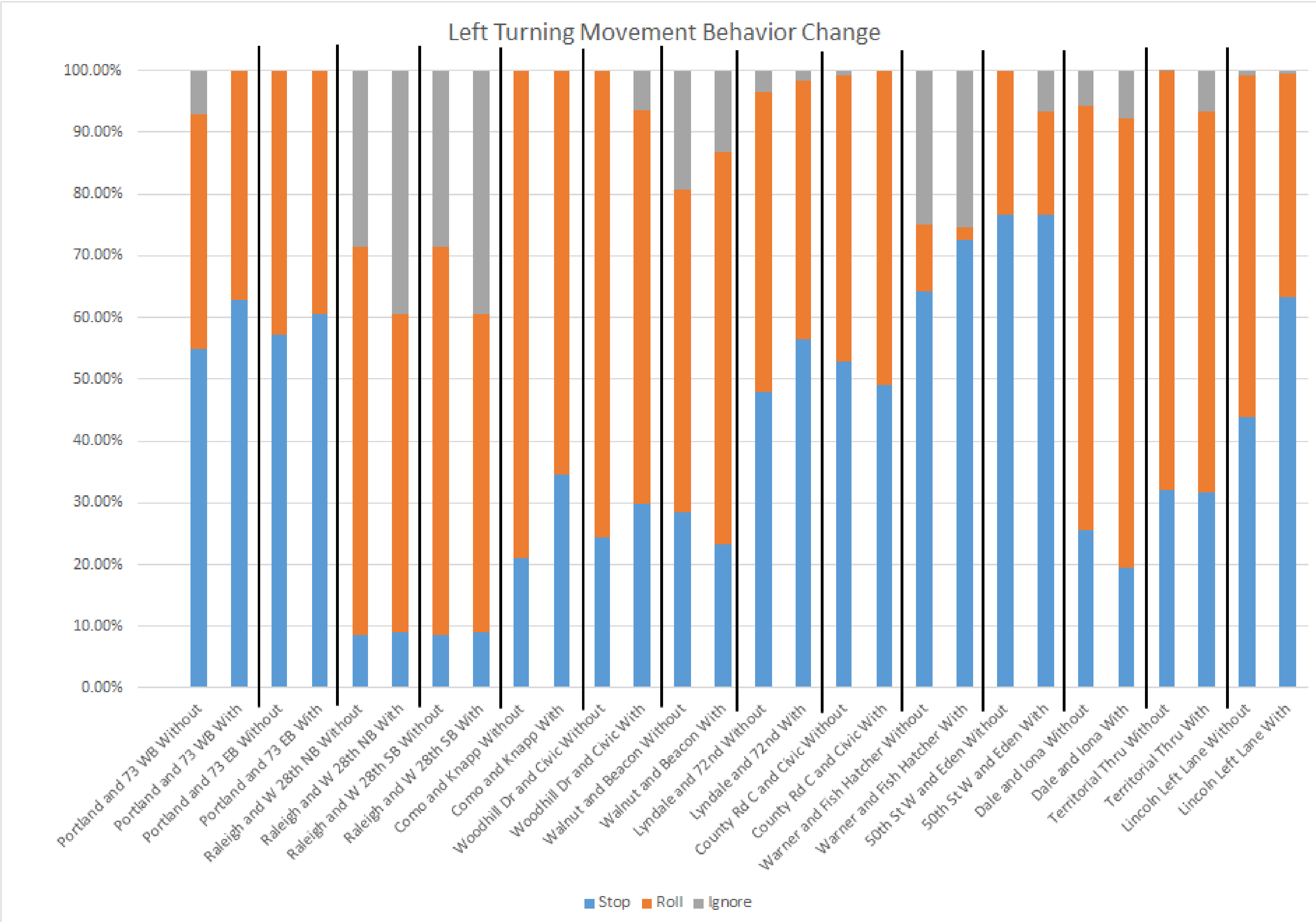

Figure 3.120 Left Turning Movement Crossing Behaviors before and after the Stop Line installation

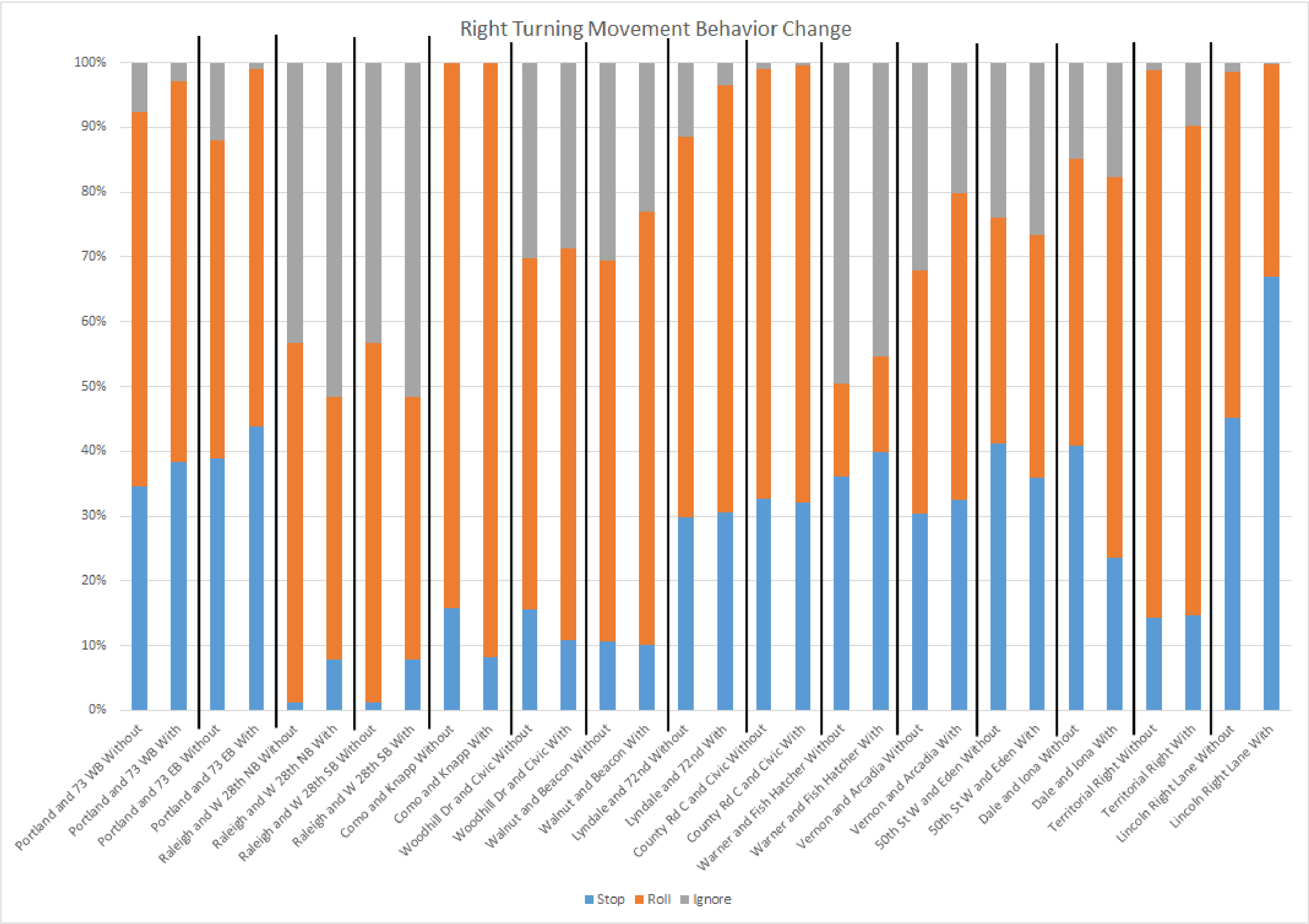

Figure 3.121 Right Turning Movement Crossing Behaviors before and after the Stop Line installation

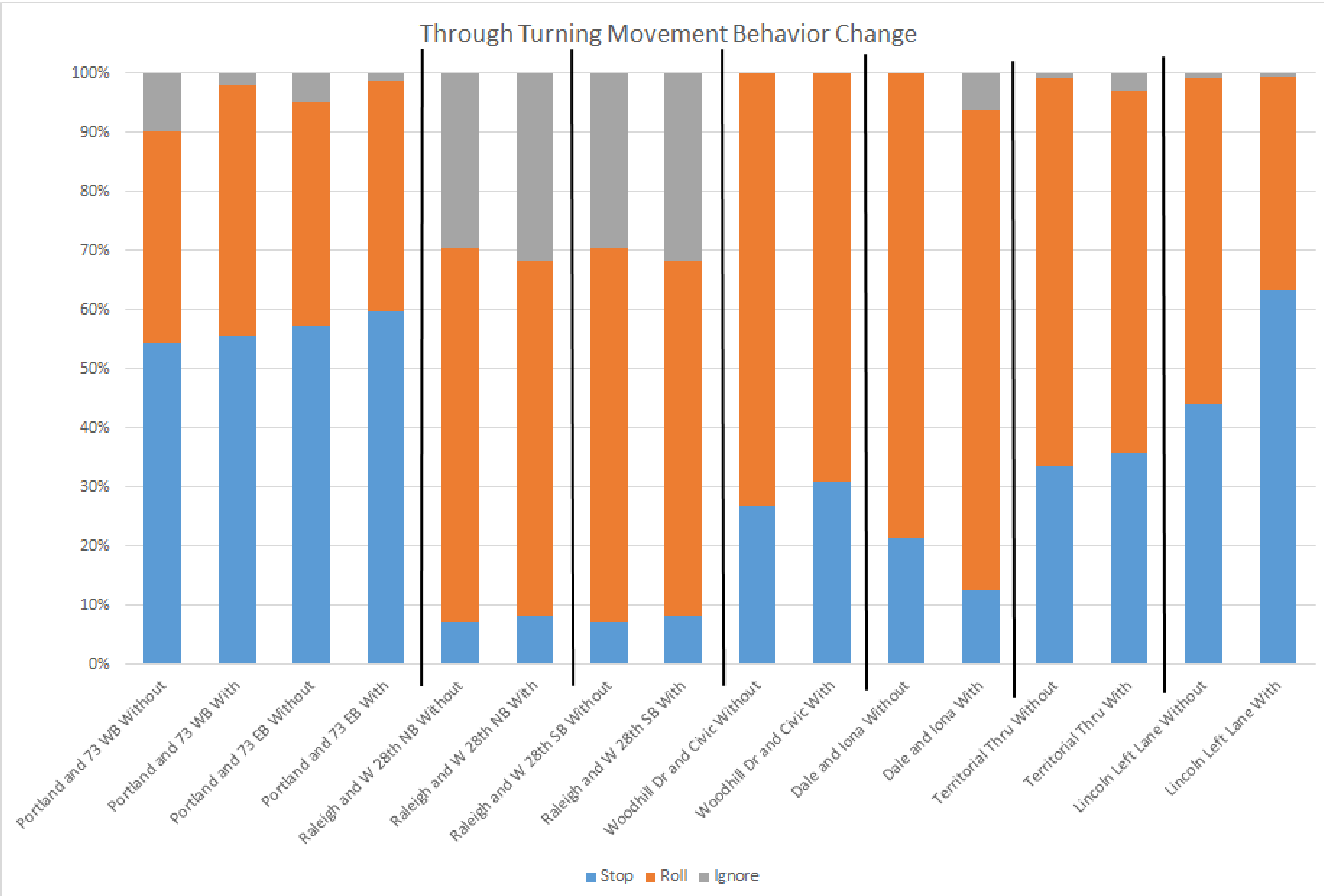

Figure 3.122 Through Movement Crossing Behaviors before and after the Stop Line installation

CHAPTER 4: CONCLUSIONS

This project had two parallel research efforts attempting to determine the effect of stop lines: a cross sectional safety study and an observational study. The safety study was developed to address stop lines' effects on crashes. The observational study was developed to determine if stop lines have an effect on driver behavior at intersections and to look at where drivers were stopping. Three primary questions and related sub-questions drove the decision to follow this study format:

- Do stop lines have an impact on crashes?
- Do stop lines have an effect on overall driver behavior?
    - Do stop lines impact the number of drivers rolling, stopping or ignoring the stop sign?
    - Are there substantial numbers of drivers ignoring the stop sign?
        - Are they an extension of the general behavior or a separate population?
        - How does the presence of a stop line alter the above?
    - Does the ratio of rolls to stops change after the placement of the stop line?
    - Is the crossing behavior different among the three major turning movements?
    - Did the crossing speed among drivers rolling or ignoring the stop sign change with the placement of a stop line?
- Do stop lines affect where drivers are stopping, if they stop?
    - Did the distribution of stopping distances change?
    - Where were the most drivers stopping before the stop line was added, and did the stop line appear to impact that location?

4.1 CROSS-SECTIONAL SAFETY STUDY

The safety study's scope covered only five cities that were able to provide comprehensive GIS maps of all stop-controlled intersections within city limits: Edina, Roseville, Richfield, St. Louis Park, and Golden Valley. Several different types of safety studies were considered, but due to the limitation of available information, a cross sectional safety study format was chosen. Cross-sectional analyses using the observational database described in

Table 2.1 were used to determine whether there was a reliable association between the presence of stop lines and the occurrence of relevant crashes. If such an association was found, then future work using more rigorous designs would be needed to determine if there was a causal relation between stop lines and crash risk. On the other hand, if no association was found then a causal connection was unlikely.

Ideally, analyses should be based on crashes where stop line relevant configurations have been explicitly identified but such identification was difficult from the crash coding used in the Minnesota crash database prior to 2017, which results in ambiguities regarding the actual crash type. Resolving these ambiguities has, in the past, usually required manual review of the drawings and narratives provided by investigating officers. For this exploratory research it was decided to conduct separates analyses for T-intersection and 4-legged intersection approaches, using both right-angle crashes only and right-angle plus turn crashes as measures.

Using T-intersections as an example, there was a maximum of 14,548 approach-years of data available, but some data were missing for some variables; 13,769 rows were missing minor approach ADTs, leaving a very poor sample size in regard to this variable. Looking at the crash totals, the overwhelming majority of approach-years showed no reported crashes, with only one reported crash being the next most frequent outcome. This was especially true when we considered specific crash types like right-angle or left-turn. Of the 14,548 approach-years of data available, 14,106 showed no right-angle crashes, 401 showed one right-angle crash, 41 showed between two and five crashes, and none showed more than five crashes. The fraction of cases with one crash was 0.0275 and the fraction of cases with more than one crash was only 0.0028. In situations like this, where probability of one crash is approximately equal to the probability of one or more crashes, a reasonable approximation was to model crash outcomes as binary, with the outcomes being zero crashes or one for one or more crashes.

Section 2.6 describes the results of the cross-sectional safety study in detail. When used as the only predictor, the presence of a stop line showed no association with crash occurrence, but a negative association occasionally occurred when other predictors were added to a model. This was often the case when the presence of a crosswalk was included in the model. Unfortunately, the lack of reliable data on the minor approaches prevented us from reliably decoupling the effects between stop lines and crosswalks. The suggestion that the presence of crosswalks is associated with increases in the likelihood of crashes requires further investigation. Overall, the influence of the presence of a stop line on crash frequency was at best weak and influenced greatly by the surrounding environment.

We did see a rather puzzling association between right-side sight distance and crash occurrence at T-intersections and with left-side sight distance on 4-legged intersections, which could merit more detailed investigation. There was some difficulty in reliably identifying relevant crashes from the available crash codes. Beginning in 2017, the Minnesota Department of Public Safety instituted a new coding system that should resolve some of these issues, and it would probably be useful to repeat these analyses once several years of data using the new system become available.

4.2 OBSERVATIONAL FIELD STUDY

As per the work plan, the research team solicited the help of the TAP in identifying stop-controlled intersections for the field study. Edina provided several intersections of concern. The research team also identified several sites to investigate from their familiarity with certain areas around the Twin Cities. Other methods employed by the research team included a survey sent out to TAP members and city and county engineers throughout Minnesota, analysis of MnCMAT crash records statewide, and analysis of city and county maintanace records looking for recent mill/overlay projects that didn’t restore stop lines on the minor approaches. The survey asked the recipients to give the location of an intersection – either via the interactive map or by giving the coordinates – where stop lines were added or removed. Unfortunately, as indicated by the recepients, very rarely has such information been recorded so the survey didn't provide any uselful information. Unfortunately, no intersections had more than two crashes and fewer than 10 had two crashes. Additionally, many of the sites returned in the list of 100 crashes from the intersections with the most crashes have been since signalized. As a result, the crash record method was also deemed insufficient in providing suggested sites for the field study. The discussions with road maintenance departments provided some good insights enhanced with informal interviews with local police departments mainly in the metro region.

Sixty-eight candidate sites were considered for video collection, from which 23 approaches at 16 intersections were selected for video collection. The 23 included an all-way-stop intersection in Roseville, which was not reduced because of the pressing time schedule. Sites were selected in such a way as to give a variety of combinations of site characteristics. Particular emphasis was placed on selecting sites with a variety of left and right available sight distances, the angle at which the major and minor road met, the major road speed limit, AADT of the major and minor roads, presence of traffic islands, number of lanes, and number of approaches at the intersection. Sites with a history of crashes were prioritized and any site without a pole or tree on which to brace a camera was excluded from the list. In the end, as summarized in Table 3.3, out of the 23 approaches where video was collected, 16 were finally used for the main analysis. Nicolet Ave and 68th in Richfield was excluded because road construction did not conclude in time to allow for the after video collection.

Quentin Ave and W 28th St. was included in the video collection process following locals' reports that stop sign compliance was worse than at the nearby Raleigh Ave and W 28th St. However, a stop line was not painted at this site due to budget constraints and the site's geometric similarity to the Raleigh Ave. site. Following a fatal crash at this intersection, and upon request by a member of the TAP, a partial analysis for Quentin Ave. was accomplished and is included as Appendix C.

Chapter 3 covers the results on each site in great detail. In these conclusions, we present some highlights and the overall findings. A first, obvious observation is that, in all cases, both before and after the implementation of the stop lines, the drivers always stopped 10 feet or more after the stop line and/or sign. A relatively consistent observation was that, the more space there was between the stop line and the absolute edge of the conflicting driving lane the more drivers ignored the stop line. Out of a total of 16 test sites, 7 exhibited a positive change, meaning that drivers started stopping closer to the stop line after it was installed. Still over it but less. At least three (3) sites showed no significant change. From the remaining 6 sites on which the drivers exhibited a counter behavior, meaning they started to stop even farther than before, three (3) had crosswalks, two (2) had considerable distance between the stop line and the conflicting lane, and the remaining one (Lyndale Ave) had a very bad sight distance to the right and a large distance between the stop sign and the edge of the conflicting lane.

It is interesting that both sites with crosswalks exhibited the same patterns that differ from the norm. In these sites, drivers stopped from a lot more forward to in extreme cases where they encroached on the major road conflicting lane. The other three sites that exhibited similar patterns all had a considerably long safe space between the stop line and the edge. In a counterintuitive way on the crosswalk sites, the presence of the stop line exaggerated the negative behavior. From these observations, we can say that the potential influence that crosswalks have on safety, as suggested by the safety study, as well as the interplay with the stop lines, were supported by the field observations. Further, analysis was justified to uncover these relationships. Regardless, the negative trend of the stop location on these intersections, both a large increase of vehicles stopping instead of rolling and a clear reduction in rolling speed, was also observed after the stop lines were installed. We consider these improvements much more encouraging than the push forward stop location was discouraging.

In the majority of cases, we can observe that the presence of the stop line resulted in fewer outliers, meaning the stop location of the drivers who did stop was reduced in variability. This observation was more evident on 4-way intersections on which it was also observed that the forward (closer to the edge) outliers were considerably reduced or eliminated. On T-intersections we observed the same but in a less pronounced way.

The presence of the stop line also reduced the roll speed for vehicles that didn't come to a full stop. Although we used the term ignored to describe the cases where the vehicle didn't display any visible deceleration in its approach to the intersection, the observation was highly subjective. The measurement of the travel time over the last 30 feet before the conflict point was a less subjective metric. Using that, in most cases, the extreme high speeds (low decelerations) were greatly reduced. In the few worst cases, the stop line had no positive or negative effect.

4.3 RECOMMENDATIONS

This report serves as a comprehensive look at stop lines' effectiveness in increasing the safety of intersections. Our hope is that it will serve as a reference for planners and engineers when considering placement of a stop line at one or many intersections. Our recommendations are based on the knowledge acquired regarding the three main questions of the project:

DO STOP LINES HAVE AN IMPACT ON CRASHES?

Based on the results of the safety study, there is no evidence supporting that the presence of a stop line has a significant independent impact on crashes. Specifically, in the case of intersections with four or more approaches, even when other contributing factors are controlled for, there is no statistically significant association between the presence of a stop line and crash occurrence.

In the case of T-intersections, still there is no evidence supporting that the presence of a stop line has a significant independent impact on crash occurrence. Regardless, when the analysis controls for the effect of exposure, through AADT on the major road, we see that stop lines display a marginally significant beneficial effect, meaning that the presence of a stop line is associated with a decrease in the probability of a crash.

A similar combined influence is also observed in the case of painted crosswalks, where it seems that the painted crosswalk increases the probability of a crash. Unfortunately, the sample population is not large enough to explore this with certainty especially because of the lack of AADT information on the minor approach.

In conclusion, we do not see the use of stop lines as an effective intervention to improve the safety of TWSC intersections.

DO STOP LINES HAVE AN EFFECT ON OVERALL DRIVER BEHAVIOR?

From the observational study, a number of results suggest that stop lines do influence driver behavior. Unfortunately, the influence is rarely the desired one and only in specific ways is it beneficial. Therefore, practitioners are advised to explore the contributing factors and aspects of the driving behavior they would like to influence before defaulting to implementation of a stop line at a a particular intersection.

Although there was no significant effect observed between the presence of a stop line and the decision of drivers to come to a complete stop instead of performing a “rolling” stop, the presence of the stop line reduced the roll speed for vehicles that didn’t come to a full stop. In most cases, the extreme high speeds (low decelerations) were greatly reduced. In the few worst cases, the stop line had no positive or negative effect.

Therefore, in cases where sight distances are challenging, or more time is needed to detect a conflicting vehicle approaching (busy background, horizontal or vertical curves on the major road, etc.) implementing a stop line may be a beneficial intervention. Still, avoid placing the stop line too far from the boundary of the nearest conflicting lane.

DO STOP LINES AFFECT WHERE DRIVERS ARE STOPPING, IF THEY STOP?

The answer to this question is yes but not always in a good way. It is important to clarify that, with or without the presence of a stop line, in all cases, drivers stopped 10 feet or more after the stop line and/or sign. In fact, when there is a stop line present, the more space there is between the stop line and the absolute edge of the conflicting driving lane the more drivers ignore the stop line.

For this reason, we do not consider the use of stop lines to be an effective way to prompt drivers to stop at an appropriate location or distance from the major road lanes. In fact, if on a particular approach, there is already a painted crosswalk, the use of a stop line should be avoided.

In addition, if there are other visual cues indicating the boundary of the major road’s closest driving lane (pavement markings and seams, asphalt or concrete color, etc.), placing the stop line more than 10 feet upstream may result in drivers stopping even closer to the conflicting lane. Therefore, painting stop lines less than 10 feet from the conflicting lanes should be avoided.

A practice that makes the above cases very common is the habit of painting the stop lines at the same location as the stop sign. In many cases, due to the presence of a sidewalk or curvature of the curb, the stop sign is located much more than 10 feet from the boundary of the nearest conflicting lane. The aforementioned practice results in a negative impact, in terms of stop location.

4.4 FUTURE WORK

The project collected a large amount of high-quality data that can support further analysis. Unfortunately, limitations in time and budget did not allow us to explore all possible uses for these data. Regardless, the additional data collected at the field sites involving the state of traffic on the major road as the vehicle on the minor approaches, and others, are being used in an exploratory regression analysis. If the results become available before the final publication deadline of this report, they will be added. Otherwise, we will deliver them to the TAP in the form of a white paper.

Finally, more work needs to be done in locating and including the ADT of the minor road in the safety analysis as well as the use of the new and better crash records format.

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APPENDIX A
IDENTIFICATION AND ASSIGNMENT OF APPROACHES

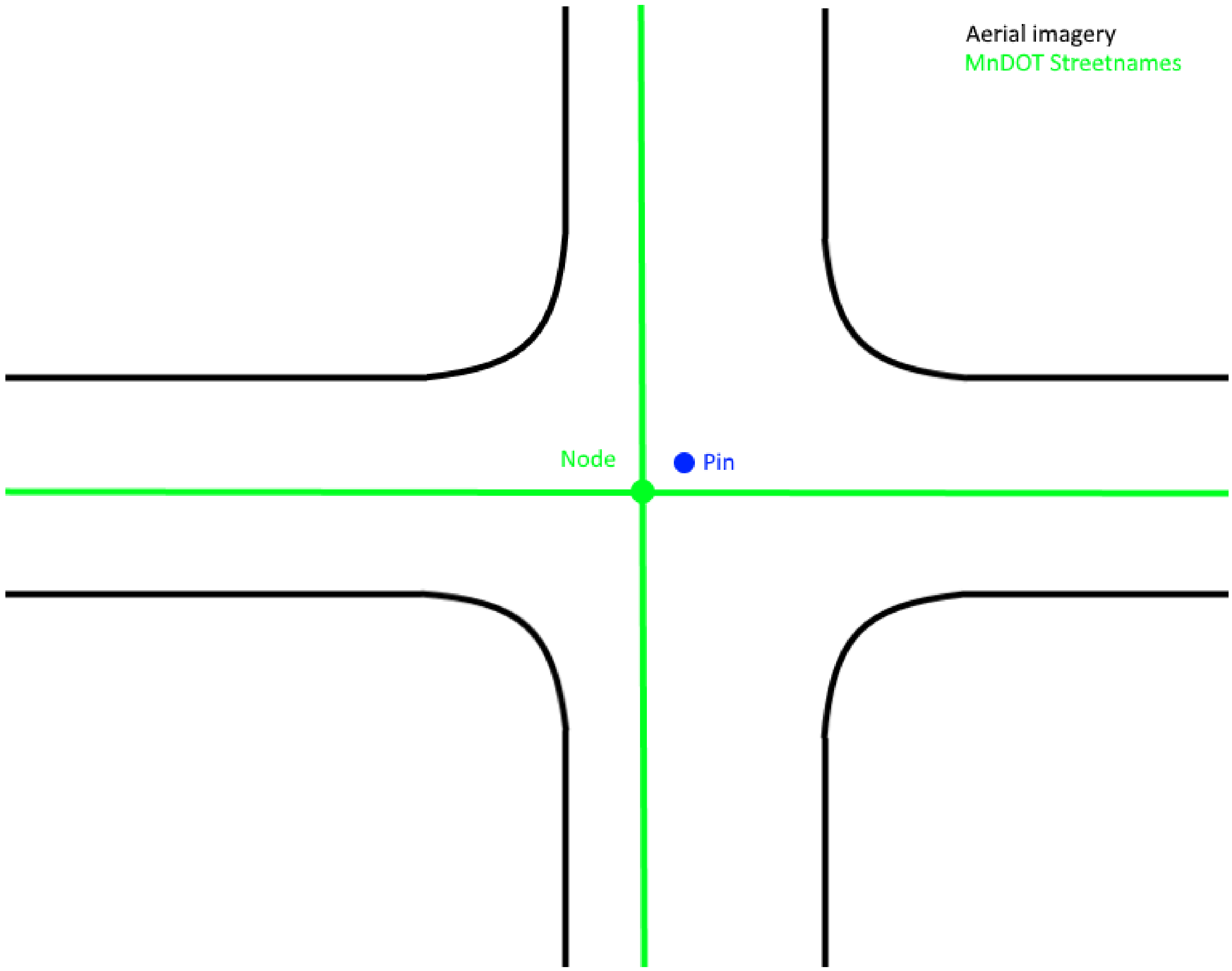


Figure A-0.1 Identification and assignment of approaches – Step 1

Approach identification and assignment begins by importing a list of pins corresponding to the center of the intersection as shown in the Google My Maps aerial imagery. The pins are plotted on the MnGeo aerial imagery. The MnDOT Streetnames layer is then overlaid on top of the aerial imagery. The intersection of the polylines (AKA "the intersection node") is found by returning all polylines within 20m of the intersection pin and finding an endpoint shared by all of the returned polylines. If not all polylines share and endpoint, more than four polylines are found, or fewer than two polylines are found, all minor approaches at the intersection are flagged for further review.

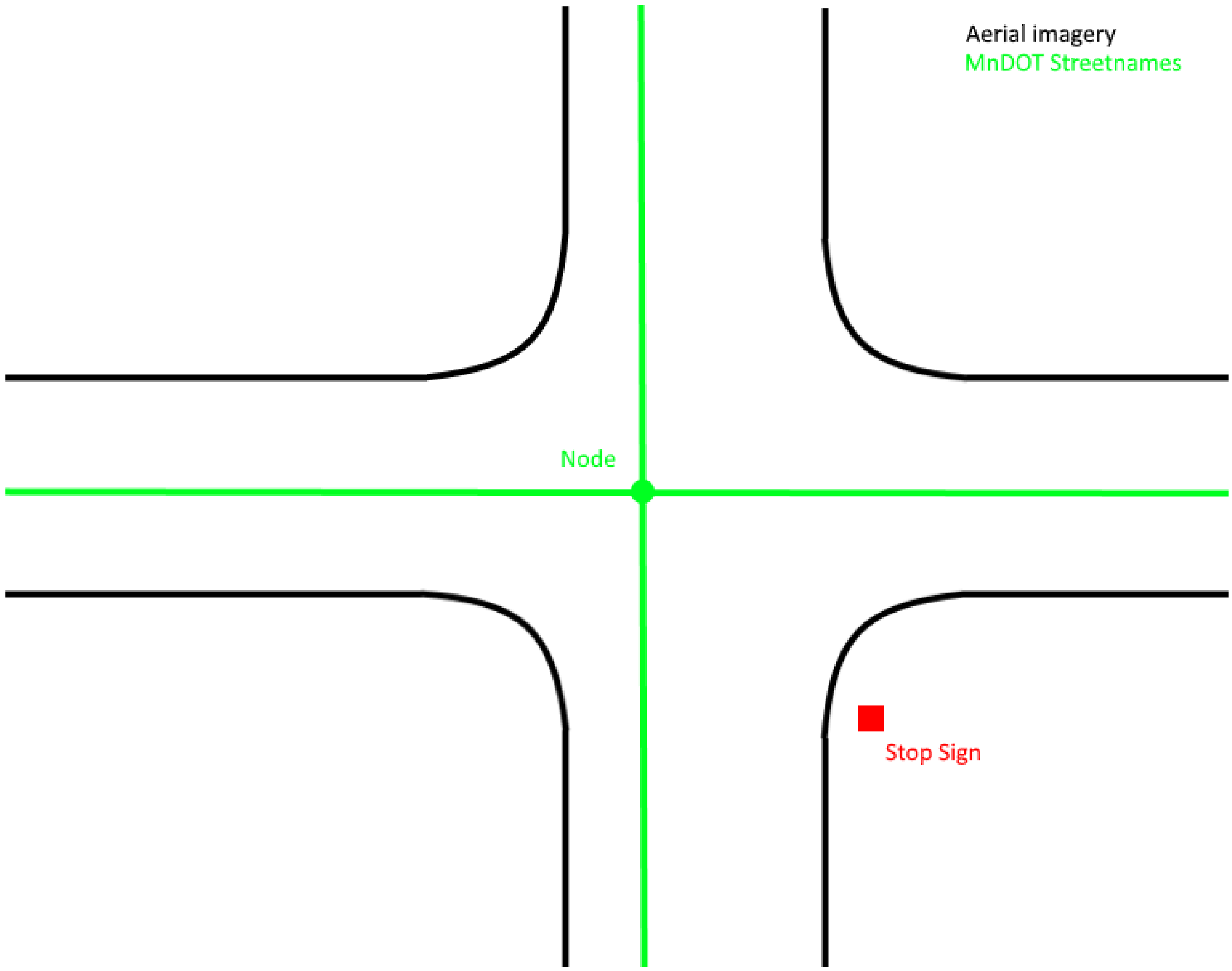


Figure A-0.2 Identification and assignment of approaches – Step 2

The layer containing all stop sign markers is then queried to find all stop signs within 20m of the intersection node. If no stop signs are found or more than two stop signs are found, all of the minor approaches are flagged for manual review. The following steps are followed iteratively for each stop sign identified at the intersection.

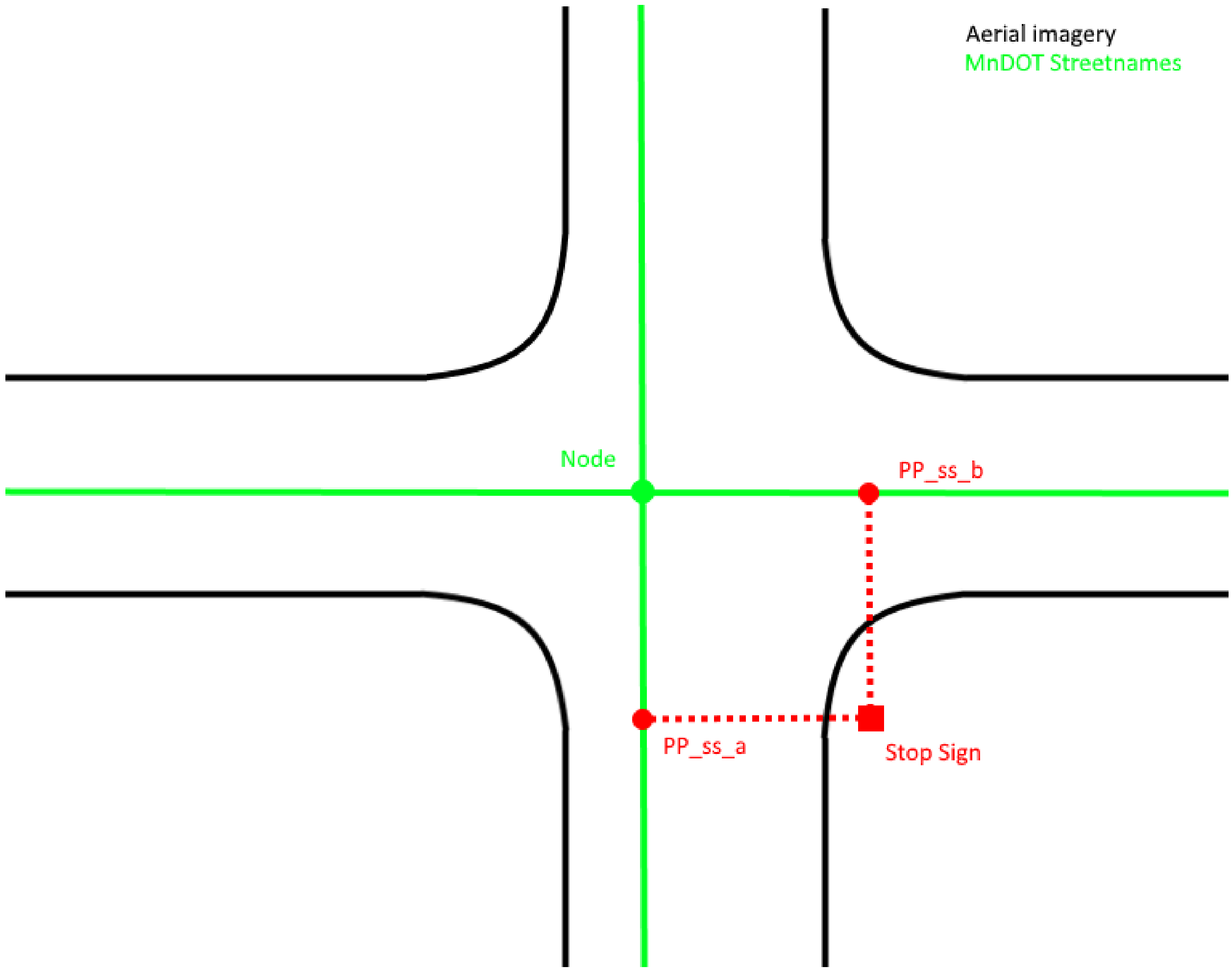


Figure A-0.3 Identification and assignment of approaches – Step 3

The stop sign markers are then projected onto the two nearest polylines. These points are referred to as "projection points". If no projection points are possible, the minor approach is flagged for manual review.

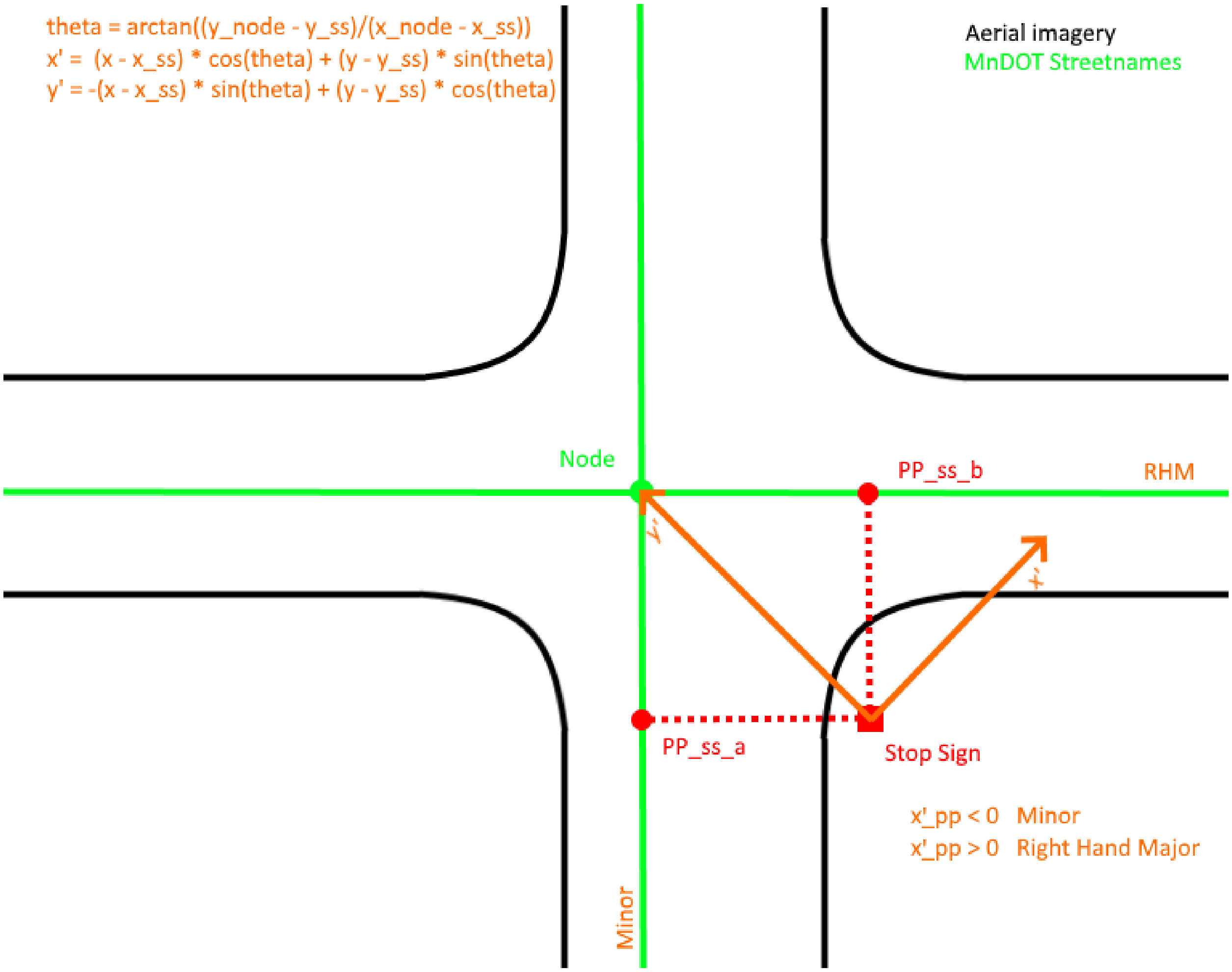


Figure A-0.4 Identification and assignment of approaches – Step 4

A temporary coordinate transformation is created with the origin at the stop sign and the y'-axis pointing towards the intersection node. If a projection point has an x' value less than 0, the road it is on is labelled as the minor road. If a projection point has an x' value greater than 0, the road it is on is labelled as the right hand major (RHM) road. If no minor approach is found, the minor approach is flagged for manual review.

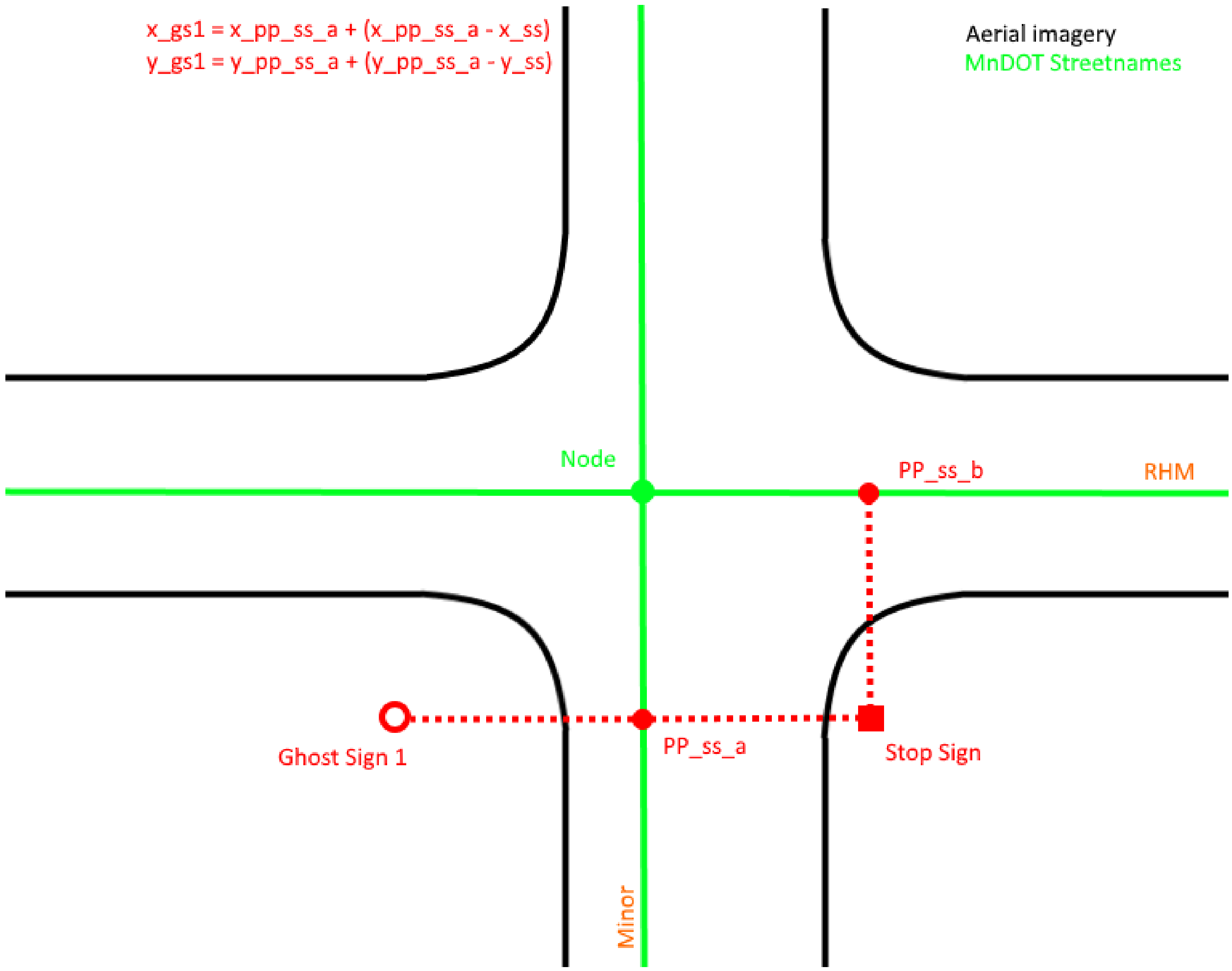


Figure A-0.5 Identification and assignment of approaches – Step 5

The stop sign marker is reflected across the minor road polyline to create a “ghost sign”.

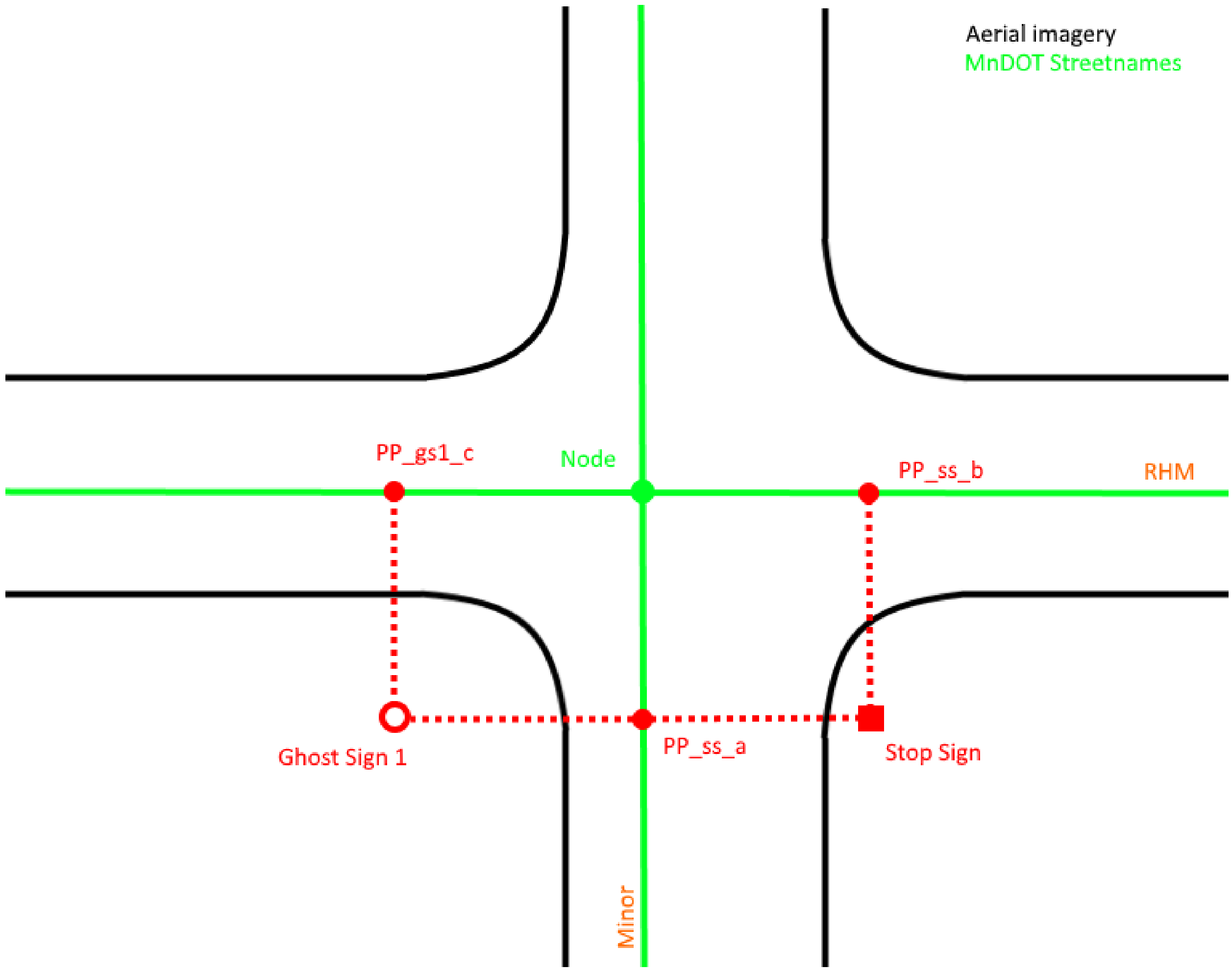


Figure A-0.6 Identification and assignment of approaches – Step 6

The ghost sign is projected onto the nearest two polylines.

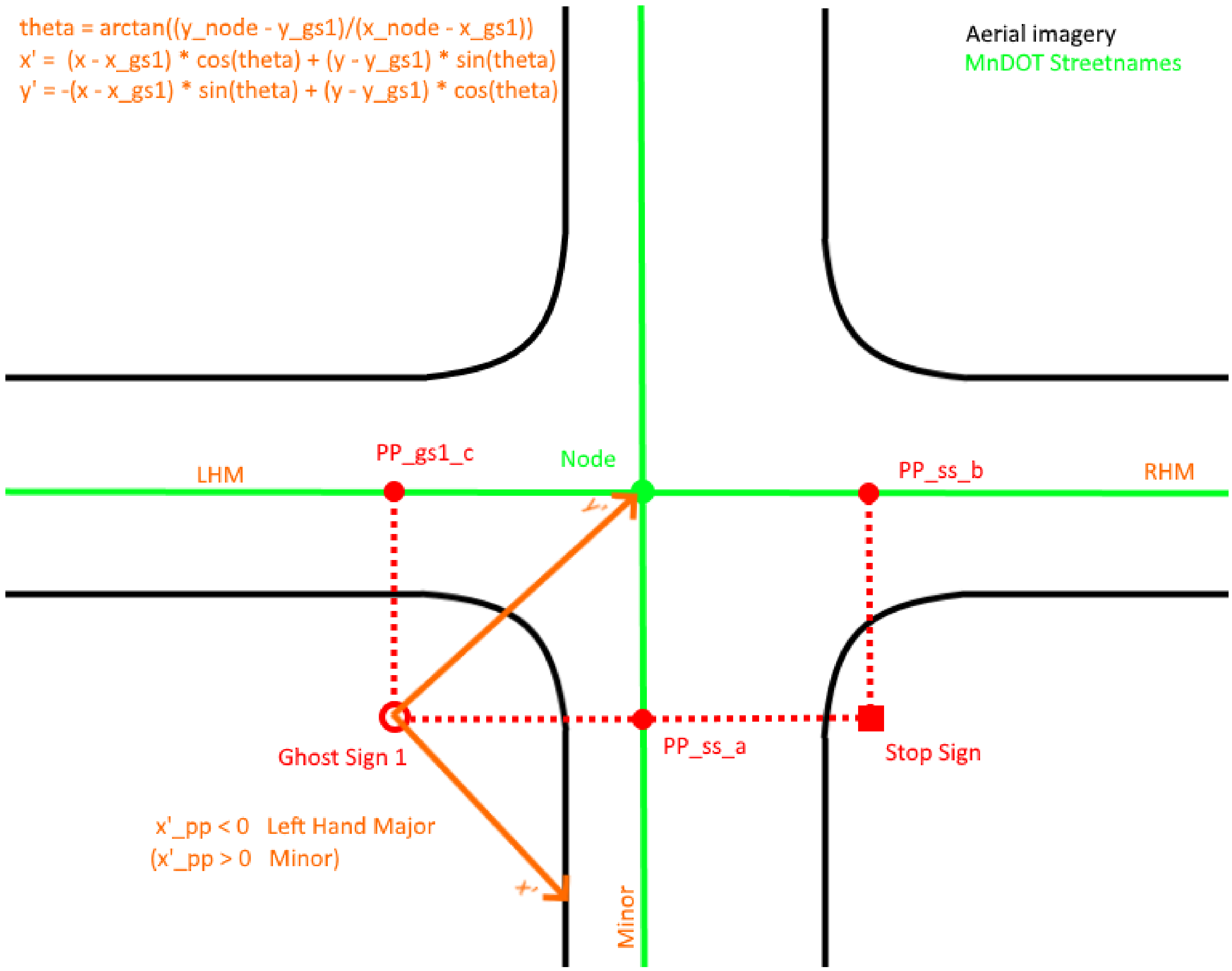


Figure A-0.7 Identification and assignment of approaches – Step 7

A temporary coordinate transformation is created with the origin at the ghost sign and the y'-axis pointing towards the intersection node. If a projection point has an x' value less than 0, the road it is on is labelled as the left hand major (LHM) road. If a projection point has an x' value greater than 0, the road it is on should have been labelled as the minor road. If the minor approach is not identified again, the minor approach is flagged for manual review.

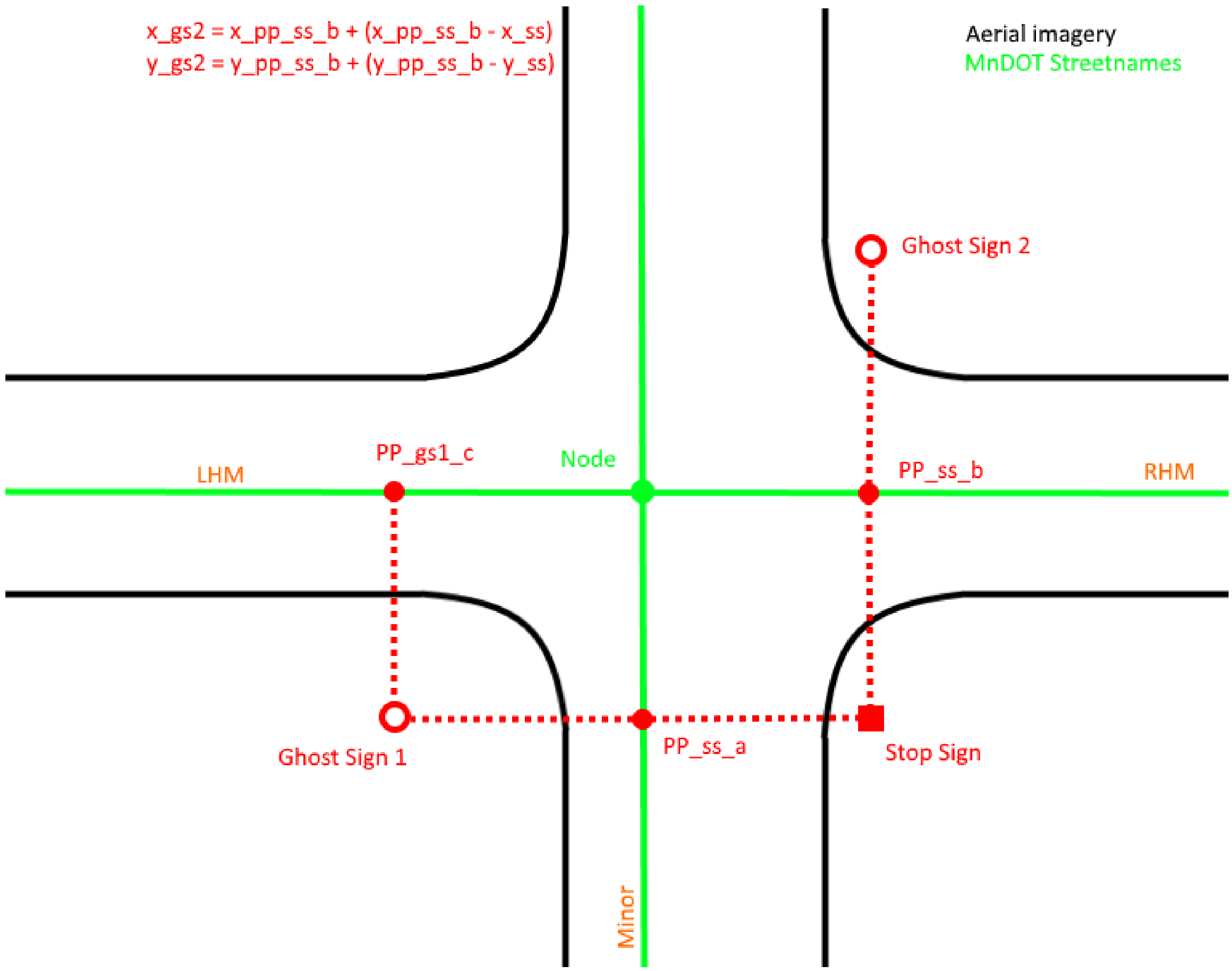


Figure A-0.8 Identification and assignment of approaches – Step 8

The stop sign marker is reflected across the RHM road polyline to create a second ghost sign. If no RHM exists, the minor approach is flagged for manual review.

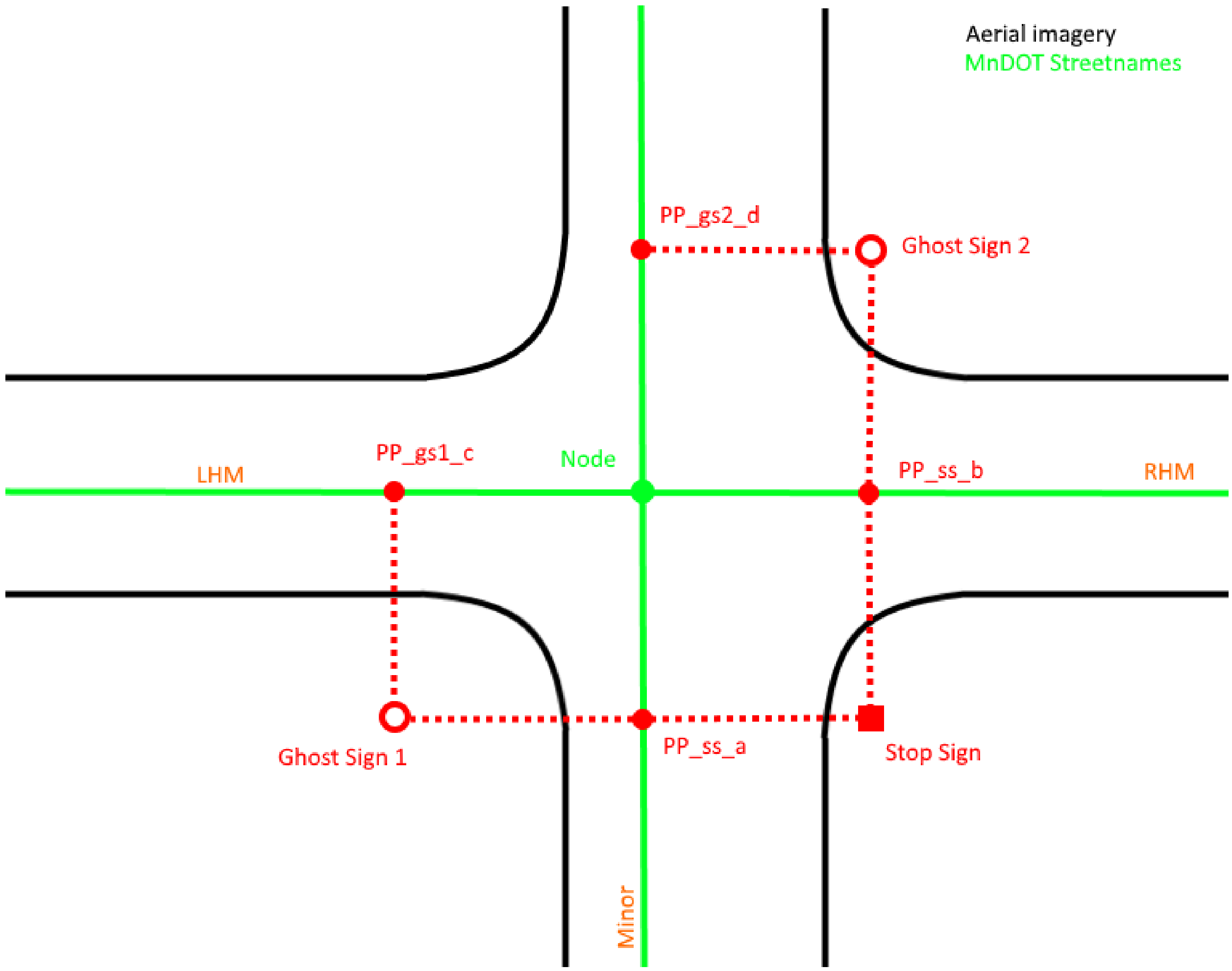


Figure A-0.9 The new ghost sign is projected onto the two nearest polylines.

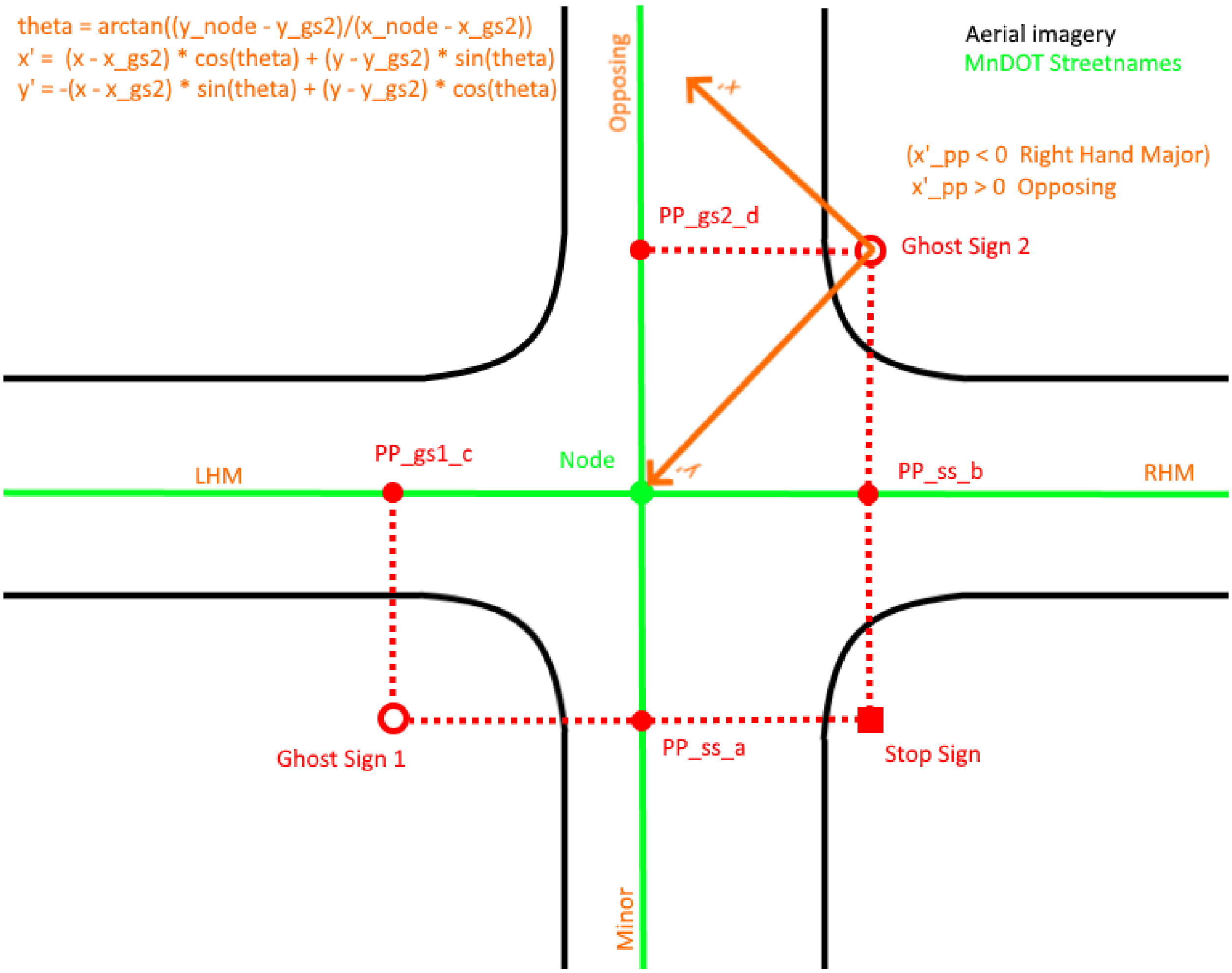


Figure A-0.10 Temporary coordinate transformation creation.

A temporary coordinate transformation is created with the origin at the new ghost sign and the y'-axis pointing towards the intersection node. If a projection point has an x' value less than 0, the road it is on should have been labelled as the RHM road. If a projection point has an x' value greater than 0, the road it is on is labelled as the opposing road. If the RHM road is not identified again, the minor approach is flagged for manual review.

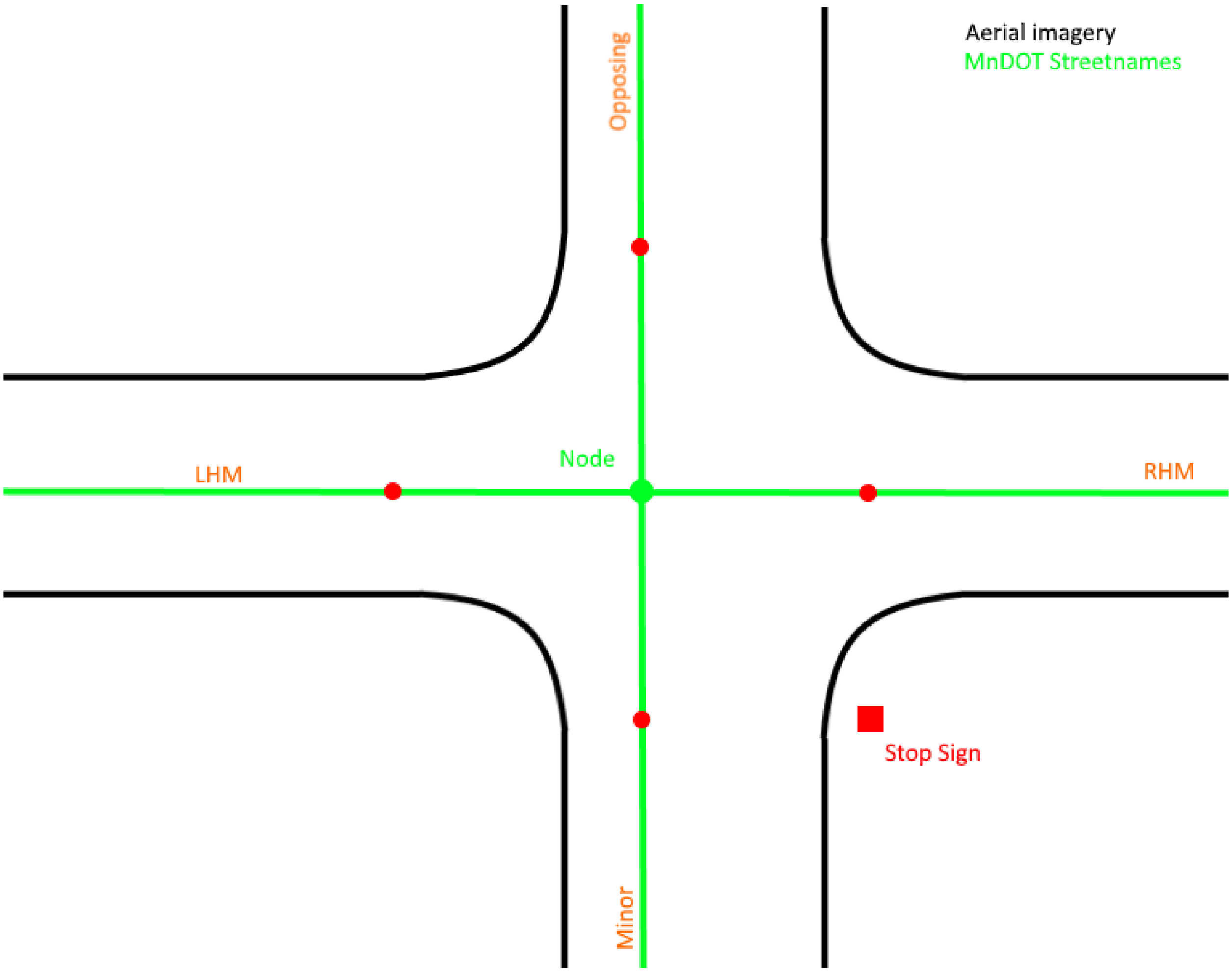


Figure A-0.11 Final correction.

The result is the name and projection point location for all roads at the intersection (each with a label relative to the minor road), the location of the intersection node, the location of the intersection pin, and location of the stop sign associated with the minor approach. If the number of roads identified does not equal the number of road polylines identified, the minor approach is flagged for manual review.

APPENDIX B
CREATION OF RUDIMENTARY REQUIRED SIGHT DISTANCE TRIANGLES

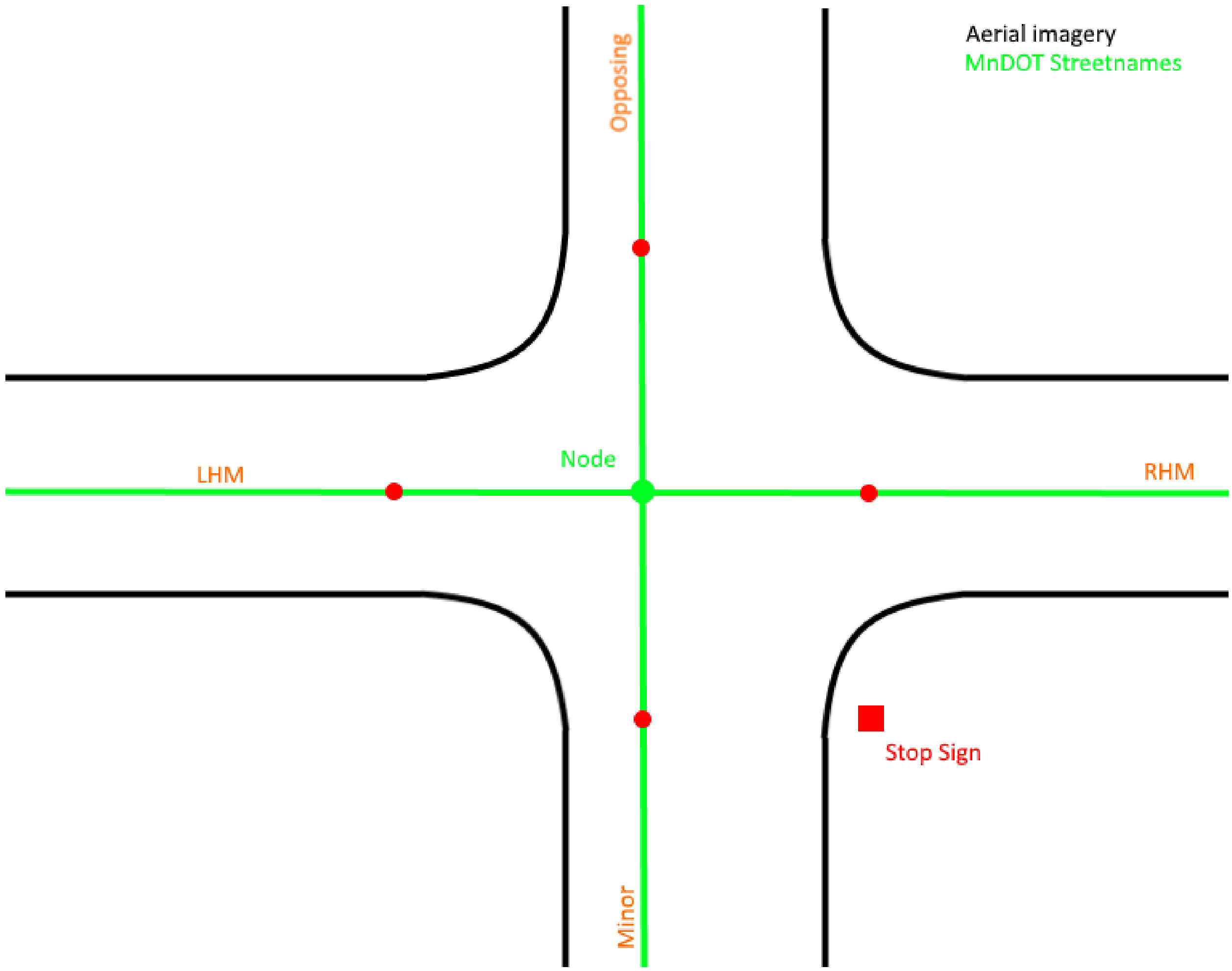


Figure B-0.1 Creation of rudimentary required sight distance triangles – Step 1

The creation of the sight triangles begins with importing the output of the approach identification and assignment process (see Appendix A).

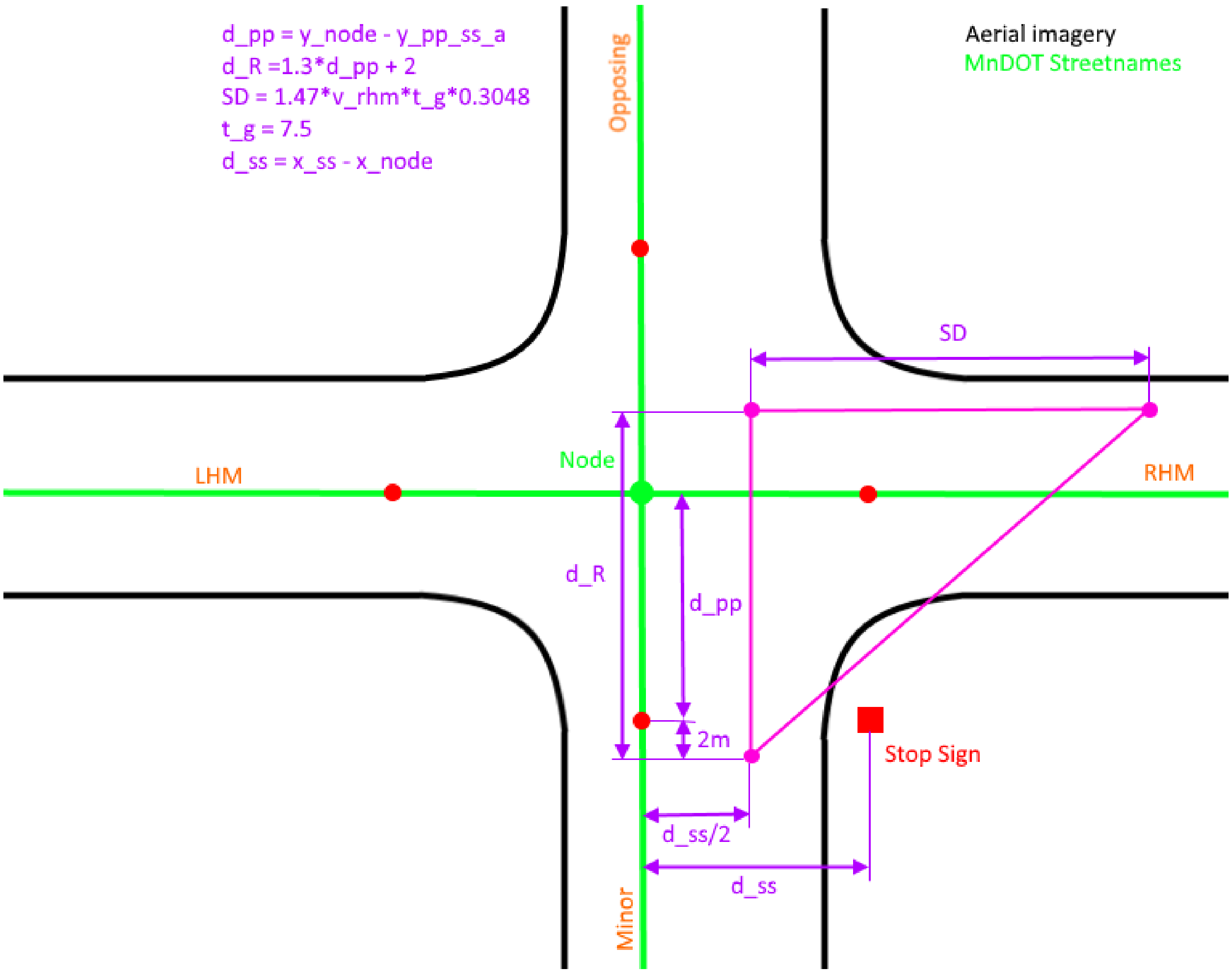


Figure B-0.2 Creation of rudimentary required sight distance triangles – Step 2

The vertex of the right sight triangle corresponding to the driver's eye is located halfway between the stop sign and its projection point on the minor road and 2m (an average length of a vehicle's hood) upstream of the stop sign. The other two vertices should be located in the center of the nearest driving lane on the far side of the major road but that distance is difficult to calculate automatically. Instead, the vertices are located at a distance of 1.3 times the distance from the stop sign to its projection point on the RHM road from the projection point on the minor road. This has proven by trial and error to be a good approximation of the actual distance. The length of the far leg of the triangle is equal to the required sight distance. The required sight distance is calculated using the formulas for calculating the required sight distance at a stop controlled intersection provided in AASHTO's *A Policy on Geometric Design of Highways and Streets*. The time gap used is that of a passenger car crossing an intersection on level ground (7.5 seconds).

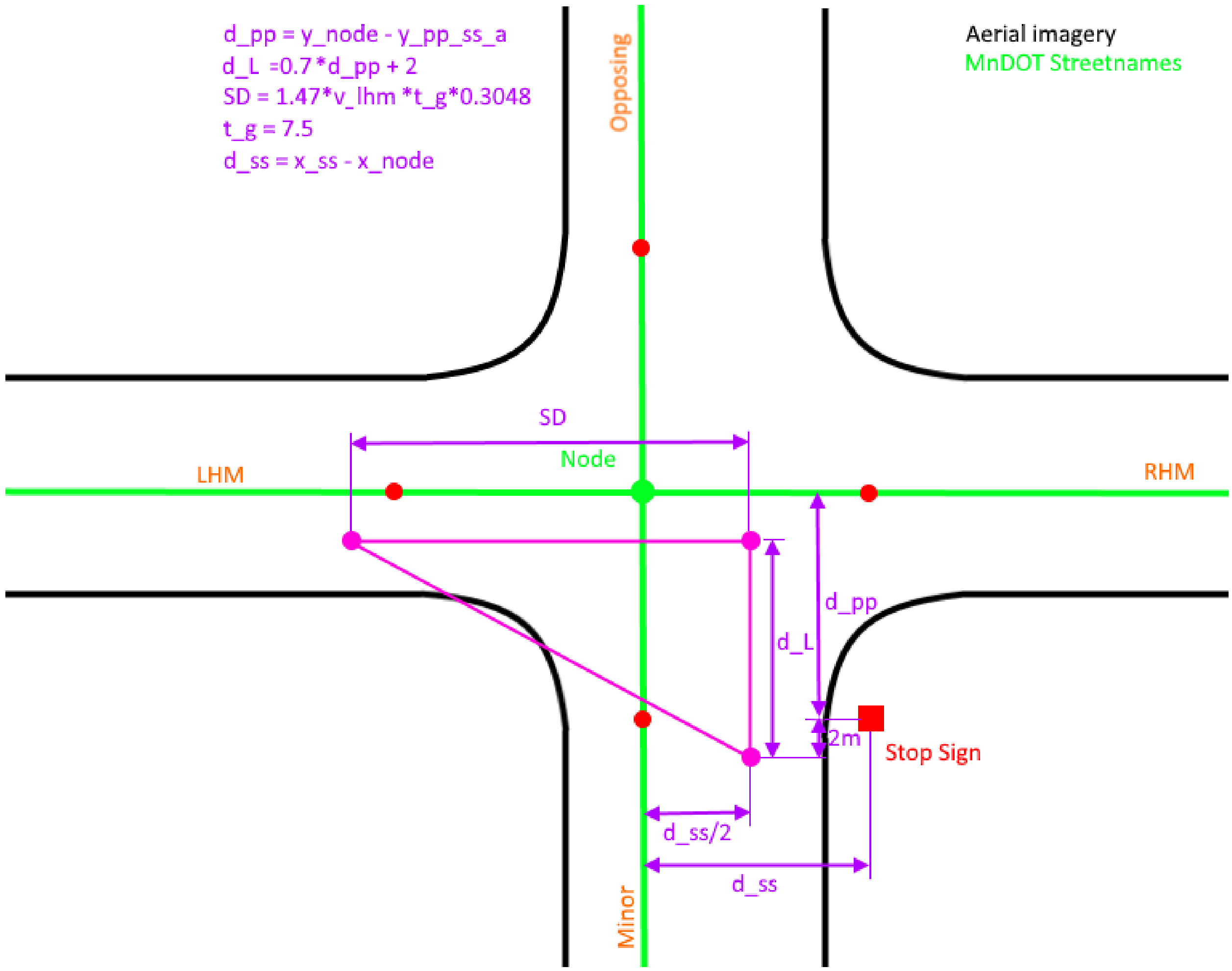


Figure B-0.3 Creation of rudimentary required sight distance triangles – Step 3

The vertex of the left sight triangle corresponding to the driver's eye is located halfway between the stop sign and its projection point on the minor road and 2m (an average length of a vehicle's hood) upstream of the stop sign. The other two vertices should be located in the center of the farthest driving lane on the near side of the major road but that distance is difficult to calculate automatically. Instead, the vertices are located at a distance of 0.7 times the distance from the stop sign to its projection point on the LHM road from the projection point on the minor road. This has proven by trial and error to be a good approximation of the actual distance. The length of the far leg of the triangle is equal to the required sight distance. The time gap used is that of a passenger car crossing an intersection on level ground (7.5 seconds).

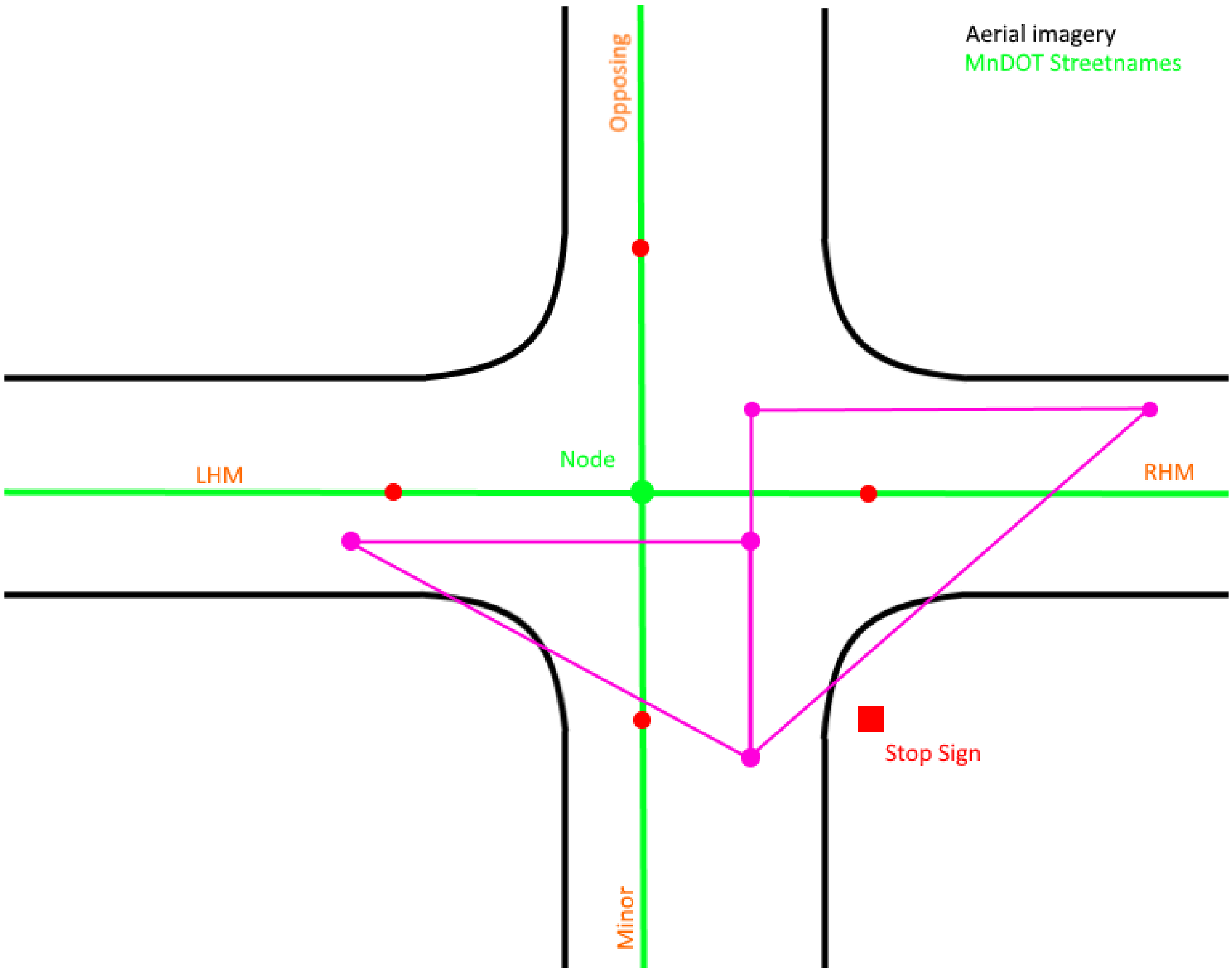


Figure B-0.4 Creation of rudimentary required sight distance triangles – Step 4

The vertices of each triangle are connected and the two triangles are plotted together on the aerial imagery.

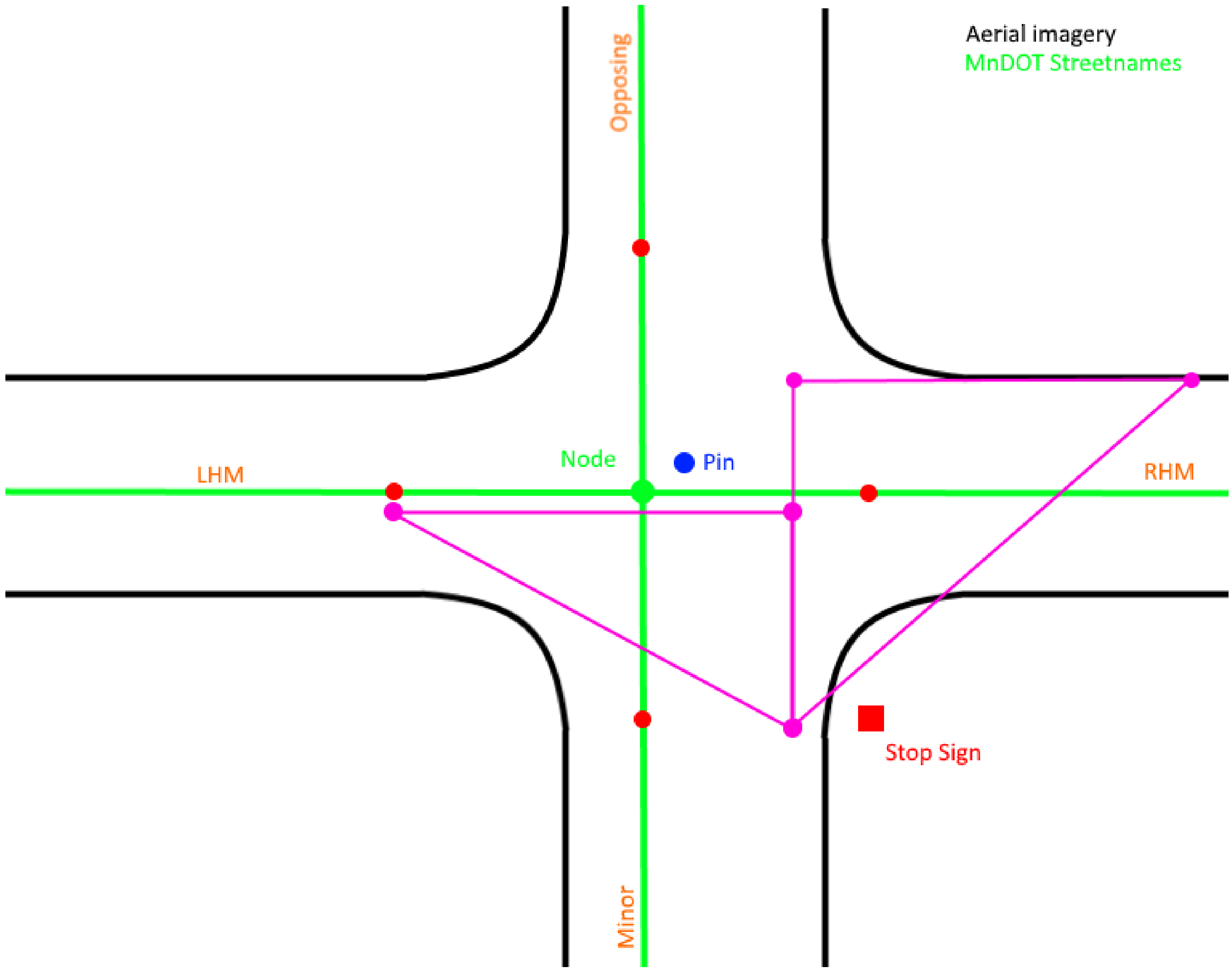
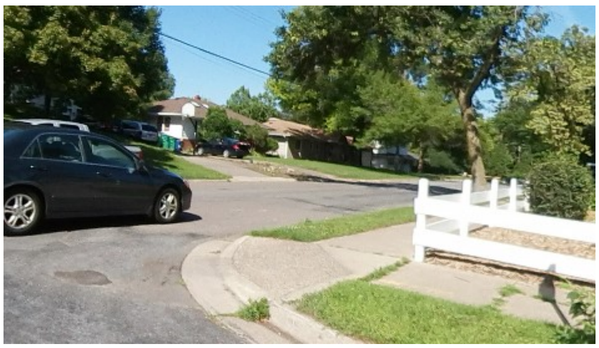


Figure B-0.5 Creation of rudimentary required sight distance triangles – Step 5

In many cases the road polylines do not match the aerial imagery. To align the sight triangles with the aerial imagery, the triangles are translated by the vector from the intersection node to the intersection pin which is located at the center of the intersection according to the aerial imagery.

APPENDIX C
QUENTIN AVE CASE STUDY

Quentin Ave is not included in the study due to non-uniformity with average intersection geometry as well as reported differences in stopping behavior from locals. Generally, it would not allow for generalizable results. Regardless, because of the local residents' anecdotal evidence of it being a "bad" intersection the research team relocated the surveillance station during the period the stop line on Raleigh was painted and collected 3 days of video. Following a fatal traffic incident, and upon request from the city of St. Louis Park, the site was more closely examined for irregularities in site characteristics and driver behavior, as well as similarities to the Raleigh Ave site, just down the block. AADTs of the major and minor roads are unknown. The sight distance was deemed insufficient, especially on the southbound approach.


A) Right hand


B) Left hand

Figure C-0.1 Sight distance from stop sign at Quentin Ave NB


A) Right hand

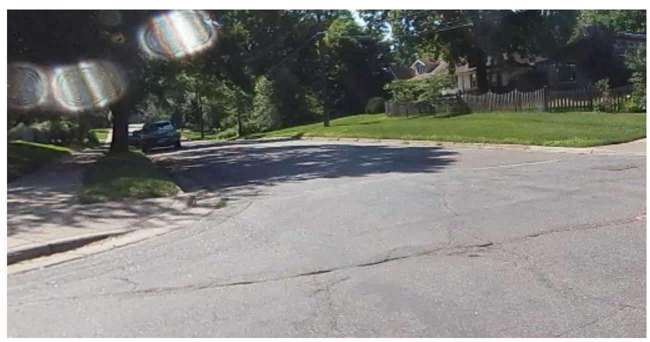

B) Left hand

Figure C-0.2 Sight distance from preferred stop location at Quentin Ave NB


A) Right hand


B) Left hand

Figure C-0.3 Sight distance from stop sign at Quentin Ave SB

B) Right hand B) Left hand

Figure C-0.4 Sight distance from preferred stop location at Quentin Ave SB

An aerial image of Quentin Ave and W 28th St is provided here for reference.

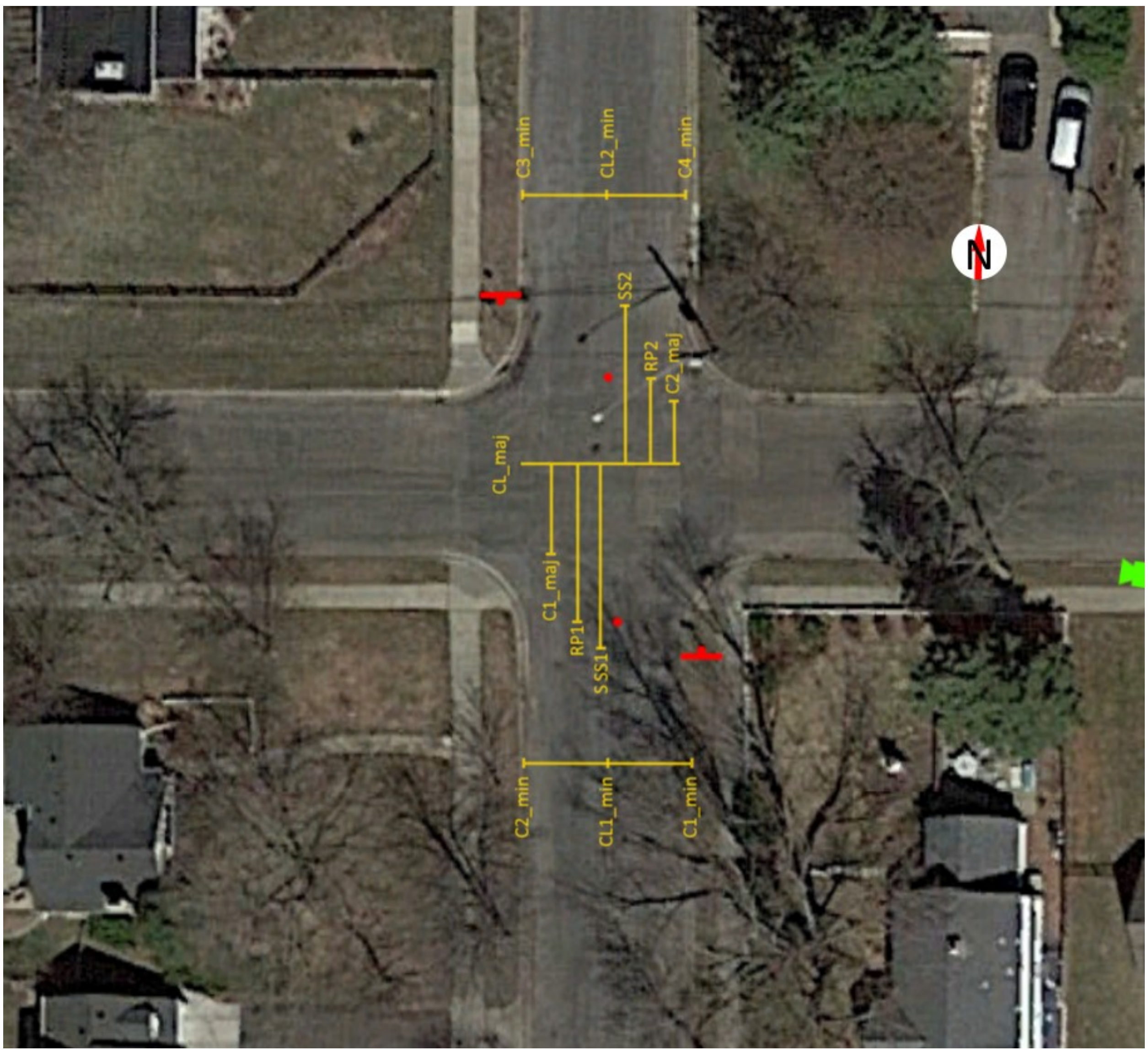


Figure C-0.5 Aerial view of Quentin Ave NB and SB with measurements

Distances labeled in Figure C-0.5 are defined in Table C.1, and marked on Figure C-0.7, Figure C-0.8, Figure C-0.10, and Figure C-0.11 to show the location of the stop lines and curbs.

Table C.1 Measurements at Quentin Ave NB and SB

From CL_maj to…	**SS1**	**RP1**	**C1_maj**	**C2_maj**	**RP2**	**SS2**	
	31.25	24.08	15.08	15.08	18.58	27.58	
From CL1_min to…	**C1_min**	**C2_min**					
	15.50	15.50					
From CL2_min to…	**C3_min**	**C4_min**					
	15.50	14.16					

1. Quentin Ave Northbound

As shown in Figure C-0.6, the majority of drivers rolled at this site. Section 3discusses additional information gathered about the roll and ignore events.

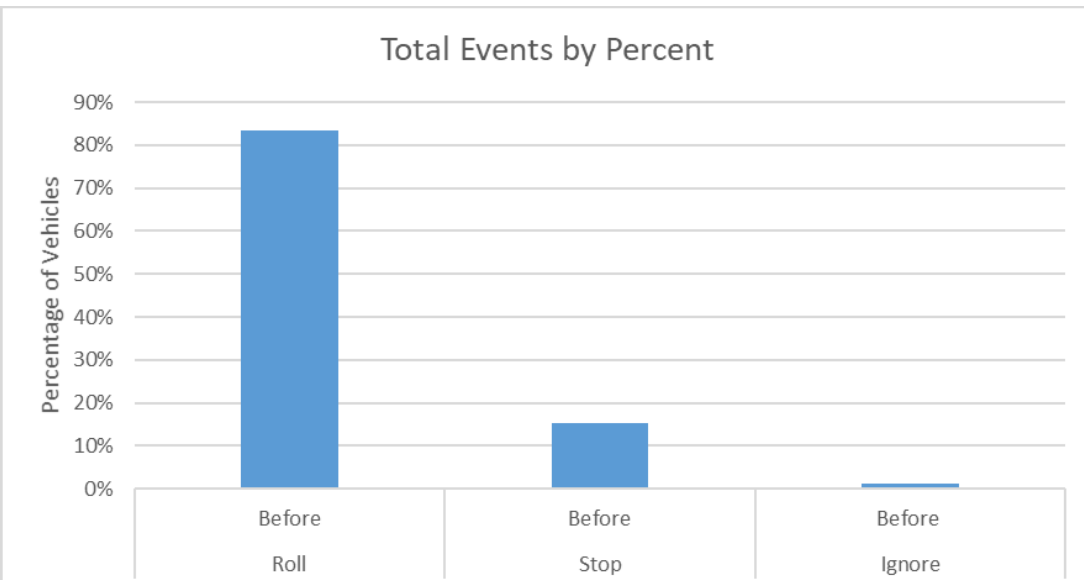


Figure C-0.6 Quentin Ave NB distribution of driver crossing behavior

Drivers appear to be stopping mainly between the stop line and curb line, seen in Figure C-0.7 and Figure C-0.8. However, a small percentage of vehicles are stopping after the curb line, past the point of collision. This may be due to the inadequate sight distance at the stop line, where drivers are forced to pull ahead to see up a small hill to the right and around trees and parked vehicles to the left.

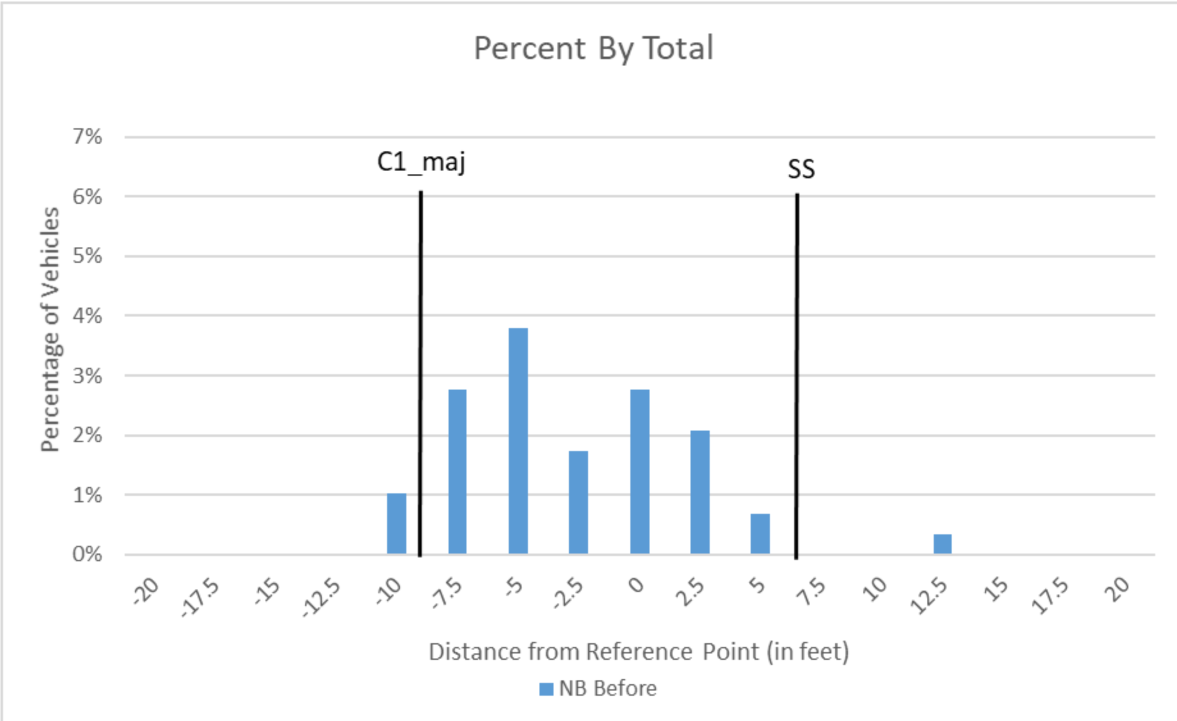


Figure C-0.7 Quentin Ave NB Distribution of Stopping Distance During All Events

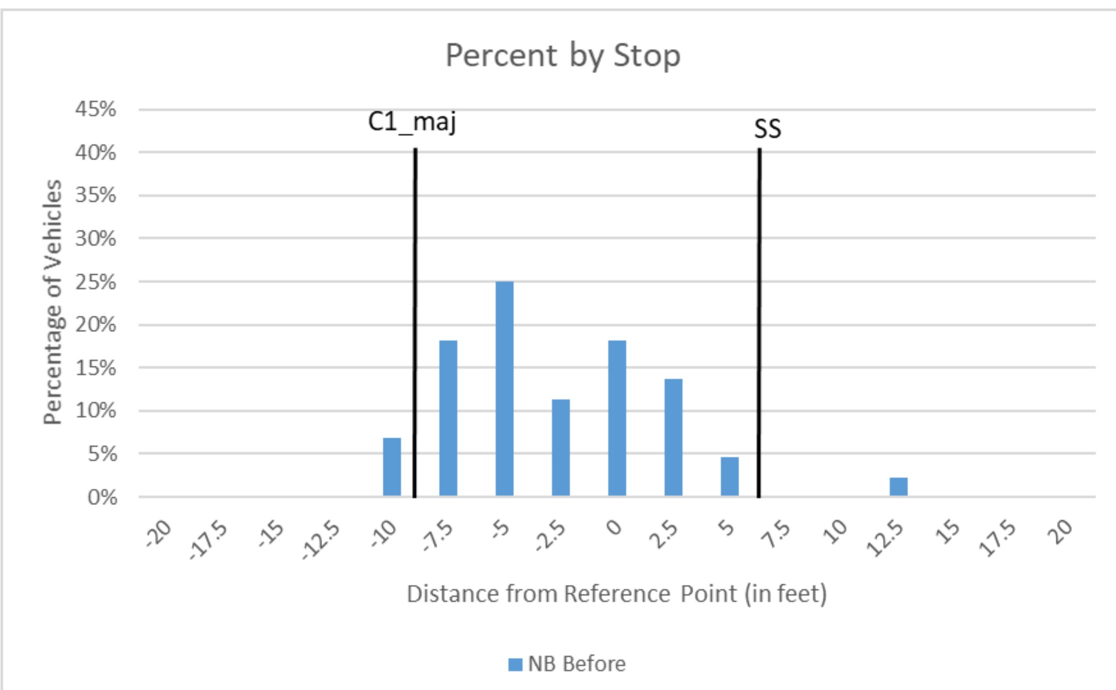


Figure C-0.8 Quentin Ave NB Distribution of Stopping Distance During Stop Events

Removing pedestrian events did not alter the results, shown in Figure C-0.9, Figure C-0.10, and Figure C-0.11.

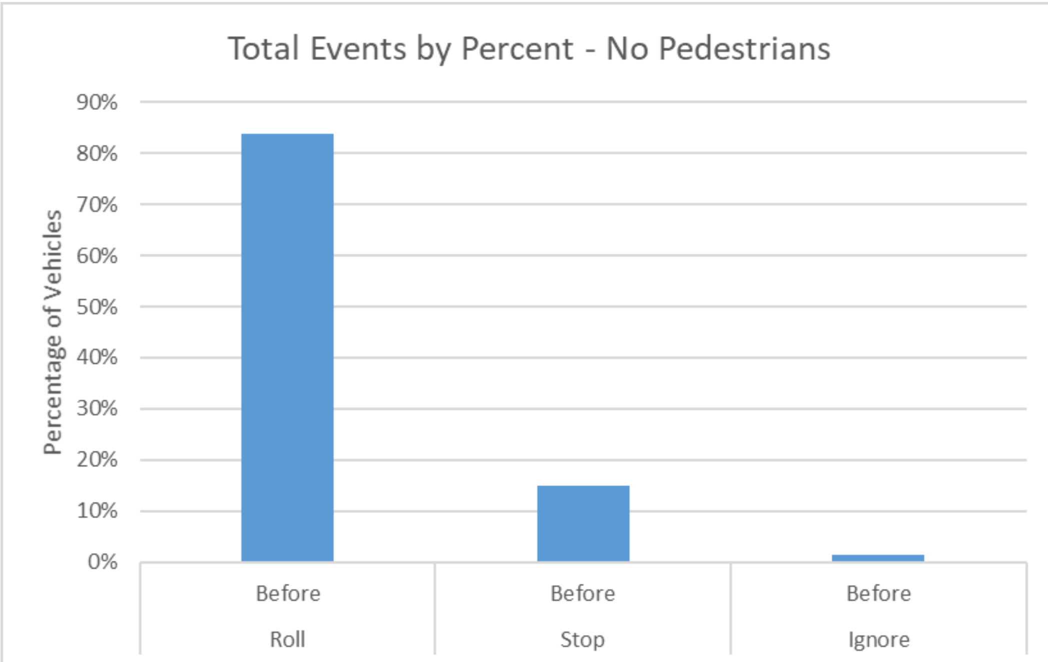


Figure C-0.9 Quentin Ave NB distribution of driver crossing behavior – No Pedestrians

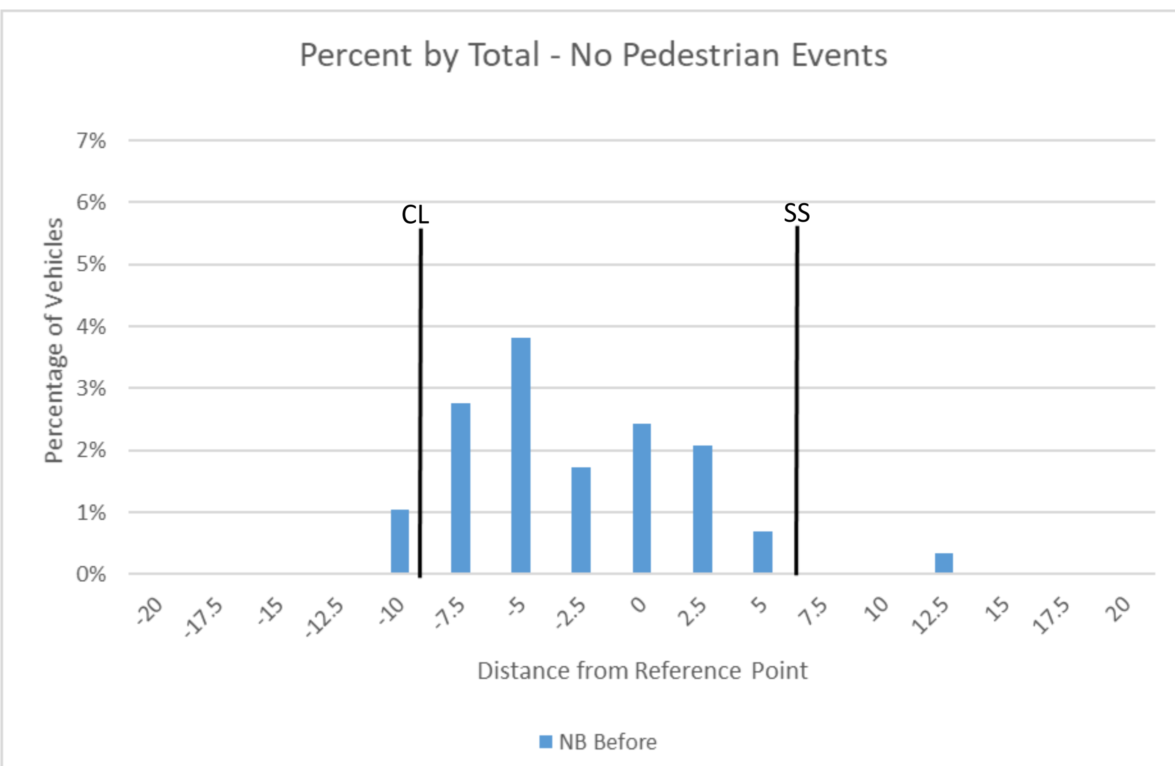


Figure C-0.10 Quentin Ave NB Distribution of Stopping Distance During All Events – No Pedestrians

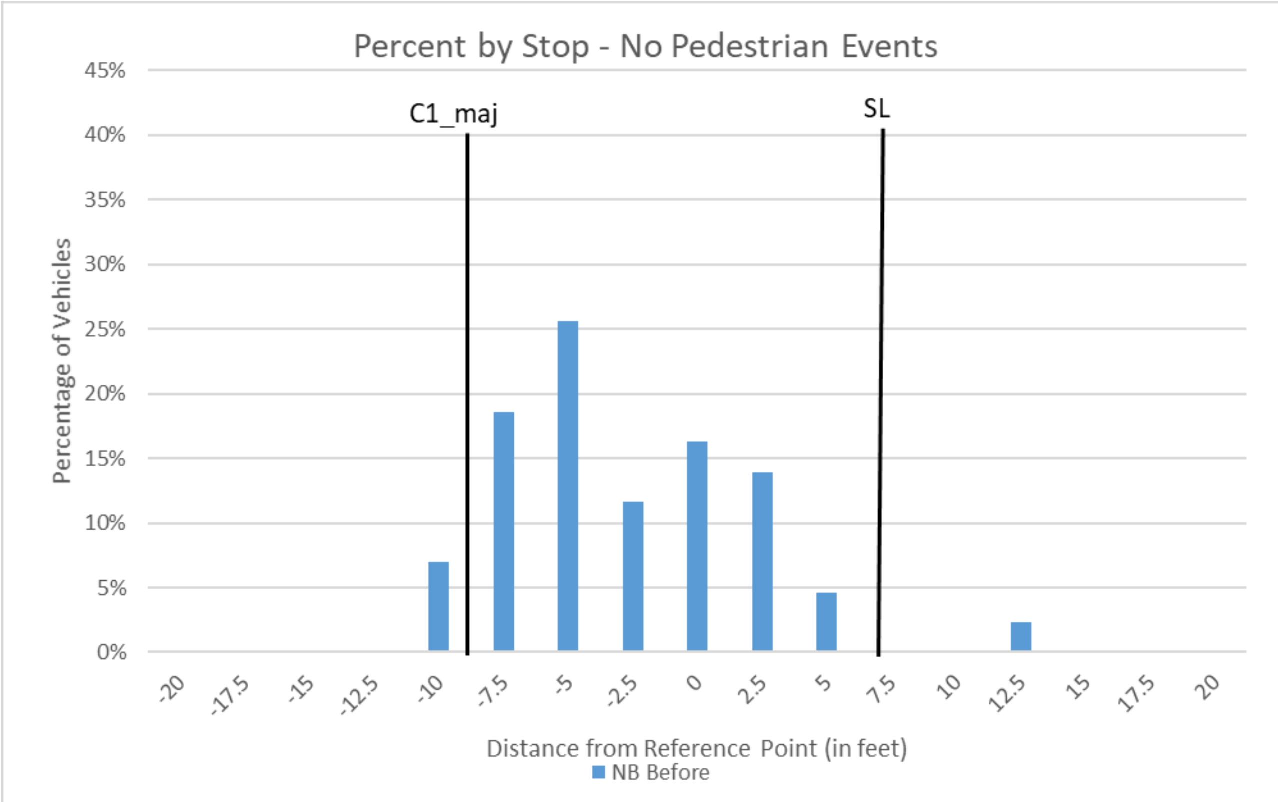


Figure C-0.11 Quentin Ave NB Distribution of Stopping Distance During Stop Events – No Pedestrians

2. Quentin Ave Southbound

Like Quentin Ave NB, the majority of drivers are rolling through this intersection, as seen in Figure C-0.12. Section 3discusses behavior during roll events at both approaches more thoroughly.

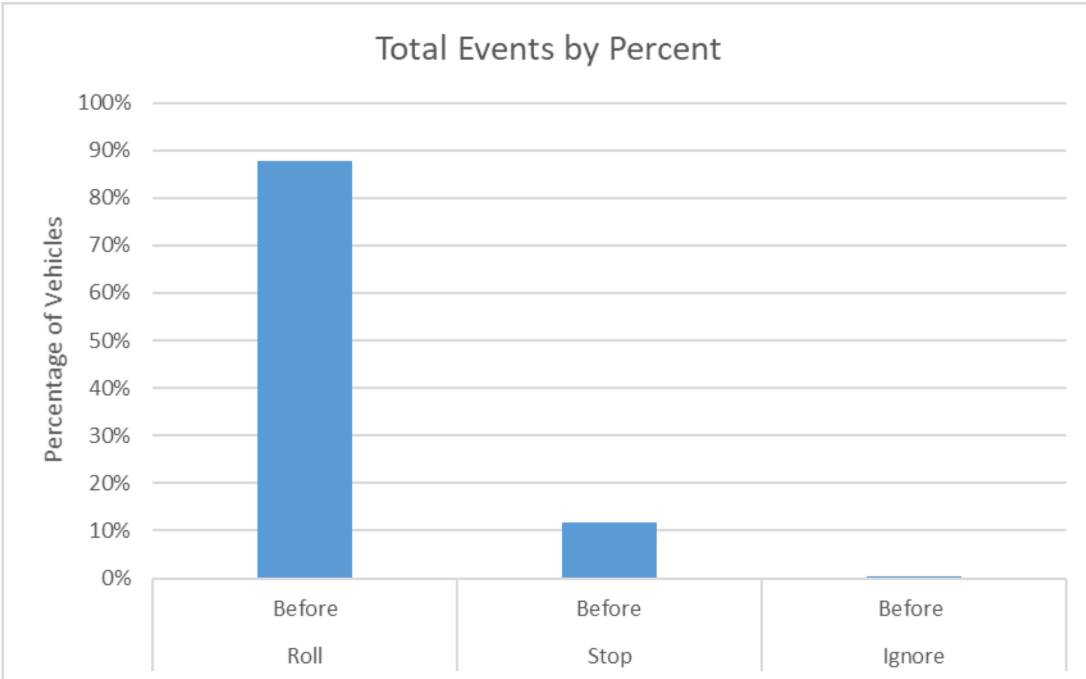


Figure C-0.12 Quentin Ave SB distribution of driver crossing behavior

Alarmingly, nearly 4% of all drivers (Figure C-0.13) and 26% of drivers that stopped (Figure C-0.14) were observed to stop after the curb line, past the point of collision. The geometry of this approach is one factor as to why drivers are stopping at a point of danger; drivers accelerate from the previous intersection over a hill and then must rapidly decelerate to obey the stop sign at Quentin Ave. Coupled with poor sightlines from trees, poles, signage and parked cars – especially to the left – this could lead drivers to stop past where they are safe.

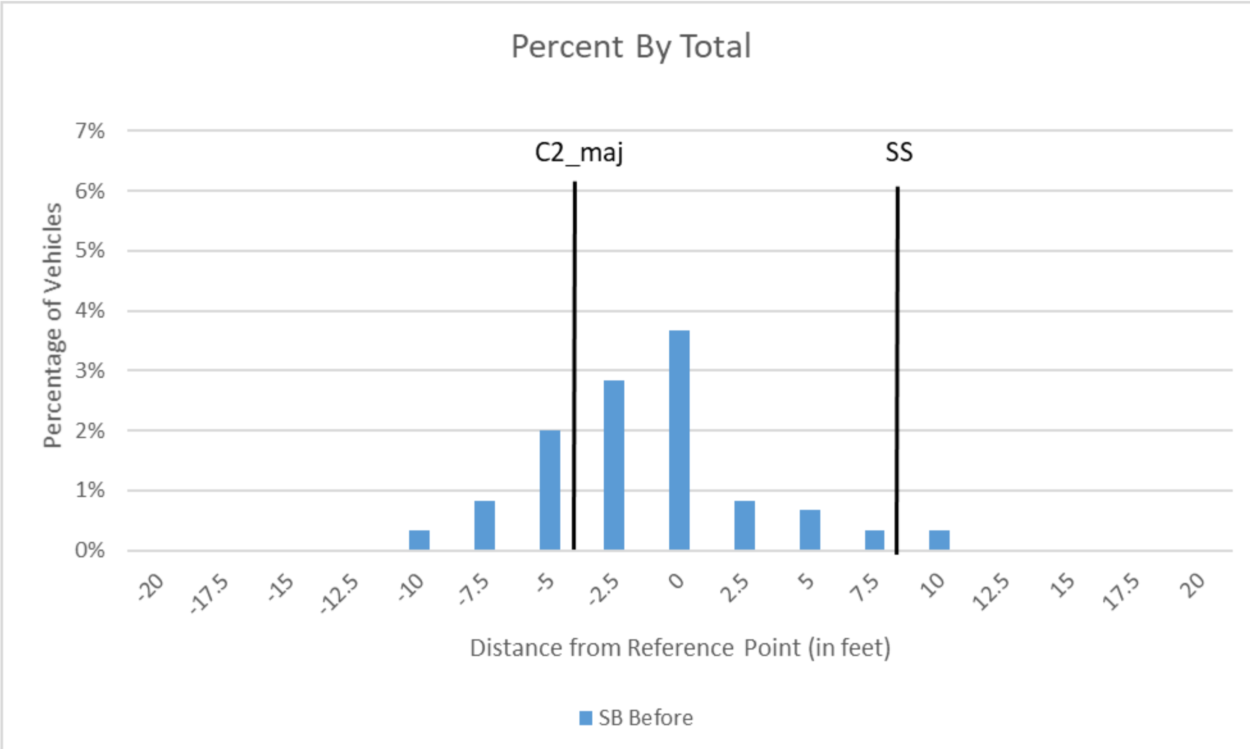


Figure C-0.13 Quentin Ave SB Distribution of Stopping Distance During All Events

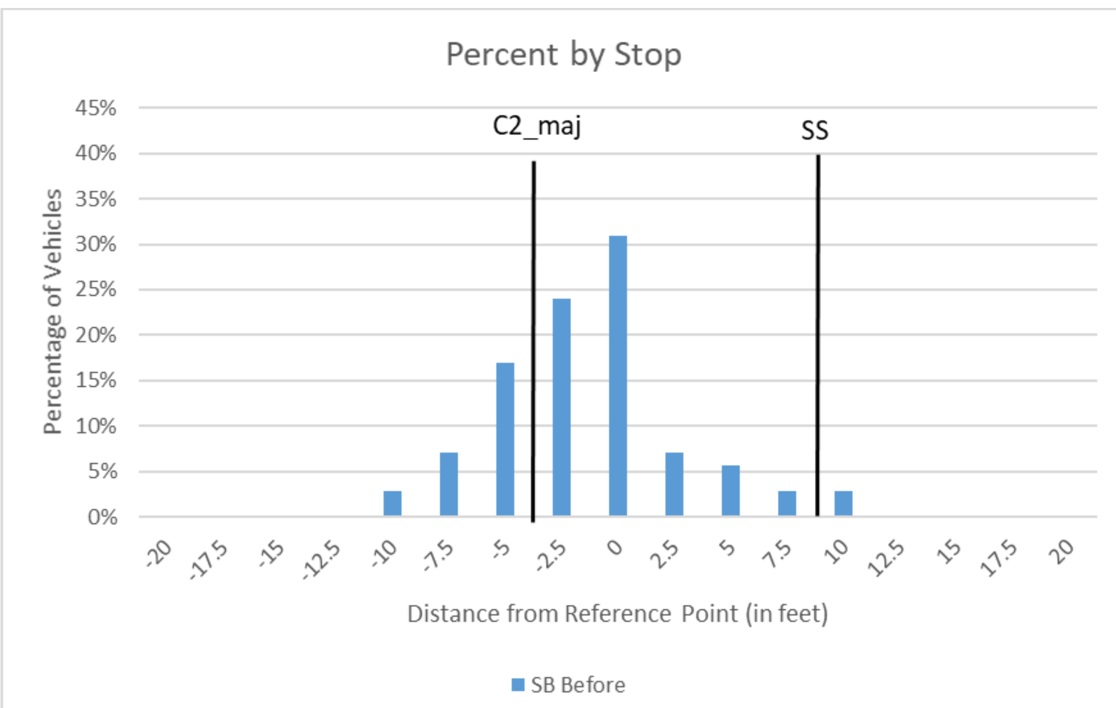


Figure C-0.14 Quentin Ave SB Distribution of Stopping Distance During Stop Events

Removing pedestrian events did not impact the results, seen in Figure C-0.15, Figure C-0.16, and Figure C-0.17.

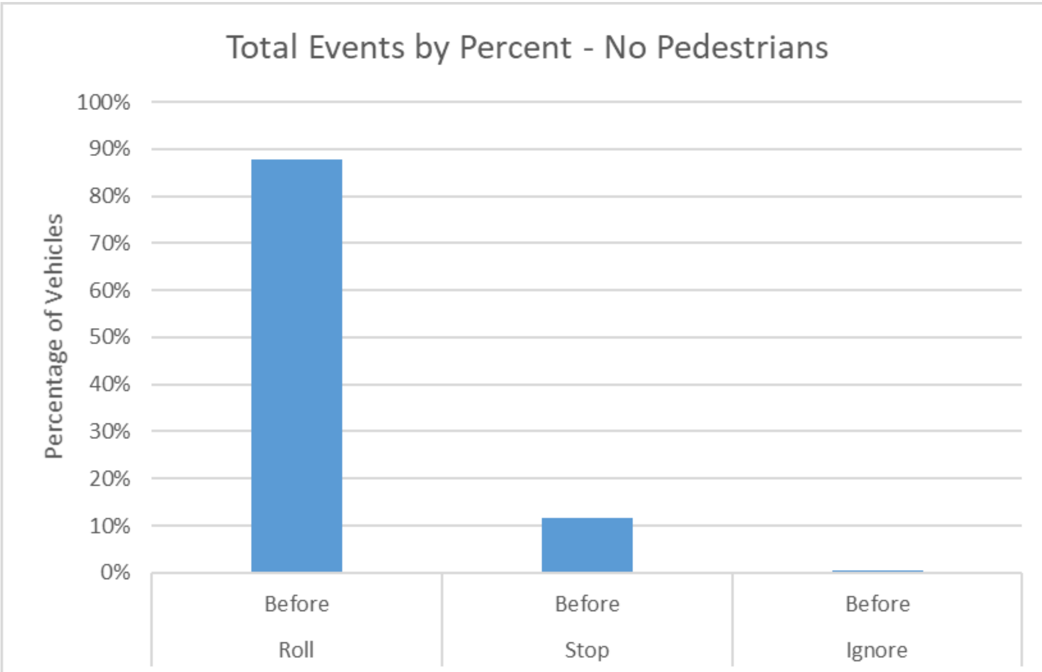


Figure C-0.15 Quentin Ave SB distribution of driver crossing behavior – No Pedestrians

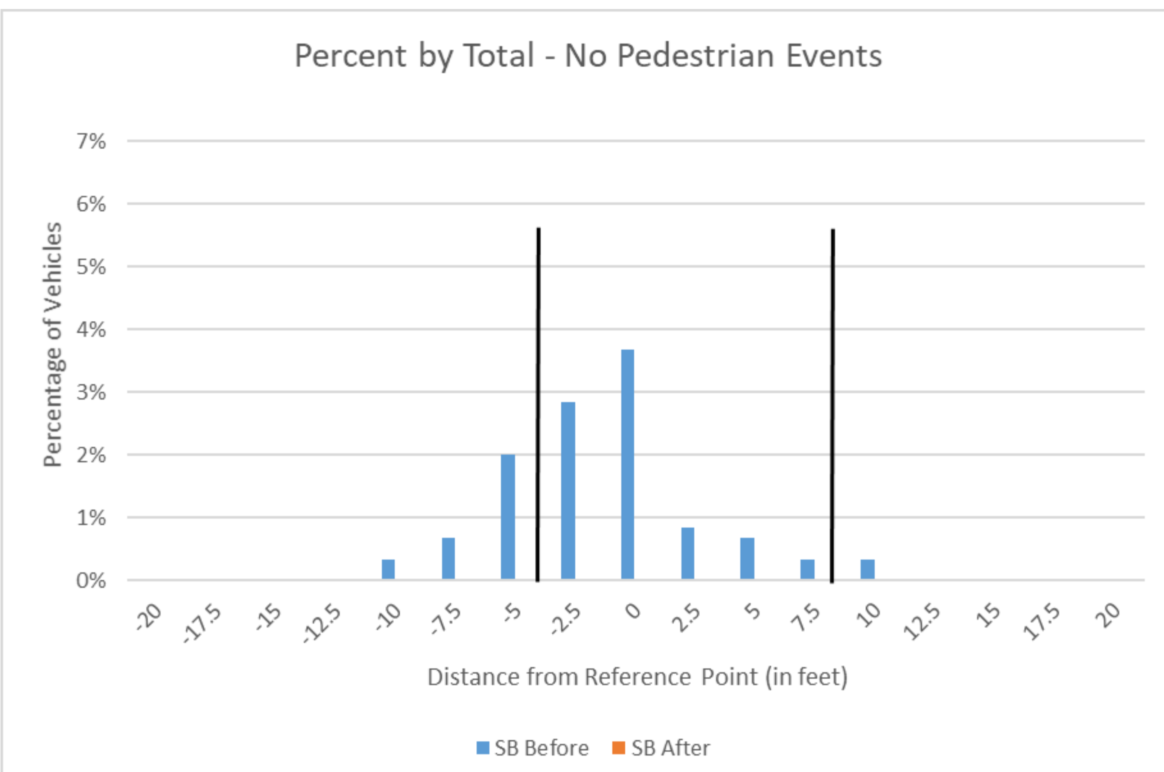


Figure C-0.16 Quentin Ave SB Distribution of Stopping Distance During All Events – No Pedestrians

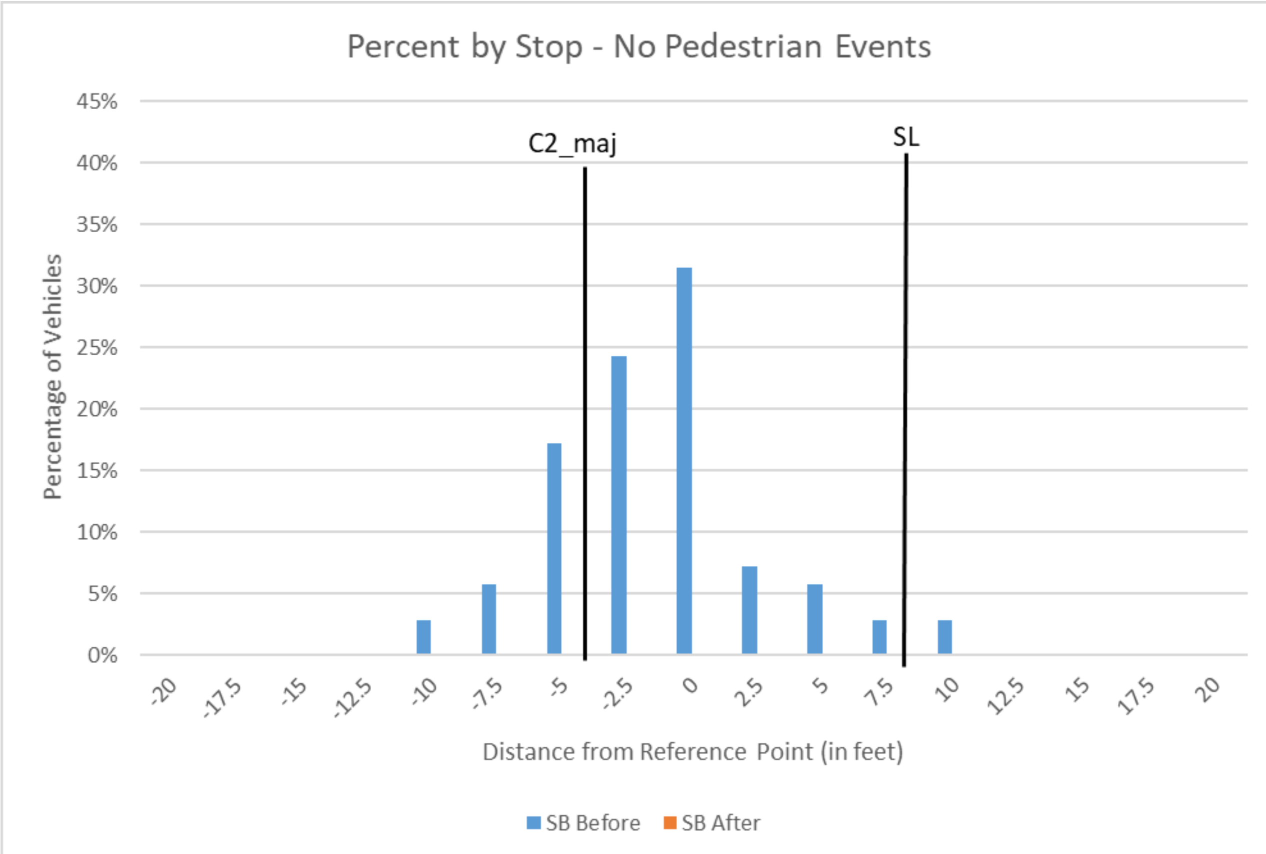


Figure C-0.17 Quentin Ave SB Distribution of Stopping Distance During Stop Events – No Pedestrians

3. Quentin Ave Roll and Ignore Events

This site was the first to undergo the new methodology for analyzing roll and ignore events, where the number of frames a vehicle took to pass the 25 feet before the stop line through to 5 feet past it is recorded at the time the event was logged. The video is recorded at 15 frames per second, so the difference in those frame numbers were converted into time, and a histogram of roll and ignore events was created (Figure C-0.18).

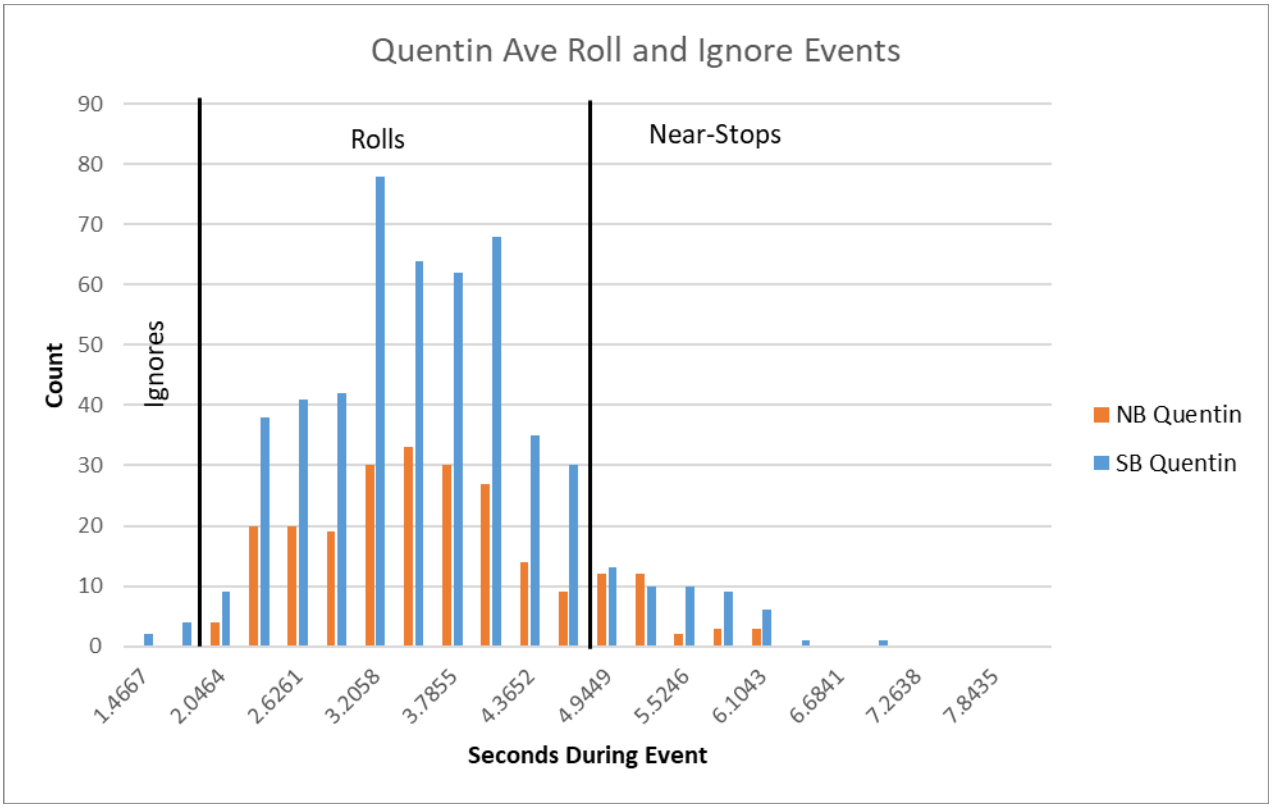


Figure C-0.18 Histogram of time drivers spent at stop sign during roll and ignore events

The cutoff for an ignore event was considered two seconds or less. True roll events are defined as being between three and five seconds. Anything over five seconds is currently considered a near-stop, where the vehicle likely came close to a full stop at some point in the 30-foot range, but was not observed stopping for a full 10 consecutive frames at any point. These thresholds may change as more sites are analyzed and a better understanding of driver behavior is achieved.

As seen in Figure C-0.18, few vehicles truly ignored the stop sign. The northbound approach has a fairly normal distribution of roll events, with some skew toward the shorter-time side of the distribution. The southbound approach has more of a tri-modal shape, having a distinct peak in the middle of the roll event distribution. Smaller peaks are observed to the immediate left and right.

4. Comparison of Quentin Ave and Raleigh Ave

As Quentin Ave and Raleigh Ave are neighbor intersections on W 28th St, in order to better understand the difference in driver behavior at Quentin Ave, the northbound and southbound approaches at each will be compared.

a. Quentin Ave NB and Raleigh Ave NB

Figure C-0.19 compares the Quentin Ave NB numbers to the without-stop line Raleigh Ave NB numbers.

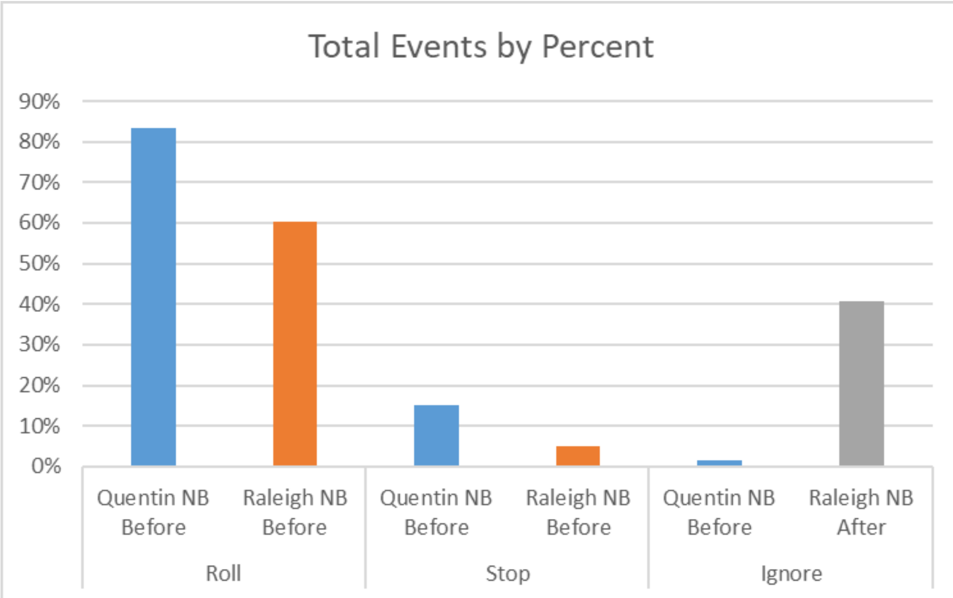


Figure C-0.19 Quentin Ave NB and Raleigh Ave NB, no stop line

This graph highlights the abnormality of the Raleigh Ave ignore events, which ultimately led to an improved method of data capture for this type of event.

The majority of drivers at Quentin Ave NB and Raleigh Ave NB stopped between the stop sign and the curb, before the point of collision. A small number of drivers encroached or came close to encroaching past the curb at both sites.

b. Quentin Ave SB and Raleigh Ave SB

Figure C-0.20 compares the Quentin Ave NB numbers to the without-stop line Raleigh Ave NB numbers.

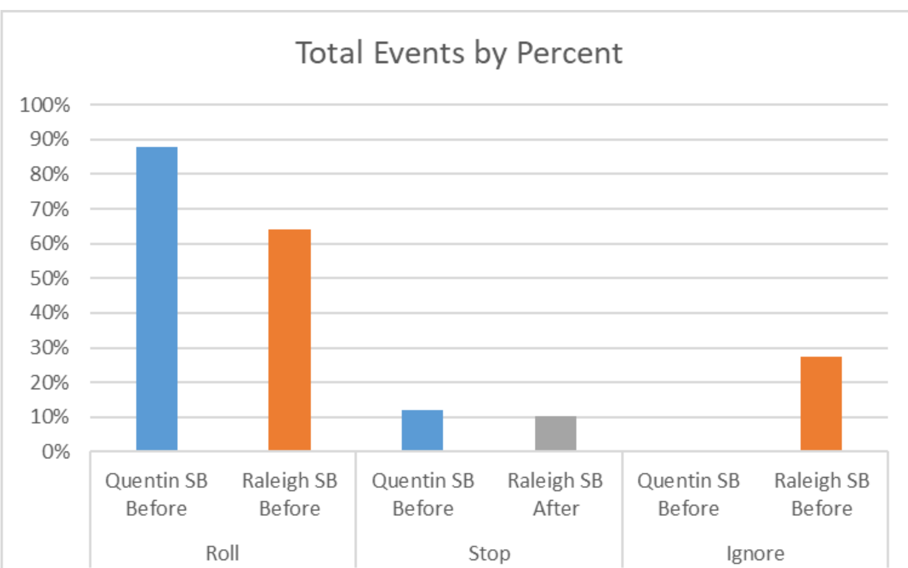


Figure C-0.20 Quentin Ave NB and Raleigh Ave NB, no stop line

This graph again highlights the abnormality of the Raleigh Ave ignore events, though the number of ignore events is not as high for southbound Raleigh as it is northbound Raleigh.

Figure C-0.20 compares the stop locations relative to the centerline of the major road (at 0) at each site. This graph is normalized to have the curb line at 0, consistant for both sites. The stop line and stop sign location are annotated. (Note: due to limitations of Excel's ability to graph multiple sets of data accurately as clustered columns, this figure was generated with Matlab.)

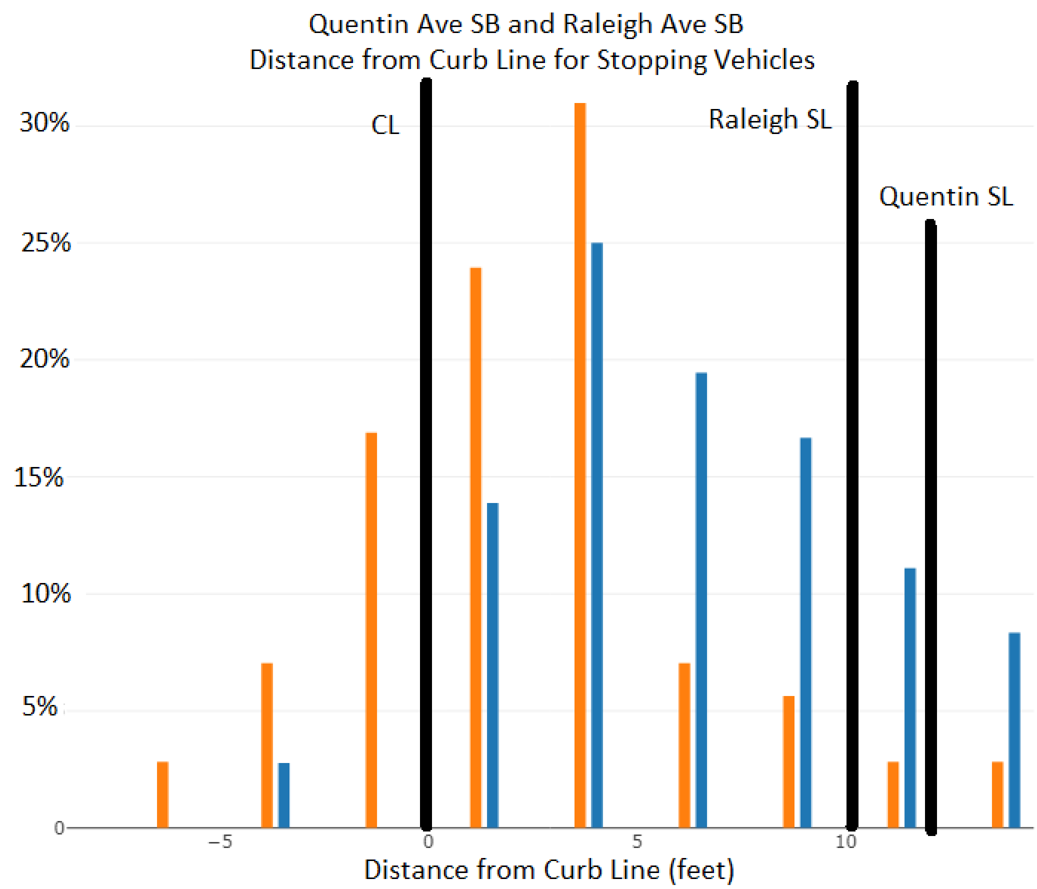


Figure C-0.21 Comparison of Stop Events at Quentin Ave SB and Raleigh Ave SB

Observing Figure C-0.21, drivers at Raleigh Ave SB have a more normalized distribution of stopping distances, located closer to the stop sign than at Quentin Ave SB. Another difference between the Quentin Ave SB and Raleigh Ave SB drivers is the large peak at about 18.5 feet from the centerline of the major road. Overall, Drivers at Quentin Ave are stopping much closer to the centerline of the major road, on average, with nearly a quarter of all stopping events occurring past the point of collision.

In summary, the majority of drivers at both approaches on Quentin Ave roll, and based on results from other sites (especially Raleigh Ave), placement of a stop line would not have affected this behavior.

Depending on where the stop line was placed, it would likely not result in a much different stopping distribution from drivers who did stop. Sight distance and site geometry are much larger factors in how many drivers are stopping, and if they are stopping safely.