# MID-AMERICA TRANSPORTATION CENTER

Report # MATC-UNL: 055

Final Report
WBS:25-1121-0003-055

# Dilemma Zone Protection on High-Speed Arterials


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2014


A Coopertative Research Project sponsored by
U.S. Department of Tranportation-Research, Innovation and Technology Innovation Administration

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A Report on Research Sponsored by

Mid-America Transportation Center

University of Nebraska-Lincoln

March 2014

## Technical Report Documentation Page

| 1. Report No.<br>25-1121-0003-055 | 2. Government Accession No. | 3. Recipient's Catalog No. | |
|---|---|---|---|
| 4. Title and Subtitle<br>Dilemma Zone Protection on High-Speed Arterials | | 5. Report Date<br>March 2014 | |
| | | 6. Performing Organization Code | |
| 7. Author(s)<br>Bhaven Naik and Justice Appiah | | 8. Performing Organization Report No.<br>25-1121-0003-055 | |
| 9. Performing Organization Name and Address<br>Nebraska Transportation Center<br>2200 Vine St.<br>PO Box 830851<br>Lincoln, NE 68583-0851 | | 10. Work Unit No. (TRAIS) | |
| | | 11. Contract or Grant No. | |
| 12. Sponsoring Agency Name and Address<br>Mid-America Transportation Center<br>2200 Vine St.<br>PO Box 830851<br>Lincoln, NE 68583-0851 | | 13. Type of Report and Period Covered<br>August 2012-July 2013 | |
| | | 14. Sponsoring Agency Code<br>MATC TRB RiP No. 32778 | |
| 15. Supplementary Notes | | | |

16. Abstract

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| 17. Key Words<br>Dilemma Zone, Advance Warning, VISSIM, SSAM | | 18. Distribution Statement | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>76 | 22. Price |

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Acknowledgments

We would like to acknowledge the contributions of numerous individuals and organizations that made the successful completion of this project possible. We are especially grateful to:

- The Federal Highway Administration for making the Surrogate Safety Assessment Module available to us; and
- The business team at the Mid-America Transportation Center who provided technical support.

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## Abstract

Driver behavior within the dilemma zone can be a major safety concern at high-speed signalized intersections, especially for heavy trucks. The Nebraska Department of Roads (NDOR) has developed and implemented an Actuated Advance Warning (AAW) dilemma zone protection system. The AAW system has been documented as being effective at improving traffic safety at isolated signalized intersections. However, the system is yet to be used at signalized intersections operating in the coordinated mode.

This study tested the feasibility of deploying the system on arterials where the signals are closely spaced and operate in a coordinated mode. A microsimulation approach – integration of traffic microsimulation and surrogate safety performance measures – was developed to assess the potential benefits (safety and operational) in-lieu of observed traffic and crash data. The analysis of conflicts indicated that, on average, there were 30%, 7%, and 30% reductions in the number of rear-end, lane change, and crossing conflicts respectively when the AAW system was used. In terms of the relative productivity of the system, the number of vehicles that were processed during a specified analysis period revealed that there were generally more vehicles processed when the AAW system was not in place. Also, the overall link travel times were slightly higher when the system was in place.

It should be noted that this research established a starting point for NDOR to make more informed decisions about where to deploy AAW devices, though a field evaluation involving real data is recommended.

# Chapter 1 Introduction

## 1.1 Background

Driver behavior within the dilemma zone can be a major safety concern at high-speed signalized intersections, especially for heavy trucks. The Nebraska Department of Roads (NDOR) has developed and implemented an actuated advance warning dilemma zone protection system. The system continually monitors traffic at an upstream detector as well as at stop line detectors to predict the onset of the yellow indication and provides information to drivers (via flashing signal heads and a warning sign) regarding whether they should be prepared to stop as they approach a traffic signal.

The system has been documented as being effective at improving traffic safety at isolated signalized intersections where the controller operates in the fully actuated mode. The NDOR is currently considering the feasibility of deploying these devices on its coordinated arterials.

One objective of this research is to test the feasibility of deploying the NDOR actuated advance warning system on coordinated arterials. A traffic microsimulation model was developed and further used to test the potential benefits of deploying the NDOR system on coordinated arterials. The findings of this study will help the NDOR make more informed decisions about where to deploy the system.

## 1.2 Problem Statement

As a signal indication changes from green to yellow, drivers must decide whether to stop or proceed through the intersection. The section of roadway upstream of the intersection in which neither decision is satisfactory is known as the dilemma zone. In the dilemma zone, some drivers might stop abruptly, thereby increasing the risk of rear-end collisions; others might proceed through the intersection and thus increase the risks of red light running and right-angle collisions with vehicles entering the intersection from the cross road. Common mitigation strategies have involved the three complementary techniques of signal timing, vehicle detection, and advance warning.

The NDOR was one of the first state transportation agencies to implement advance detection systems at isolated intersections. These systems provide information (via flashing signal heads and a warning sign) to drivers regarding whether they should be prepared to stop as they approach a traffic signal. The decision on whether to provide information to the drivers is a function of a number of parameters including the presence of vehicles on the roadway (identified via an upstream detector), the phase sequence, and where in the cycle the current signal timing plan is operating. A number of states have adopted similar systems; however, the operating algorithm is unique to Nebraska. The successes of the NDOR system at improving intersection safety at isolated signalized intersections operating in the fully-actuated mode have been documented (McCoy and Pesti 2002, Appiah et al. 2011). However, the system is yet to be deployed at closely-spaced high-speed signalized intersections operating in the coordinated mode.

### 1.3 Objectives

While it is common practice in traffic control not to combine dilemma zone protection and signal coordination (because the fixed time features of coordinated signals typically overrides any detectors providing dilemma zone protection), the reality is that this often occurs. It is hypothesized that as cities grow and many signalized intersections operate in the coordinated mode rather than the fully actuated mode, keeping the NDOR actuated advance warning system may have some benefit and will not result in riskier driver behavior such as red-light running and abrupt stopping. This study will test this hypothesis by studying the potential benefits of deploying the NDOR dilemma zone protection system on high-speed arterials operating in the coordinated mode.

## 1.4 Relevance to MATC Thematic Thrust Areas

This research is directly related to the US DOT's Strategic Goal of "enhancing safety." Additionally, motor vehicle traffic crashes exact a severe toll in loss of life, injuries, property damage, and reduced productivity. The findings of this research will improve the region's economic competitiveness by helping identify where implementation of the NDOR system are likely to be beneficial and thus promote better allocation of highway funds.

## 1.5 Research Approach and Methods

The research approach involved emulating traffic operations on a selected arterial using the VISSIM microscopic traffic simulation software. Vehicle trajectory data collected from the VISSIM model were analyzed using the Federal Highway Administrations' Surrogate Safety Assessment Model (SSAM). The integration of microsimulation and surrogate safety performance measures allowed for the assessment of the benefits (safety and operational) in-lieu of observed traffic and crash data.

## 1.6 Organization

This report is organized into five chapters. Chapter 1 is an introduction to the research work and discusses the background of the problem, the problem statement, research objectives, relevance to MATC theme, research approach, and the organization of the report. A review of past research work is compiled in Chapter 2. Chapter 3 presents details on the research methodology including concepts of traffic microsimulation modeling, the surrogate safety assessment module, and the simulated test corridor. Chapter 4 discusses the analyses to identify the potential of using the NDOR actuated advance warning system. Chapter 5 provides conclusions and suggestions for further research.

# Chapter 2 Literature Review

## 2.1 Dilemma Zone

At high-speed signalized intersections, there exists an area upstream of the intersection – a dilemma zone, inside which the potential for vehicle crashes is high. The dilemma zone often poses a problem for drivers in stopping safely during the yellow interval or proceeding through the intersection before the beginning of the red interval. This is because a driver is exposed to a potentially hazardous scenario in which a rear-end crash may occur if an abrupt stop is made during the yellow interval or an angle crash may occur if an attempt to proceed through the intersection is made at the onset of the red interval. There are generally two types of dilemma zones; Type I and Type II.

### *2.1.1. Type I Dilemma Zone*

The Type I dilemma zone is more traditional and is defined as the area in which, at the onset of yellow, a driver has neither sufficient distance to bring his/her vehicle to a comfortable stop nor sufficient intergreen time to proceed safely through the intersection before the signal indication changes to red (Gazis et al. 1960). Figure 2.1 depicts the traditional Type I dilemma zone.

### *2.1.2. Type II Dilemma Zone*

The Type II dilemma zone, as shown by figure 2.2, was formally identified in a technical report by the Southern Section of the Institute of Transportation Engineers (ITE 1974). The Type II dilemma zone is defined as the region which begins at the point on the roadway upstream of the signalized intersection where most drivers choose to stop the vehicle when presented with the yellow indication and ends at the point where most drivers choose to continue through the intersection. Strict definitions of the boundaries for the Type II dilemma zone are difficult to define because they are dynamic in nature and directly influenced by driver decision making. Several researchers have provided methods to quantify the location of the Type II dilemma zone (McCoy and Pesti 2002, Chang et al. 1985, Zegeer and Deen 1978).

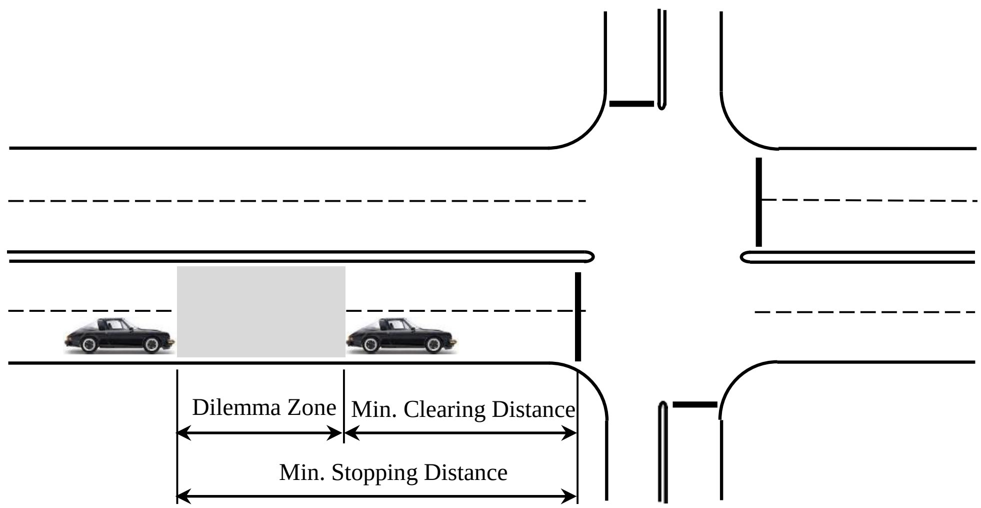



**Figure 2.1** Type I dilemma zone (Gazis et al., 1960)

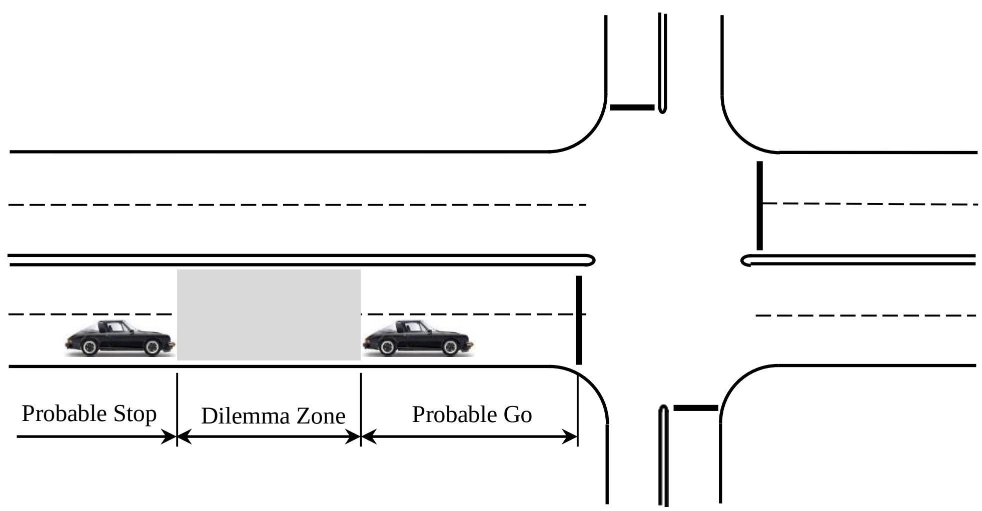



**Figure 2.2** Type II dilemma zone (ITE, 1974)

## 2.2. Dilemma Zone Protection

In theory, it is possible to eliminate the dilemma zone through proper timing of the traffic signal. However, the stochastic nature of driving means that some drivers will invariably find themselves in the dilemma zone. For example, they may misjudge the distances involved and elect to stop when they should proceed, they may have slower perception/reaction times than the design driver, or their vehicles may lack the necessary braking power required. Because drivers exhibit distinct differences in their desire or ability to stop when they are in the dilemma zone at the onset of the amber indication, they are potentially at risk of being in a crash. In other words, some drivers may stop abruptly, therefore increasing the risk of a rear-end collision and other drivers might proceed through the intersection which increases the risk of red-light running and the possibility of a right-angle collisions with vehicles entering the intersection from the cross road.

The potentially negative impact of dilemma zones on the operational capacity and safety of signalized intersections, especially at high-speed locations, has prompted a great deal of effort focused on the mitigation of the dilemma zone issue. These mitigation efforts include 1) reducing the likelihood of a driver being in the dilemma zone at the onset of the amber indication, 2) increasing the awareness of the driver that the green indication will be changing from red to amber in the near future thus allowing them a greater probability of choosing the appropriate action, or 3) both options 1 and 2 above. The common methods of providing dilemma zone protection at high-speed signalized intersections are the use of advanced detection, advance warning flashers, or a combination of both advance detection and advance warning flashers.

*2.2.1 Advance Detection (AD)*

Advance Detection (AD) has been used to provide dilemma zone protection at high-speed approaches to signalized intersections. In general, advance detection involves the placement of two to four detectors in each through lane of the high-speed approach, as depicted by figure 2.3. This detection is provided primarily by in-pavement inductive loops that allow for extensions to be added to the green such that vehicles can clear the intersection safely (Zegeer and Deen 1978).

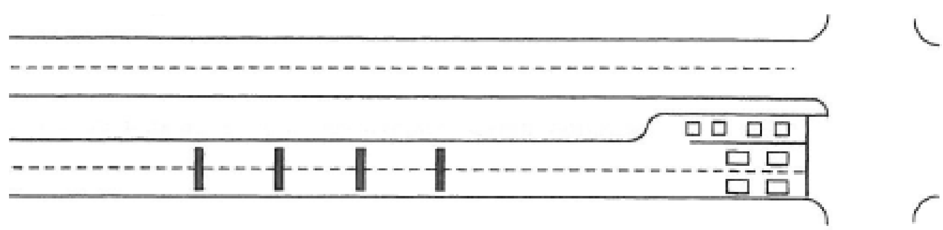


**Figure 2.3** Advance Detection (McCoy and Pesti, 2002)

Essentially, with AD the green is extended when the presence of a vehicle is detected at the upstream detectors. The amount of time by which the green is extended per actuation is known as the “passage time.” This varies from one system to the other but most systems implement a value of approximately 2 seconds per detector actuation (a total of 8 seconds for fig. 2.3 above). By extending the green time, the number of drivers that have to make a decision whether to stop or proceed through the intersection is reduced.

Recent computational advances have being incorporated to overcome the limitations of the traditional, multiple advance detector systems and therefore reap the full benefits of advance detection. Bonneson et al. (2002) developed an alternative detection and control system for providing dilemma zone protection for the Texas Department of Transportation. This system, referred to as the Detection-Control System (D-CS), uses external computer processing to intelligently forecast the best time to end the signal phase and then, in real time, instruct the signal controller to end the phase at the appropriate time. An evaluation study indicated that the D-CS was able to reduce delay by 14%, stop frequency by 9%, red-light violations by 58%, heavy-vehicle red-light violations by 80%, and severe crash frequency by 39% (Zimmerman and Bonneson, 2005).

Advances in detection technology, such as the Wavetronix SmartSensor Advance, have made it possible not only to detect the presence of a vehicle, but to dynamically (in real-time) identify individual vehicle approach speed and distance from stop bar in real-time and as such determine if the vehicle will be caught in a dilemma zone and need green extension.

In most situations advanced detection provides safety (Pant et al. 2005; Zimmerman 2007), but under moderately congested conditions, the green will be extended until it "maxes-out," exposing remaining vehicles to the hazard of a dilemma zone.

### *2.2.2 Advance Warning Flashers (AWF)*

Advance warning flasher (AWF) systems provide information to drivers via flashing signal heads and warning signs about whether they should be prepared to stop as they approach a signalized intersection. Typically, implementation of an AWF system includes a pair of flashing beacons mounted above a warning sign. A variety of warning sign and flasher combinations are being used. Sayed et al. (1999) categorized the available warning sign and flashers into three distinctive groups:


(a) (b)

**Figure 2.4** Advance Warning Flasher systems

(i) A warning sign with the text "*Prepare To Stop When Flashing*" complemented by a pair of flashing yellow beacons that begin to flash a predetermined time before the onset of the yellow interval and that continue to flash until the end of the red interval (Figure 2.4a)

(ii) A warning sign with a schematic of a traffic signal (instead of the "*Prepare To Stop When Flashing*" text) and complemented by a pair of flashing yellow beacons that operate in the same manner as (i) above. (Figure 2.4b)

(iii) A warning sign with a schematic of a traffic signal and complemented by a pair of flashing yellow beacons as in (ii) above, but the flashing yellow beacons flash all the time.

Of the three configurations of advance warning systems, a warning sign with the text "Prepare To Stop When Flashing" complemented by a pair of flashing yellow beacons (fig. 2.4a) is the most commonly adopted by departments of transportation.

Several researchers have undertaken projects aimed at quantifying the safety and operational effectiveness of AWF installations at high-speed signalized intersections. In terms of safety, AWF appear to lower left-turn, right-angle, and in some instances, rear-end crashes (Eck and Sabra 1985, Gibby et al. 1992, Klugman et al. 1992, Agent and Pigman 1994, and Sayed et al. 1999). In addition, Agent and Pigman (1994), and Knodler and Hurwitz (2009) found that the use of AWFs should be limited to locations with existing or high potential for vehicle crash problems, particularly a high percent of angle crashes. Gibby et al. (1992) provided more detail indicating that high-speed approaches with AWFs had significantly lower total, left-turn, right-angle, and rear-end approach crash rates than those without AWFs. Gibby et al. also observed significantly lower ratios of night-time crashes. The research performed by Klugman et al. (1992) in Minnesota concluded that the use of AWF devices could be effective at reducing right-angle and rear-end accidents under certain situations, but device usage does not automatically increase the safety of all intersections.

Sayed et al. (1999) provided the most detailed crash analysis, indicating that AWF intersections showed 10% fewer total crashes and 12% fewer severe crashes. Negligible reductions were observed with respect to rear-end crashes. The crash reduction was not statistically significant at the 95% level. Sayed et al. (1999) also found a correlation between the crash frequency of AWF sites and the minor street traffic volumes. It was observed that when the minor street traffic volumes are low, sites with AWF had a higher frequency of crashes than non-AWF sites; however, with increasing minor street traffic volumes, the crash frequency for

AWF equipped intersections was found to be lower than at non-AWF sites. The specific results indicated that AWFs were effective at locations with a minor street Annual Average Daily Traffic (AADT) of 13,000 vehicles per day (vpd) or greater.

In terms of operations, Farraher et al. (1999) collected data on red-light-running and vehicle speeds at an intersection with AWFs. Farraher et al. observed an overall reduction of 29% in red-light-running, a 63% reduction in truck red-light-running, and an 18.2% reduction in the speed of trucks. Although the data indicate that AWFs were effective at the site studied, the number of overall violators and their speeds remained unacceptably high (Farraher et al. 1999). Pant and Xie (1995) compared the way drivers respond to various types of AWF systems. The study was based on a speed and intersection conflict analysis and studied the effects of the three advance warning systems presented above. The authors found that both, a warning sign with the text "Prepare To Stop When Flashing" complemented by a pair of flashing yellow beacons; and a warning sign with a schematic of a traffic signal and complemented by a pair of flashing yellow beacons increased vehicular speeds. This increase in speeds was attributed to drivers' attempt to sneak through the yellow signal phases.

*2.2.3 Combined AD and AWF Systems*

Also available are a variety of dilemma zone protection systems that combine features of both advance detection and advance warning flashers. These modified systems are also referred to as Active Advance Warning Systems.

Messer et al. (2004) developed the Advance Warning for End-Of-Green System (AWEGS) for high-speed (≥ 45mph) traffic signals in Texas. The AWEGS uses a combination of advance detection and advance warning flashers. Three architectures of AWEGS were examined during the course of the study: Levels 0, 1, and 2. The Level 1 technology used “trailing overlaps” to provide a fixed amount of advance warning of the end-of-green phase, but this method was rejected because it gave up existing dilemma zone protection. The Level 1 technology, using average speed while still predicting when the traffic-actuated controller would gap-out, was substituted. The Level 2 AWEGS added a feature that was capable of identifying aggregate vehicle classification (car, truck) and individual speed measurement to better estimate when the signal controller would gap-out. The AWEGS was found to reduce red-light running, during the targeted first 5 seconds of red, by 38-42% (Sunkari et al. 2005). The Level 2 architecture was the more preferred option because it improved operations (provided less delay) and safety by providing extra dilemma zone protection for trucks and high-speed passenger cars.

The Nebraska Department of Roads (NDOR) developed a system (referred to as an Actuated Advance Warning [AAW] system) that also combines AD and AWF systems with the legend “PREPARE TO STOP WHEN FLASHING” as shown in figure 2.5. The system has one advance detector in each approach lane as well as an AWF assembly positioned on either side of the roadway approach downstream of the advance detector. In addition stop line detection is also provided in the through lanes and left-turn bays. The range of stop-line detection is 30 to 40 feet in the left-turn bays. The advance detector operates in the pulse mode, which means that each

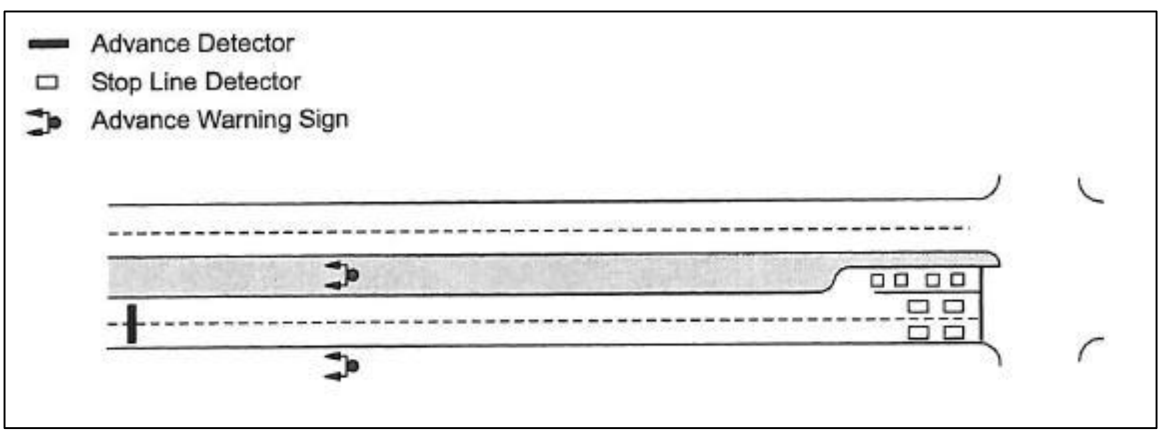



**Figure 2.5** Schematic diagram of NDOR AAW system (McCoy and Pesti, 2002)

vehicle crossing the detector transmits a single pulse to the controller, regardless of the time that the vehicle spends in the detection area. The stop line detectors operate in the presence mode (a continuous call is transmitted to the controller as long as a vehicle is within the detection area) but are not active during the extendible portion of the green interval (McCoy and Pesti 2002). Specific details on the operation of the AAW system are available in the literature (McCoy and Pesti 2002).

In general, the design algorithm combines the functionality of advance detection and advance warning, and uses a shorter maximum allowable headway (MAH) to extend the green (McCoy and Pesti 2003). A study evaluating the safety effectiveness of the NDOR system showed crash reduction rates of 0.5% for heavy vehicle crashes, 1.2% for rear-end crashes, 43.6% for right-angle crashes, 11.3% for injury crashes and 8.2% for all crashes combined (Appiah et al. 2011). In addition, the system improved operations at signalized intersections by reducing delay on minor approaches (Appiah et al. 2011).

### 2.3 Summary

Driver behavior within the dilemma zone can be a major safety concern at high-speed signalized intersections. The common methods to mitigate the potential risks of the dilemma zone are the use of, 1) Advanced Detection, 2) Advance Warning Flashers, or 3) a combination of both Advance Detection and Advance Warning Flashers. AWS literature indicates that these systems have been effective in reducing the number of vehicles caught in the dilemma zone and consequently, there is a reduction in the number of vehicle crashes. There is also evidence of these systems having a positive effect on driver behavior – reduced approach speeds and reduced red-light running. Most applications of the dilemma zone protection systems discussed above have been in the context of isolated intersections, that is, the dilemma zone protection systems have been deployed and evaluated at locations outside of city limits where the approach speeds are greater than 40mph. However, not all intersections are isolated. As cities grow, the systems that were initially deployed at isolated locations can become part of arterials where the signals are closely spaced and operate in a coordinated mode. While it is not an option to provide green extension(s) using AD in a coordinated setting, the use of AWF (or a combination of both AD and AWF) remains an option. There can be a significant difference between driver behavior in isolated versus coordinated settings, so there is need to assess the potential effectiveness of dilemma zone protections systems when deployed in a coordinated environment.

# Chapter 3 Research Methodology

This chapter provides a description of the methodology used to evaluate the potential of deploying NDOR’s Actuated Advance Warning (AAW) system on roadway sections where the traffic signals operate in a coordinated mode. A microsimulation approach was used as opposed to a conventional before-after study because (i) at the time of this research, there were no known coordinated corridors on which the NDOR had deployed their AAW system, and (ii) microsimulation allows for testing hypothetical scenarios which may not be possible with field studies.

The use of traffic microsimulation models in traffic operations, transportation design, and transportation planning has become widespread across the United States because of: (1) the rapidly increasing computer power required for complex micro-simulations; (2) the development of sophisticated traffic microsimulation tools; and (3) the need by transportation engineers to solve complex problems that do not lend themselves to traditional analysis techniques. Microscopic traffic simulation models closely mimic the stochastic and dynamic nature of both the vehicle-to-vehicle and vehicle-to-traffic interactions that occur within the transportation system.

Safety is often measured by recording the number and severity of actual crash occurrences, however, the FHWA has suggested microsimulation as a viable approach to safety analysis especially for new facilities and in situations where there is not enough crash data to allow for reliable statistical analysis. As noted by the FHWA, the use of microsimulation circumvents the need to wait for “abnormally high” crashes to actually occur and allows assessments of hypothetical alternatives (Gettman et al. 2008).

This study utilized the Surrogate Safety Assessment Model (SSAM), a tool developed by the FHWA that combines microsimulation and automated conflict analysis to assess the safety of traffic facilities. SSAM analyzes vehicle trajectory files produced by VISSIM and other microsimulation models to identify and classify conflict events on the basis of conflict angle and several surrogate safety measures, including post-encroachment time and time-to-collision, which are considered "valid and reliable precursors of actual crashes" (Archer and Young 2009).

## 3.1 Traffic Microsimulation: VISSIM

VISSIM is a discrete, stochastic, time step based microscopic traffic simulation model with driver-vehicle-units modeled as single entities. It was developed by Planung Transport Verkehr in Germany (PTV 2011). The model consists internally of two distinct components that communicate through an interface – first, a traffic simulator that simulates the movement of vehicles and generates the corresponding output and second, a signal state generator that determines and updates the signal status using detector information from the traffic simulator on a discrete time step basis. The input data required for VISSIM include network geometry, traffic demands, phase assignments, signal control timing plans, vehicle speed distributions, and the acceleration and deceleration characteristics of vehicles. VISSIM allows the user to model traffic signals using different control types, such as pre-timed, RBC standard signal control emulator (which can operate in fully actuated, coordinated, or semi-actuated coordinated modes), and vehicle actuated programming (VAP). The model is also capable of producing measures of effectiveness commonly used in the traffic engineering profession, including average delay, queue lengths, and fuel emissions (Ambadipudi et al. 2006).

To ensure the validity and reliability of results from microsimulation models, the parameters that govern the underlying car-following, lane-changing, and gap-acceptance models are calibrated and validated against observed traffic data. While the authors acknowledge that it is an important step to calibrate and validate a microsimulation model, the model(s) developed for this particular project were not calibrated and validated. Because the research objective was primarily to assess output from simulated alternatives, it was determined that using default parameter values would not affect the results.

## 3.2 Simulated Test Bed

After consulting with engineers at the NDOR and the city of Lincoln, the Highway 2 corridor from 56th street to 14th street in Lincoln, Nebraska was identified as the test bed for this study. This section of Highway 2 has two lanes in both directions of travel, a posted speed limit of 45 mph, the traffic signals are coordinated, and the traffic volumes are relatively high. Additionally, this corridor section is a major conduit for both passenger vehicles and heavy vehicles (trucks). Figure 3.1 depicts the suggested test corridor. The entire corridor is approximately 3.5 miles long with six signalized intersections spaced at an average distance of 0.5 miles apart. Specific details of the roadway sections between traffic signals are presented in table 3.1.

## 3.3 Model Development

The majority of the supply input data was obtained from engineering drawings and signal timing plans provided by the public works department of the city of Lincoln. The signal control information included phase assignments, maximum and minimum green times, detector lengths and locations, passage times, and detector call options. The specific traffic detection type (video or loop) at each intersection was obtained from intersection blueprints and coded accordingly.

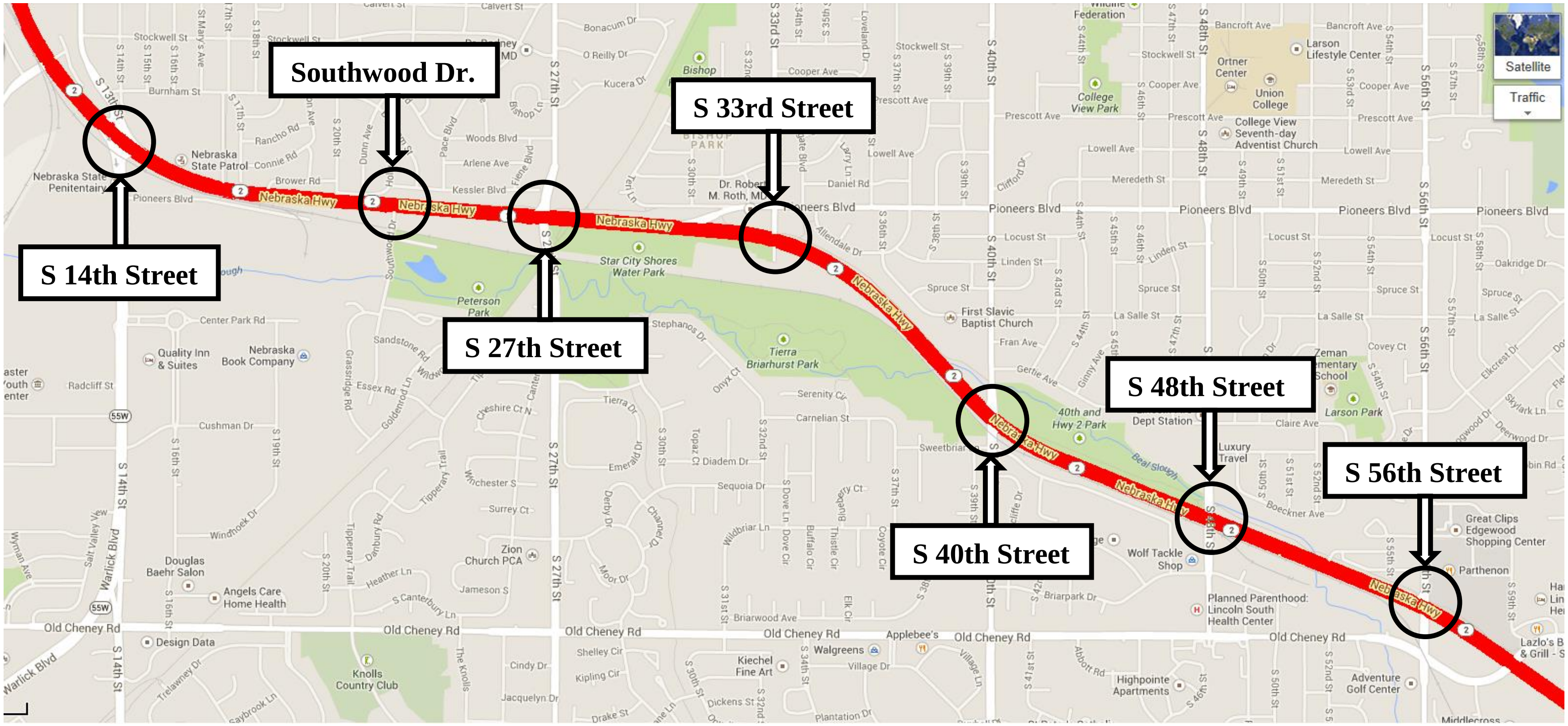



**Figure 3.1** Simulated test-bed: Highway 2 Lincoln, NE

**Table 3.1** Characteristics of roadway section

| Signals | | Dist. between signals (mile) | No. of lanes | Posted speed limit (mph) |
|---|---|---|---|---|
| To | From | | | |
| S 14th St. | Southwood Dr. | 0.7 | 2 | 45 |
| Southwood Dr. | S 27th St. | 0.3 | 2 | 45 |
| S 27th St. | S 33rd St. | 0.5 | 2 | 45 |
| S 33rd St. | S 40th St. | 0.7 | 2 | 45 |
| S 40th St. | S 48th St. | 0.5 | 2 | 45 |
| S 48th St. | S 56th St. | 0.5 | 2 | 45 |

The traffic controllers were coded in VISSIM using the Vehicle Actuated Programming (VAP) language. Other supply data sources included background images downloaded from Google Earth. These were used to trace the network in VISSIM and extract data such as number, length, and width of lanes as well as other distinguishing features related to the geometry of the road network.

The demand data, including traffic volumes and intersection turning ratios, were extracted from SYNCHRO files obtained from the Public Works Department of the city of Lincoln. This demand data was inputted into the VISSIM model as aggregated peak hour volumes with specific turning ratios at intersections. In terms of vehicle classification, the “Car,” and the “HGV” vehicle types were used. Default performance attributes for these vehicle types were utilized (PTV 2011). A traffic composition of 90% passenger cars and 10% heavy vehicles was adopted.

The NDOR AAW system, consisting of one advance detector in each approach lane as well as an advance warning flasher assembly positioned on either side of the roadway approach downstream of the advance detector, were also modeled in VISSIM. Specific details of the operation of the AAW system are presented in chapter 2 and are also available in the literature (McCoy and Pesti 2002). Figure 3.2 depicts a snapshot of part of the VISSIM microsimulation

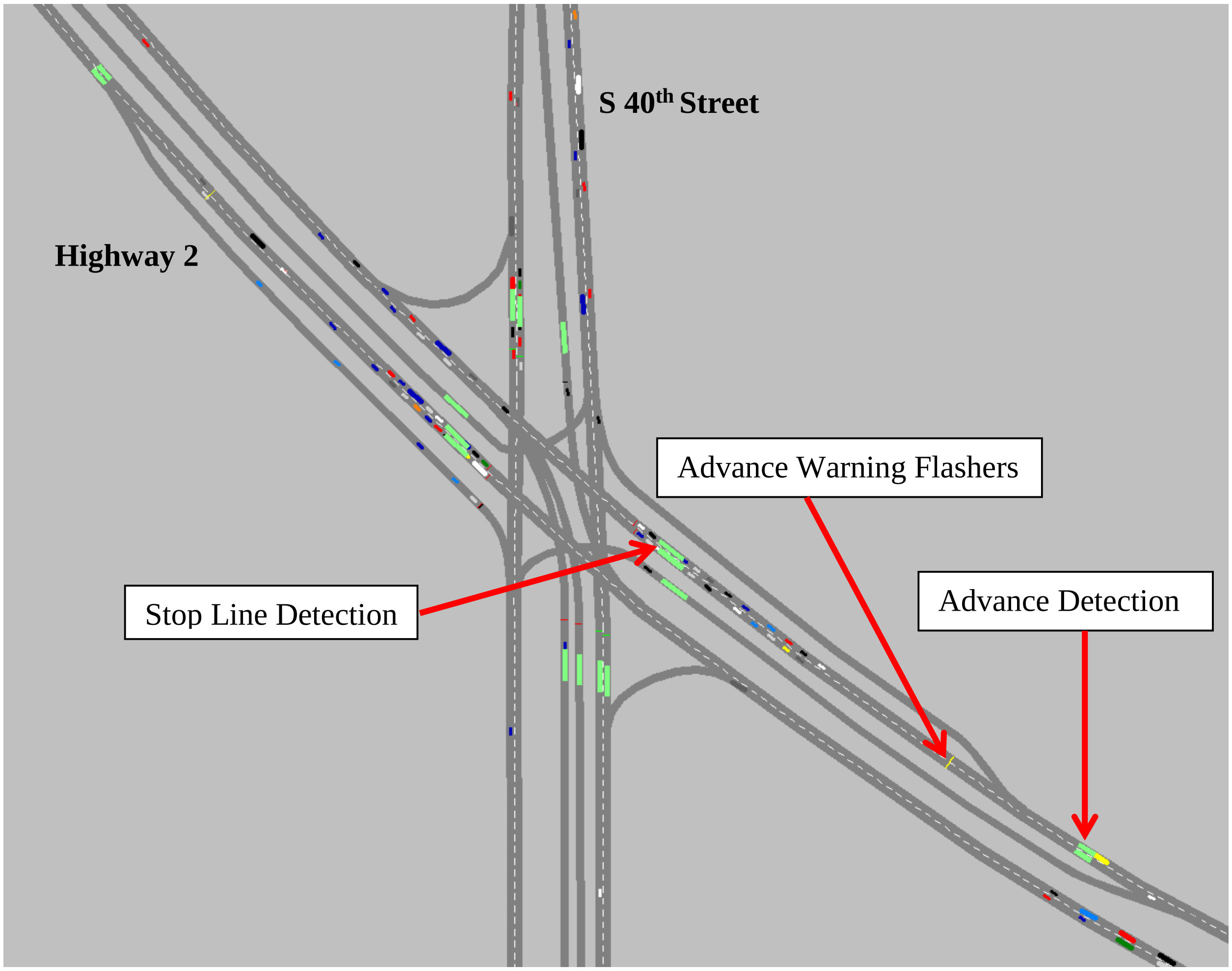



**Figure 3.2** Screen shot of microsimulation model

model. This figure features the intersection of S 40th Street and Highway 2 with the AAW system in place.

## 3.4 Simulation Runs

Two VISSIM models were developed: a base model where signals operate in coordination and there are no AAW systems, and an alternate model where signals are coordinated and AAW systems are present. Each model was simulated for two hours, with the first hour serving as a warm-up period during which traffic was loaded onto the network and the system was allowed to reach equilibrium.

By their nature, microsimulation models are deterministic, meaning they will provide the same output given the same input. Using different random seeds, however, generates stochastic variation in the input arrival flow patterns. Consequently, the results of each simulation run is usually close to the average of all runs, but each run will be slightly different from the others (Dowling et al. 2004). In this research the same 20 random seeds were used to model each alternative, thus each alternative was modeled with the same arrival flow pattern and a direct comparison could be made between alternatives. Vehicle trajectory files from the simulation runs were exported to FHWA's SSAM software for conflict analysis. Results of the 20 replications were then averaged to obtain the desired measures of performance.

# Chapter 4 Analysis and Results

This chapter presents results of the simulation modeling discussed in chapter 3. The effects of adopting the NDOR AAW system on coordinated arterials was evaluated on the basis of three measures: 1) conflicts, 2) throughput, and 3) travel times.

## 4.1. Conflict Analysis

It is a common practice in highway safety research to rely on actual crash statistics when addressing safety-related concerns, such as evaluating the effects of a safety countermeasure or program, identifying hazardous locations (black spots), and remedying irresponsible driver behaviors. While crash data has proven to be useful, there are serious limitations to their availability. To overcome this shortcoming, forms of non-accident information such as traffic conflicts have been employed. Traffic conflicts have long been used by highway engineers when exercising ‘engineering judgment’ to identify hazardous locations on the highways (Baker, 1977). By definition, a traffic conflict is “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remained unchanged” (Hyden, 1977).

For this study, a conflict analysis was conducted by comparing the SSAM surrogate safety measures obtained from a base microsimulation model with those measures obtained from an alternate model. The specific measures that were compared include post-encroachment time (PET) and time-to-collision (TTC). Both the PET and TTC are considered “indicators of crash propensity with smaller minimum values indicating a greater likelihood of a crash occurring” as depicted in figure 4.1 (Chin and Quek 1997). It can also be observed that non-conflicts form the majority of observed events, while the observed frequency or probability of occurrences decreases with increasing severity.

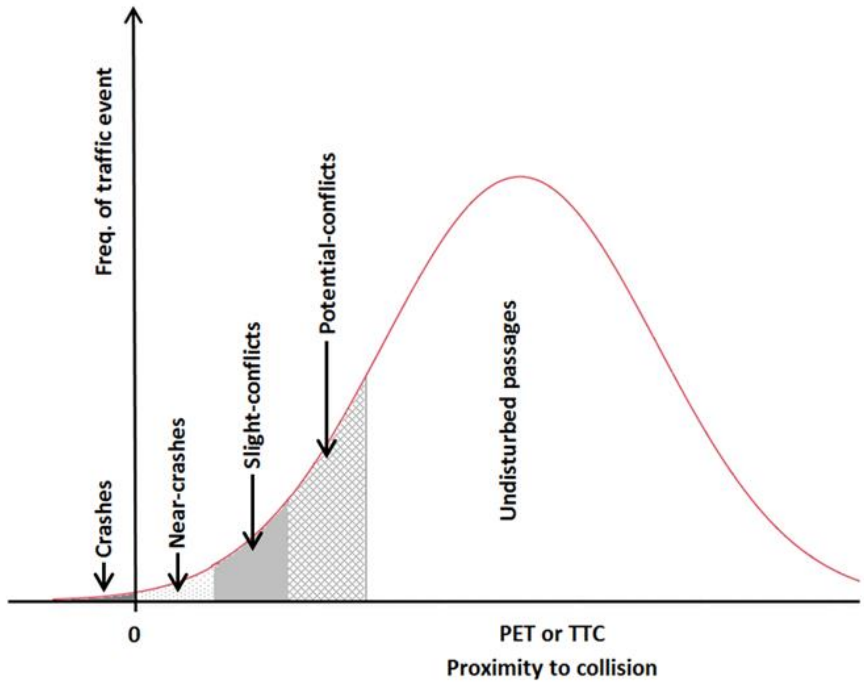



**Figure 4.1** Representation of traffic conflicts (Glauz and Migletz, 1980)

Conflicts from the two simulation models (base and alternate) were compared for the signalized intersections at Southwood Drive, 27th street, 33rd street, and 40th street.

*4.1.1. Distributions of Time to Collision (TTC) and Post-Encroachment Time (PET)*

The potential benefits of using the AAW system in coordinated arterials can be shown by comparing counts of potentially hazardous situations (conflicts), as will be seen in the next section. By establishing statistical distributions of the vehicle-vehicle interactions, the proportion of critical situations (conflicts) is not merely counted, but derived mathematically (Chin and Quek 1997).

4.1.1.1 Time-to-Collision

Time-to-collision is the projected time for two vehicles to collide if they continued at their present speed and stayed on the same path. VISSIM vehicle trajectory files were processed in SSAM to yield conflicts using a user-defined maximum threshold TTC value. Conflict data and surrogate safety measures for only those vehicle-to-vehicle interactions less than the user-defined threshold were outputted. Based on the relationship between conflict speed, time-to-accident, and conflict severity developed by Hyden (1987) and shown in figure 4.2, a TTC threshold of 3.00 seconds was used to identify serious conflicts. The dashed line denotes the TTC value for the speed limit of 45 mph (72 km/h) on the Highway 2 test bed.

The frequency distributions for the TTC were developed as shown in Figure 4.3. The figure depicts both the frequency and cumulative frequency for both the base and alternate models. For illustration purposes, only distributions from the 27th street intersection are shown. Distributions for all other intersections are provided in Appendix A.

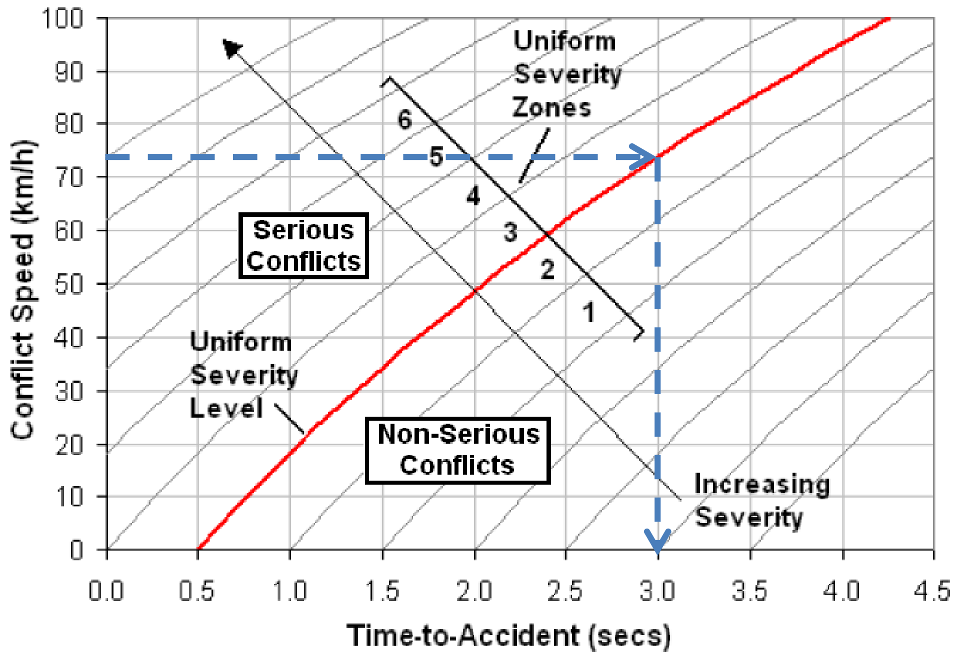



**Figure 4.2** Severity levels and severity zones (Hyden 1987)

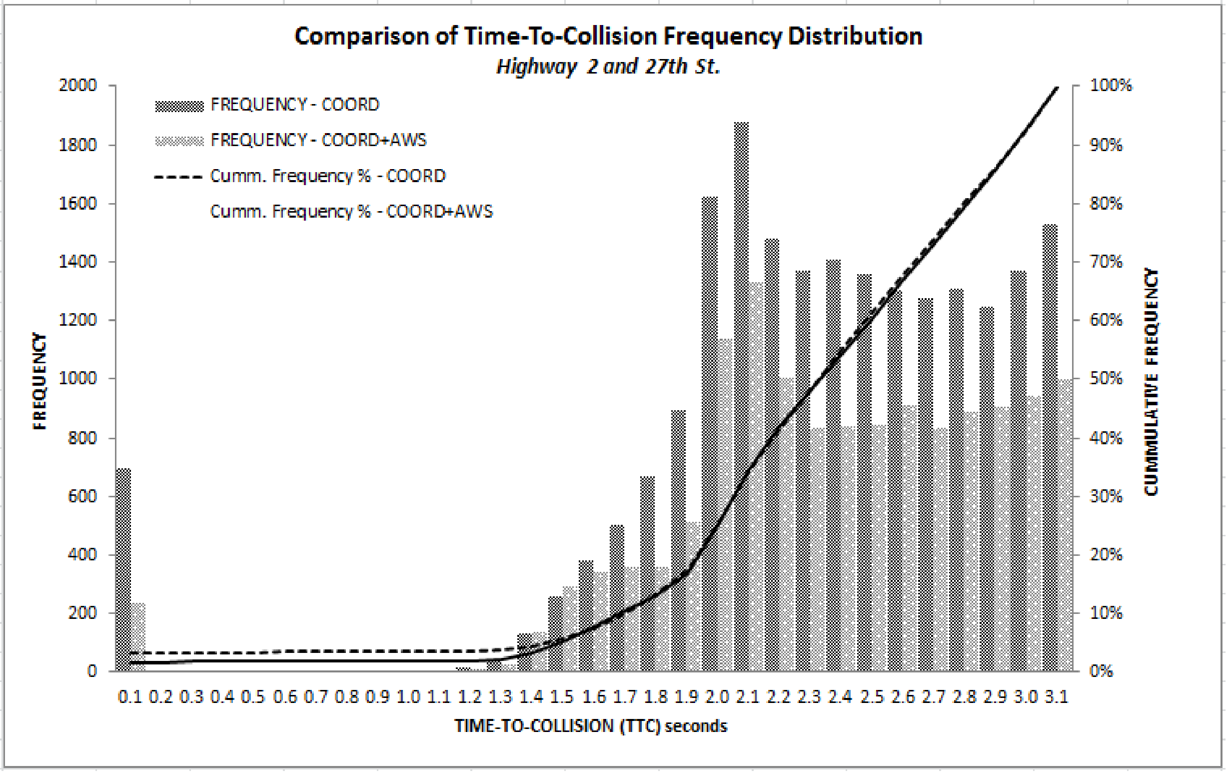



**Figure 4.3** TTC frequency distributions – 27th street

Figure 4.3 compares the distributions of the base and alternate models. It can be observed that the shape of cumulative distributions is similar for both models. However, the frequency distribution indicates that there are fewer conflicts in the alternate model than the base model. This is an indication that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. Table 4.2 shows that both models have the similar TTC distributional characteristic.

**Table 4.2** Characteristics of TTC distributions

| | Conflicts | TTC Characteristics | | | |
|---|---|---|---|---|---|
| | | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 20796 | 2.23 | 0.60 | 1.83 | 2.84 |
| Alternate Model (COORD+AWS) | 13779 | 2.26 | 0.54 | 1.83 | 2.84 |

4.1.1.2 Post-Encroachment Time

Post-encroachment time is defined as the elapsed time between the departure of an encroaching vehicle and the arrival of a trailing vehicle at the same position. The default SSAM maximum threshold value of 5.00 seconds was used for this study. The frequency distributions for the PET were developed as shown in figure 4.4. The figure depicts both the frequency and cumulative frequency for both the base and alternate models. Only the distributions for data from the 27th street intersection are shown, but distributions for all other intersections are provided in Appendix B.

As with the TTC, figure 4.4 shows that the shape of the cumulative distribution of all conflicts is similar for both models. The cumulative frequency distribution curve for the base model is above that of the alternate model indicating that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. Table 4.3 shows that both models have similar PET characteristic values.

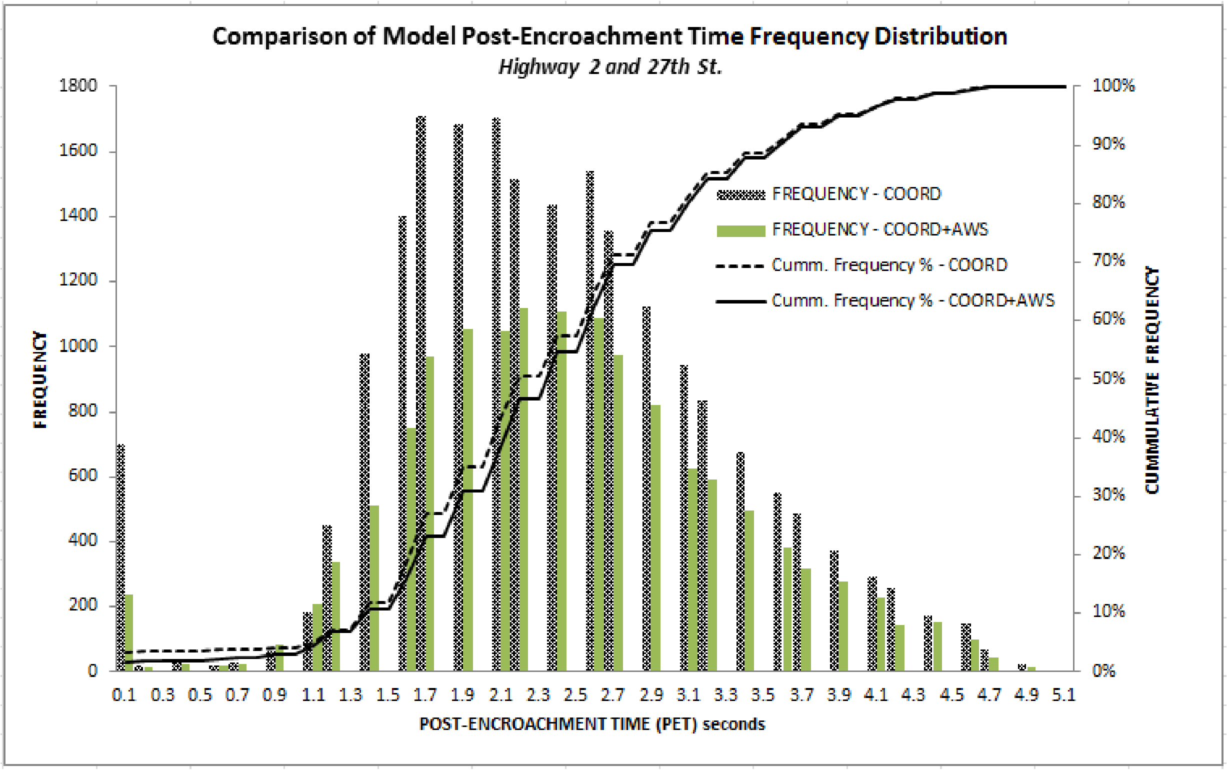



**Figure 4.4** PET frequency distributions – 27th street

**Table 4.3** Characteristics of PET distributions

| | | PET Characteristics | | | |
|---|---|---|---|---|---|
| | Conflicts | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 20796 | 2.30 | 0.90 | 1.50 | 3.25 |
| Alternate Model (COORD+AWS) | 13779 | 2.37 | 0.86 | 1.53 | 3.27 |

### *4.1.2. Number of Conflicts*

Based on the TTC and PET values, the conflicts are classified within SSAM into three types: rear-end, lane change and crossing, as presented in table 4.4. Overall, it can be observed that for all 20 simulation runs, there was a reduction in all three conflict types when the NDOR AAW system was being used with the signals in coordination mode. On average, there were

30%, 7% and 30% reductions in rear-end, lane change and crossing conflicts, respectively, across all four intersections.

Paired T-tests were performed to check if there were statistically significant differences in the number of conflicts between the models.

**Table 4.4** Comparison of conflict frequencies

| COORDINATED ONLY | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| All Conflict Types | Southwood Drive | | 27th Street | | 33rd Street | | 40th Street | |
| All Conflicts | 9109 | **(455)** | 20796 | **(1040)** | 12279 | **(614)** | 17429 | **(871)** |
| Rear-End Conflicts | 8577 | **(429)** | 18380 | **(919)** | 11028 | **(551)** | 15315 | **(766)** |
| Lane Change Conflicts | 475 | **(24)** | 2158 | **(108)** | 931 | **(47)** | 1855 | **(93)** |
| Crossing Conflicts | 57 | **(3)** | 258 | **(13)** | 320 | **(16)** | 259 | **(13)** |

| AAW + COORDINATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| All Conflict Types | Southwood Drive | | 27th Street | | 33rd Street | | 40th Street | |
| All Conflicts | 5938 | **(297)** | 13779 | **(689)** | 7541 | **(377)** | 16637 | **(832)** |
| Rear-End Conflicts | 5396 | **(270)** | 11892 | **(595)** | 6497 | **(325)** | 14556 | **(728)** |
| Lane Change Conflicts | 492 | **(25)** | 1822 | **(91)** | 790 | **(40)** | 1856 | **(93)** |
| Crossing Conflicts | 50 | **(3)** | 65 | **(3)** | 254 | **(13)** | 225 | **(11)** |

The specific hypothesis tested was:

*Ho: number of conflicts from base model = number of conflicts from alternate model*

*Ha: number of conflicts from base model < number of conflicts from alternate model*

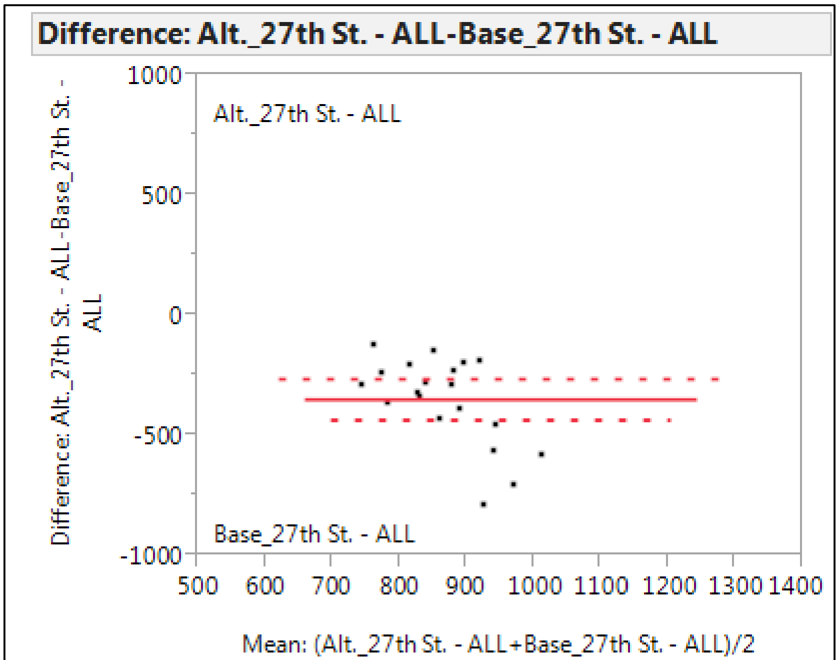
Where: conflicts = rear-end, lane change, crossing, and the total of all three conflicts types.

The paired T-tests were performed using the JMP software package. For illustration purposes only, output from tests on conflicts at the 27th street intersection are presented in figures 4.5 to 4.8. The output and corresponding conclusions for the intersections at Southwood Drive, 33rd street, and 40th street are provided in Appendix C.

*<u>27th street – All Conflict types</u>*

Figure 4.5 shows a plot and paired T-test summary. The values on the vertical axis are the paired differences between conflicts from the alternate model vs. base model. The horizontal axis value is determined by the average number of conflicts from each simulation. It can be observed from the plot that all of the paired differences are negative, which indicates that there were lesser conflicts in the alternate model (i.e., AAW in addition to coordination). The mean shift in number of conflicts (solid red line) appears to be around 375 conflicts. The plot also shows dashed lines that provide a 95% confidence interval for the true mean difference in conflicts. A horizontal line drawn at zero would not be contained within the 95% confidence interval and suggests there is enough evidence to reject the null hypothesis that there is no change in the number of conflicts between the two models.

Also, the p-value for the two-tailed test (Prob > |t|) is less than 0.05 indicating there is enough evidence to reject the null hypothesis, which states that there is no change in the mean number of conflicts between the base and alternate models. In addition, the result indicates that the number of conflicts is significantly lower for the alternate model.

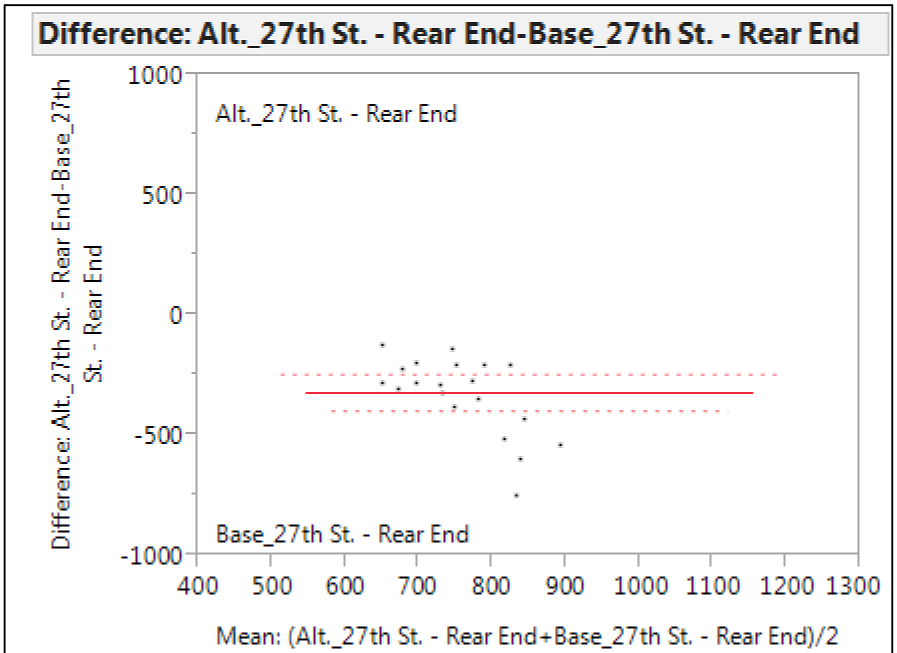



| | | | |
|---|---|---|---|
| Alt._27th St. - ALL | 688.95 | t-Ratio | -8.51781 |
| Base_27th St. - ALL | 1039.8 | DF | 19 |
| Mean Difference | -350.85 | Prob > \|t\| | <.0001* |
| Std Error | 41.1901 | Prob > t | 1.0000 |
| Upper 95% | -264.64 | Prob < t | <.0001* |
| Lower 95% | -437.06 | | |
| N | 20 | | |
| Correlation | -0.3021 | | |

**Figure 4.5** Paired T-test output for all conflict types – 27th street

*<u>27th street – Rear-End Conflicts</u>*

It can be observed from the plot in figure 4.6 that a horizontal line drawn at zero will not be contained within the 95% confidence limits (dashed red lines). Additionally, the two-tailed p-value is less than 0.05. This suggests that at the 95% significance level there is enough evidence to reject the null hypothesis, which states that there is no change in the mean number of rear-end conflicts between the base and alternate models, and conclude that the rear-end conflicts are significantly fewer from the alternate model (AAW system was used in addition to signal coordination). The results seem to suggest that drivers could be responding positively to the AAW system by slowing down as they approach the intersection.

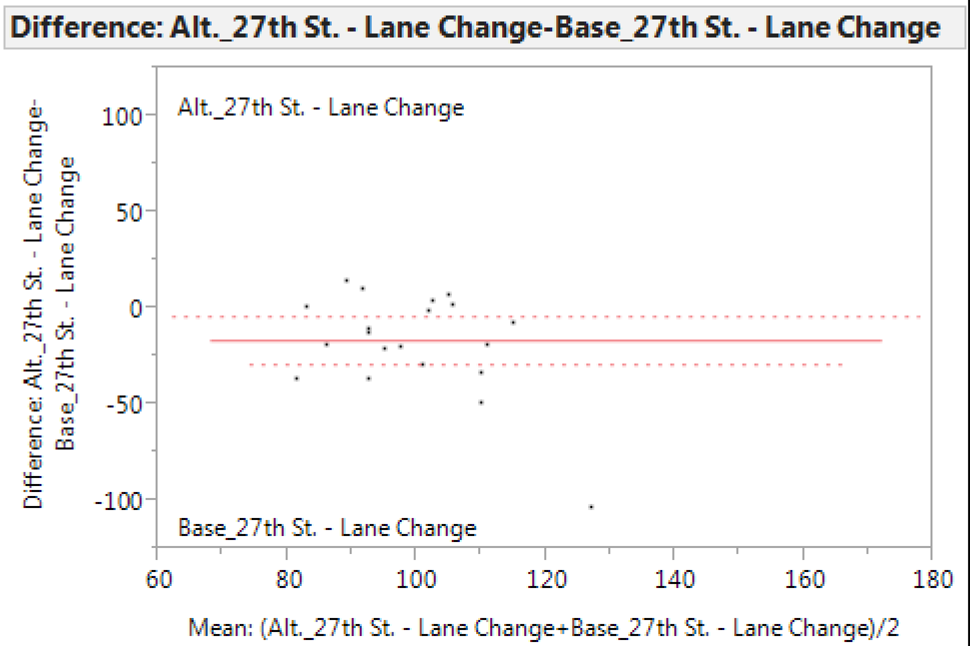



| | | | |
|---|---|---|---|
| Alt._27th St. - Rear End | 594.6 | t-Ratio | -8.87055 |
| Base_27th St. - Rear End | 919 | DF | 19 |
| Mean Difference | -324.4 | Prob > \|t\| | <.0001* |
| Std Error | 36.5704 | Prob > t | 1.0000 |
| Upper 95% | -247.86 | Prob < t | <.0001* |
| Lower 95% | -400.94 | | |
| N | 20 | | |
| Correlation | -0.2009 | | |

**Figure 4.6** Paired T-test output for rear-end conflicts – 27th street

*<u>27th street – Lane Change Conflicts</u>*

Figure 4.7 shows the output for the paired T-test performed on lane change conflicts. The p-values are less than 0.05, suggesting that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the lane change conflicts are not the same for both the base and alternate models. From the results, it can be concluded that there was a statistically significant decrease in lane change conflicts when the AAW system was used in addition to signal coordination on a corridor.

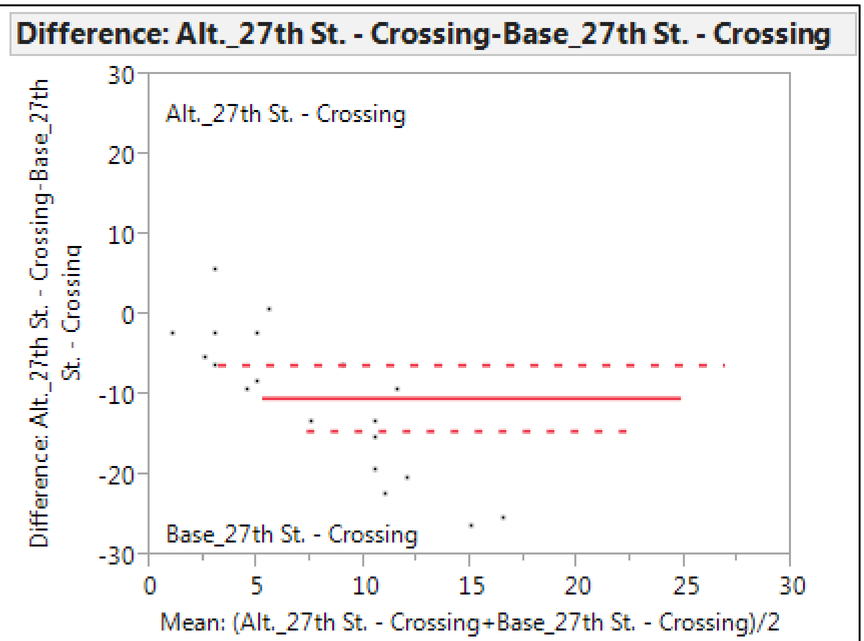



| | | | |
|---|---|---|---|
| Alt._27th St. - Lane Change | 91.1 | t-Ratio | -2.82413 |
| Base_27th St. - Lane Change | 107.9 | DF | 19 |
| Mean Difference | -16.8 | Prob > \|t\| | 0.0108* |
| Std Error | 5.94873 | Prob > t | 0.9946 |
| Upper 95% | -4.3492 | Prob < t | 0.0054* |
| Lower 95% | -29.251 | | |
| N | 20 | | |
| Correlation | -0.1545 | | |

**Figure 4.7** Paired T-test output for lane change conflicts – 27th street

*__27th street – Crossing Conflicts__*

In terms of crossing conflicts, it can be observed from figure 4.8 that there is enough evidence to reject the null hypothesis (p-values less than 0.05). Crossing conflicts are those conflicts that occur inside the intersection and are likely caused by vehicles entering the intersection at the onset of the amber indication or during the amber phase. The results of the




| | | | |
|---|---|---|---|
| Alt._27th St. - Crossing | 2.5 | t-Ratio | -5.25774 |
| Base_27th St. - Crossing | 12.9 | DF | 19 |
| Mean Difference | -10.4 | Prob > \|t\| | <.0001* |
| Std Error | 1.97804 | Prob > t | 1.0000 |
| Upper 95% | -6.2599 | Prob < t | <.0001* |
| Lower 95% | -14.54 | | |
| N | 20 | | |
| Correlation | -0.0105 | | |

**Figure 4.8** Paired T-test output for crossing conflicts – 27th street

paired T-test suggest that there is a lower number of crossing conflicts in the alternate model. This could be an indication of drivers responding to the AAW system, slowing down, and eventually coming to a safe stop.

In summary, statistically significant differences were observed between the conflicts observed from the base and alternate models. In fact, for all four intersections, the results also indicate that conflicts actually reduced with the alternate model.

## 4.2. Throughput Analysis

Throughput is defined as "an indicator of the relative productivity of the system" (FHWA 2007). It makes the analyst aware of the number of vehicles that were processed by the system during a specified analysis period. The throughput is compared for different alternatives to determine the relative productivity of each alternative. Higher values are desired. For this study, the number of vehicles that passed through each intersection during one hour was computed. Table 4.5 presents the throughput comparisons at each intersection. The throughput was computed as the 5-minute average of the 20 simulations and also as the total of the 20 simulations. Values of both the 5-minute average and total for the major approaches only (eastbound and westbound) are presented.

From table 4.5 it can be observed that the throughputs in the westbound direction are very similar at each intersection. In the eastbound direction, the throughputs are slightly lower when the AAW system is in place (alternate model). Figure 4.9 depicts the throughput comparisons.

**Table 4.5** Comparison of throughput

| Model | MOE's | WestBound | | | |
|---|---|---|---|---|---|
| | | Southwood Dr. | 27th St. | 33rd St. | 40th St. |
| Base Model (COORD) | 5-min Average (20 sims) | 108 | 86 | 100 | 83 |
| | Total (20 sims) | 1292 | 1027 | 1201 | 1001 |
| Alternate (COORD+AWS) | 5-min Average (20 sims) | 107 | 86 | 100 | 83 |
| | Total (20 sims) | 1287 | 1028 | 1199 | 999 |

| Model | MOE's | EastBound | | | |
|---|---|---|---|---|---|
| | | Southwood Dr. | 27th St. | 33rd St. | 40th St. |
| Base Model (COORD) | 5-min Average (20 sims) | 65 | 57 | 87 | 78 |
| | Total (20 sims) | 776 | 686 | 1039 | 932 |
| Alternate (COORD+AWS) | 5-min Average (20 sims) | 57 | 47 | 78 | 71 |
| | Total (20 sims) | 682 | 561 | 937 | 848 |

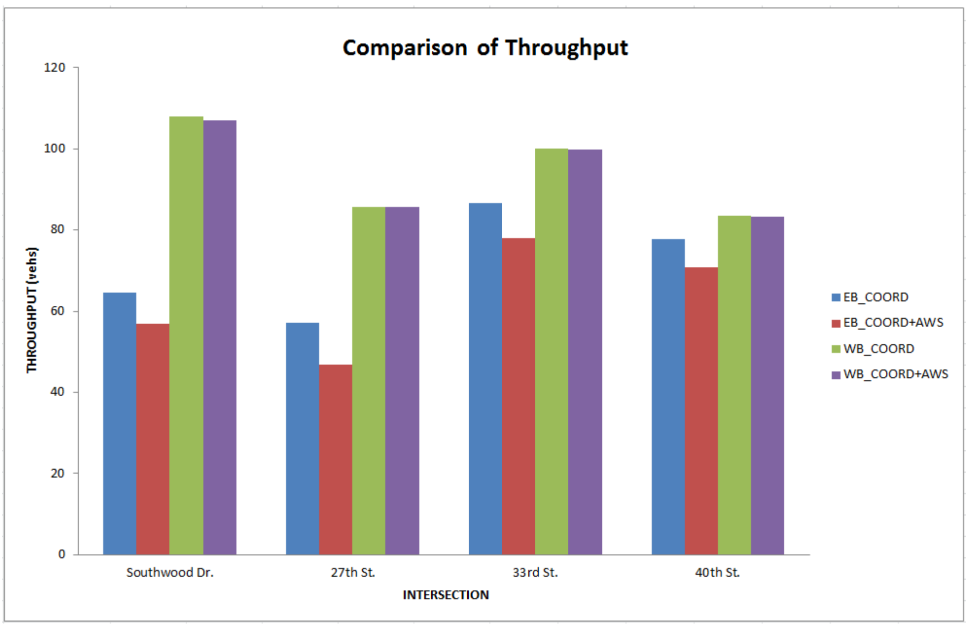



**Figure 4.9** Comparison of throughput

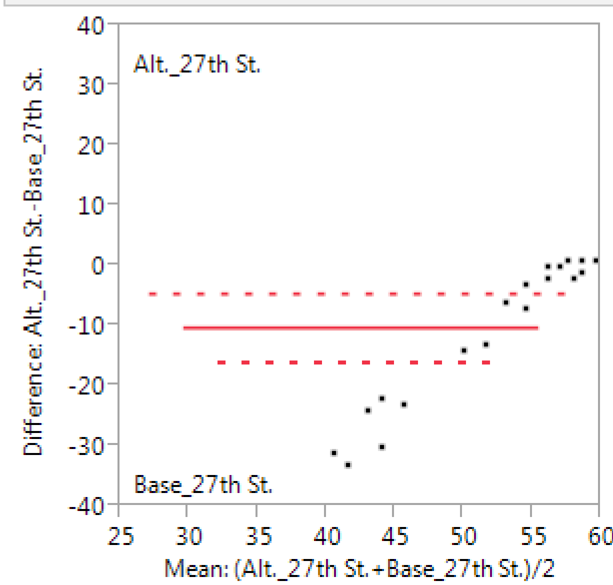
A paired T-test was performed to check if there were differences in the 5-min average throughput values from the 20 simulation runs. The hypothesis is that:

*Ho: 5-min Av. throughput from base model = 5-min Av. throughput from alternate model*

*Ha: 5-min Av. throughput from base model < 5-min Av. throughput from alternate model*

Figure 4.10 displays the output for the paired T-test performed on the 5-minute average throughput in the eastbound direction. The plot shows that all of the paired differences are negative, which indicates that the throughput was lower in the alternate model. The two-tailed p-value (Prob > |t|) is less than 0.05, suggesting that at the 95% significance level there is enough evidence to reject the null hypotheses and conclude that the throughput is not the same for both the base and alternate models. From the results, it can be concluded that there was a statistically significant decrease in throughput when the AAW system was used in addition to signal coordination on a corridor (alternate model). Paired T-test results for the other intersections are provided in Appendix D.

**Difference: Alt._27th St.-Base_27th St.**

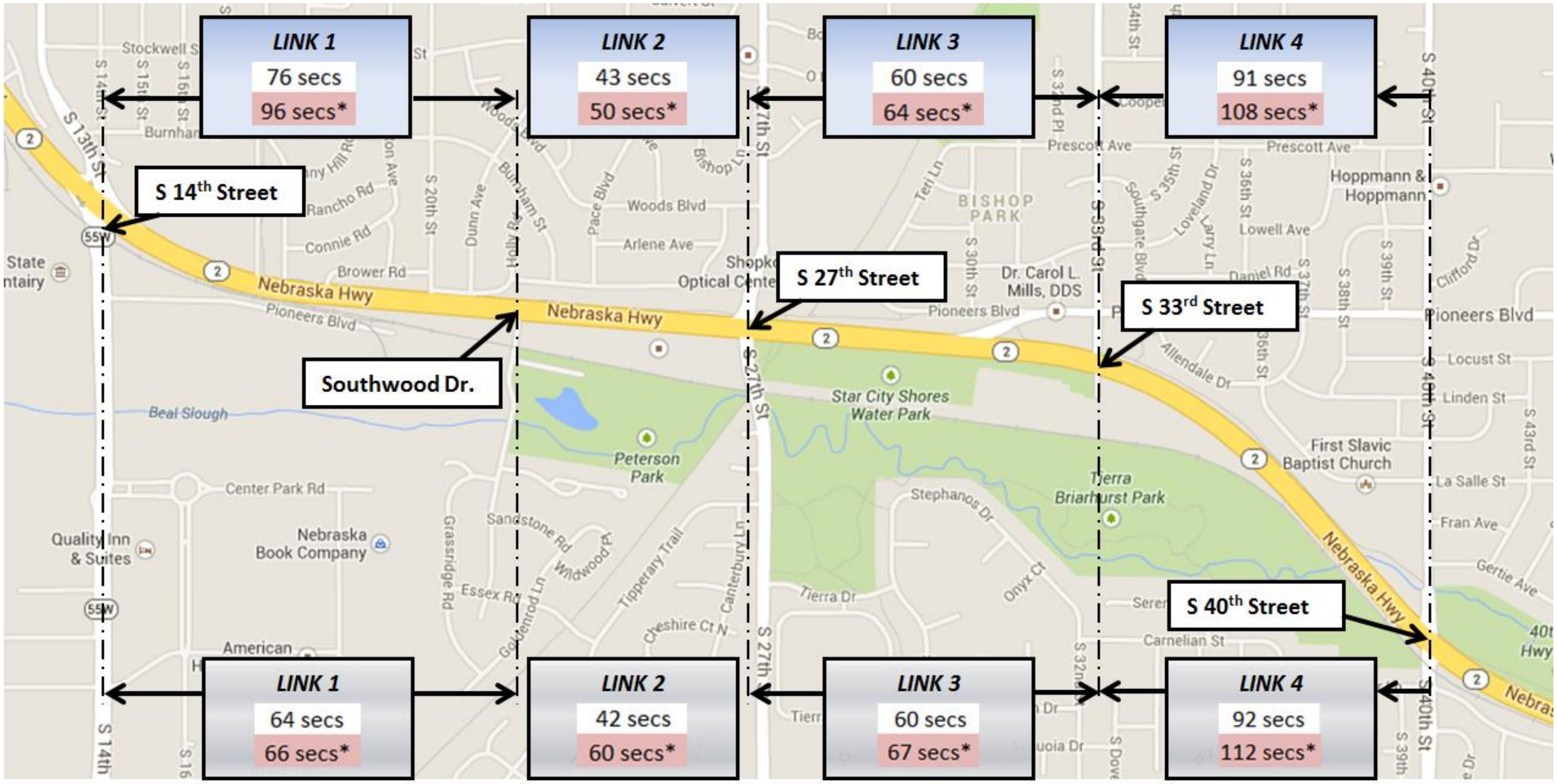



| | | | |
|---|---|---|---|
| Alt._27th St. | 46.8 | t-Ratio | -3.79968 |
| Base_27th St. | 57.2 | DF | 19 |
| Mean Difference | -10.4 | Prob > \|t\| | 0.0012* |
| Std Error | 2.73707 | Prob > t | 0.9994 |
| Upper 95% | -4.6712 | Prob < t | 0.0006* |
| Lower 95% | -16.129 | | |
| N | 20 | | |
| Correlation | 0.29058 | | |

**Figure 4.10** Paired T-test output comparing 15-min average throughput– 27th street

4.3. Travel Time Analysis

Travel time was the final MOE that was compared to provide insights into the use of the NDOR AAW system in a coordinated corridor. For each of the 20 simulation runs, link travel times aggregated at 5-minutes were collected for a period of one hour. These 5-min travel times were compared from both the base and alternate models. Figure 4.11 depicts the 5-minute travel time (average of 20 runs) for each link on the corridor. The values shown at the top of figure 4.11 are for the westbound direction, while those values shown at the bottom are for the eastbound direction.




*values on red background are travel times from the alternate model (AAW+COORD)

**Figure 4.11** Comparison of link travel times

It can be seen in figure 4.11 that the link travel times from the alternate model are slightly higher than values from the base model. This is expected given that drivers reduce their speeds when the AAW system is operational.

# Chapter 5 Conclusions and Recommendations

At high-speed signalized intersections, the dilemma zone often poses a problem for drivers in stopping safely during the yellow interval or in proceeding through the intersection before the beginning of the red interval. Drivers are exposed to a potentially hazardous scenario in which a rear-end crash may occur if an abrupt stop is made during the yellow interval or an angle crash may occur if an attempt to proceed through the intersection is made at the onset of the red interval. It can be argued that it is possible to eliminate the dilemma zone through proper timing of the traffic signal, but the stochastic nature of driving means that some drivers will find themselves in the dilemma zone. There has been on-going research in the area of mitigating the dilemma zone problem. The common methods of providing dilemma zone protection are the use of advanced detection, advance warning flashers, or a combination of both advance detection and advance warning flashers.

In Nebraska, the Department of Roads (NDOR) developed a system (referred to as an Actuated Advance Warning [AAW] system) that combines advance detection and advance warning flasher systems with the legend "PREPARE TO STOP WHEN FLASHING." The system is unique in that the operating algorithm is different from other applications. The AAW system has been proven to improve safety and operations, especially at isolated intersections, but not all intersections are isolated.

This study assessed the potential deployment of the AAW system on arterials where the signals are closely spaced and operate in a coordinated mode. A mechanistic approach – integration of traffic microsimulation and surrogate safety performance measures – was utilized to assess the potential safety and operational benefits in-lieu of observed traffic and crash data. A section of Highway 2 (14th street to 56th street) in Lincoln, NE was modeled in VISSIM. A comparison of selected MOE's was then performed between a base model where signals operate in coordination and there are no AAW systems, and an alternate model in which signals are coordinated and AAW systems are present.

## 5.1. Conclusions

The analysis of conflicts indicated that, on average, there were 30%, 7% and 30% reductions in the number of rear-end, lane change and crossing conflicts respectively when the AAW system was used. Additional statistical t-tests confirmed that not only were there significant differences in the number of conflicts between the two models, but the conflicts from the base model were higher than those from the alternate model. This suggests that having the AAW system in place with signal coordination improves safety.

A comparison of the relative productivity of the system, the number of vehicles that were processed by the system during a specified analysis period, revealed that there were generally more vehicles processed by the base model than the alternate model. The throughput in the westbound direction was very similar, while the throughput in the eastbound direction was slightly lower when the AAW system was in place (alternate model). The throughput was computed as the 5-minute average of the 20 simulations and as the total of the 20 simulations. A T-test performed on the 5-minute average throughput in the eastbound direction indicated that the throughput was not the same for both the base and alternate models. Furthermore, there was a statistically significant decrease in throughput when the AAW system was used in addition to signal coordination on a corridor.

Finally, aggregated 5-minute travel times from all links between intersections were compared for the two models. Overall, the link travel times from the alternate model were slightly higher than values from the base model. Therefore, it took drivers in the alternate model longer to traverse between intersections as well as the entire corridor altogether. This is expected given that drivers reduce their speeds when the AAW system is operational.

## 5.2 Recommendations

Based on the results of this research, the following recommendations are made in regard to the use of AAW devices:

1. From the perspective of safety effectiveness, the NDOR AAW system is worth considering for dilemma zone protection on arterials that have closely spaced signalized intersections operating in a coordinated mode. The system appears to reduce vehicle conflicts.
2. In terms of operational benefits, the NDOR AAW system is not worth considering for dilemma zone protection on arterials that have closely spaced signalized intersections operating in coordination. There were fewer cars processed through the intersections and link travel times were higher.

Overall, the decision to employ AAW devices on coordinated arterials would have to be based on whether safety or operations is a priority. It should be noted that this research was fully mechanistic. A field evaluation of the AAW system involving real data is recommended. The specific goals of such a field study would be to:

i) Perform a detailed analysis of crash records from before and after the implementation of the AAW system. A comparison of this kind will draw attention to the potential benefits with respect to safety.

ii) Perform an operational analysis using field observed data. The operational analyses will monitor the performance of AAW devices by observing characteristics such as vehicle speed profiles with particular emphasis on vehicle acceleration profiles both immediately before and after the devices become active.

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Appendix A Time-to-Collision (TTC) Distributions

*Southwood Drive*

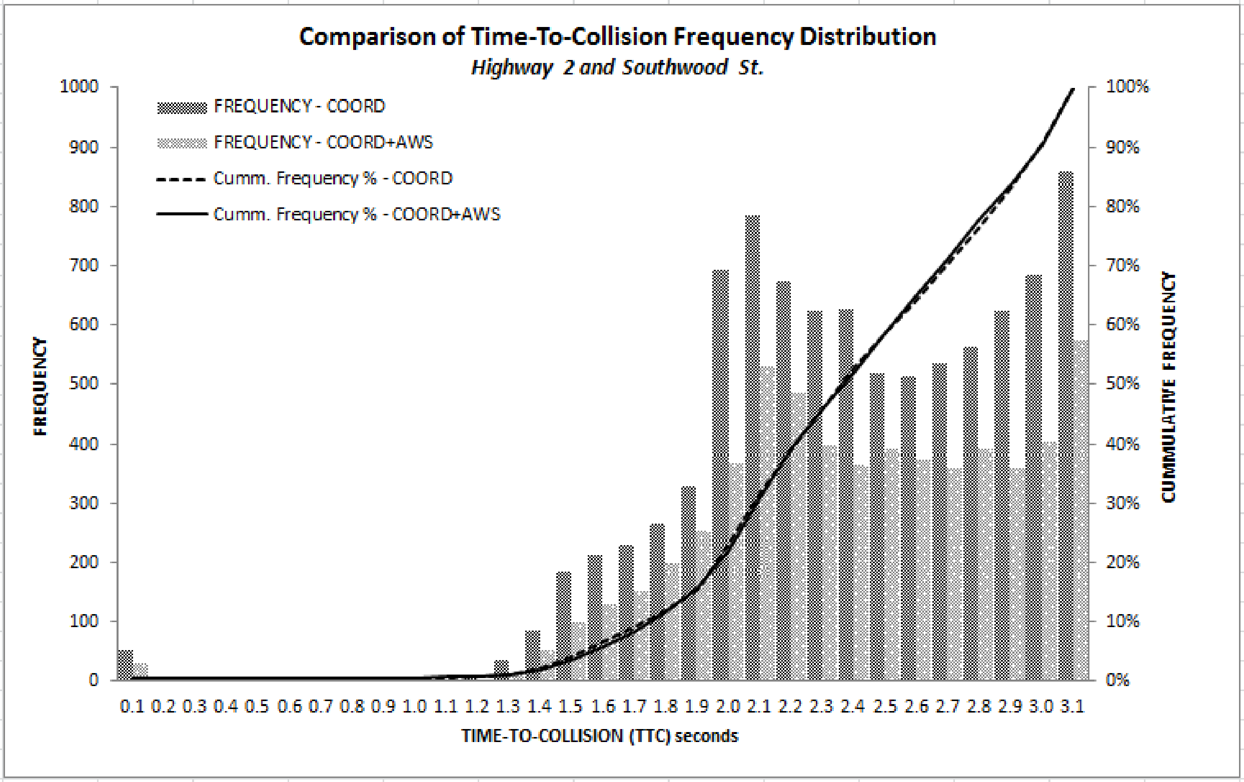



Table A.4.2

| | Conflicts | TTC Characteristics | | | |
|---|---|---|---|---|---|
| | | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 9109 | 2.31 | 0.49 | 1.80 | 2.80 |
| Alternate Model (COORD+AWS) | 5938 | 2.26 | 0.55 | 1.80 | 2.80 |

Figure depicts that the shape of the cumulative distributions is similar for both models. However, the frequency distribution indicates that there are fewer conflicts in the alternate model than the base model. This is an indication that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. Table shows that both models have similar TTC distributional characteristics.

*33rd Street*

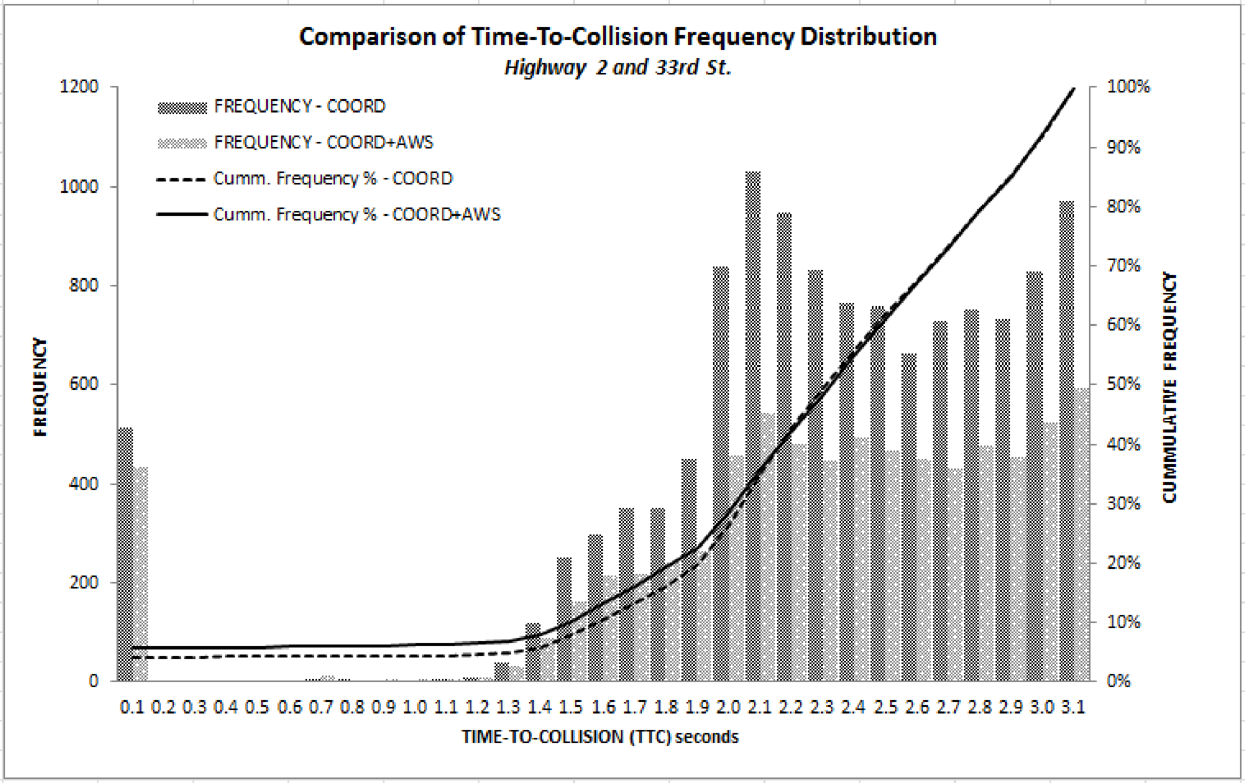



Table A.4.2

| | | TTC Characteristics | | | |
|---|---|---|---|---|---|
| | Conflicts | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 12279 | 2.20 | 0.65 | 1.70 | 2.85 |
| Alternate Model (COORD+AWS) | 7541 | 2.16 | 0.71 | 1.75 | 2.85 |

Figure depicts that the shape of the cumulative distributions is similar for both models. However, the frequency distribution indicates that there are fewer conflicts in the alternate model than the base model. This is an indication that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. Table shows that both models have similar TTC distributional characteristics.

*40th Street*

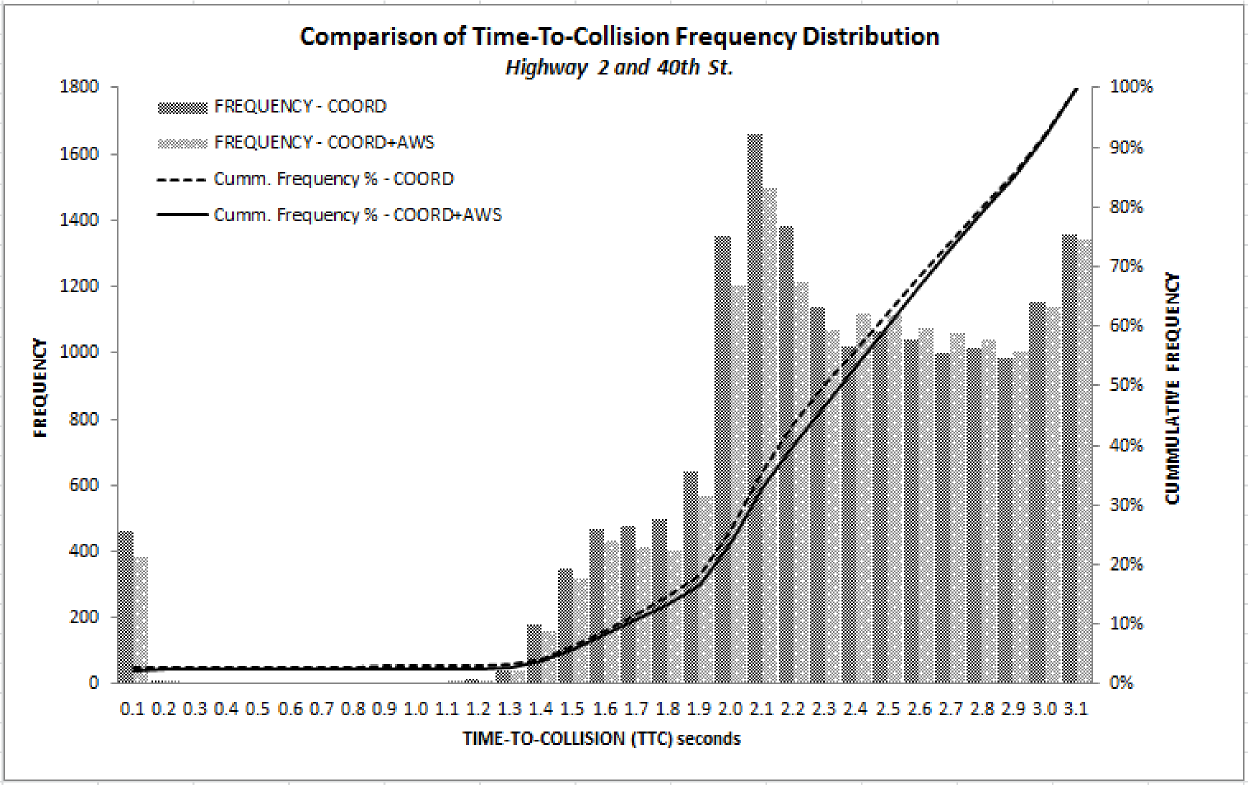



Table A.4.2

| | | TTC Characteristics | | | |
|---|---|---|---|---|---|
| | Conflicts | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 17429 | 2.23 | 0.59 | 1.75 | 2.85 |
| Alternate Model (COORD+AWS) | 16637 | 2.26 | 0.57 | 1.85 | 2.85 |

Figure depicts that the shape of the cumulative distributions is similar for both models. However, the curve for the base model is above that of the alternate model. Also, the frequency distribution indicates that there are fewer conflicts in the alternate model than the base model. This is an indication that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. Table shows that both models have similar TTC distributional characteristics.

Appendix B Post Encroachment Time (PET) Distributions

*Southwood Drive*

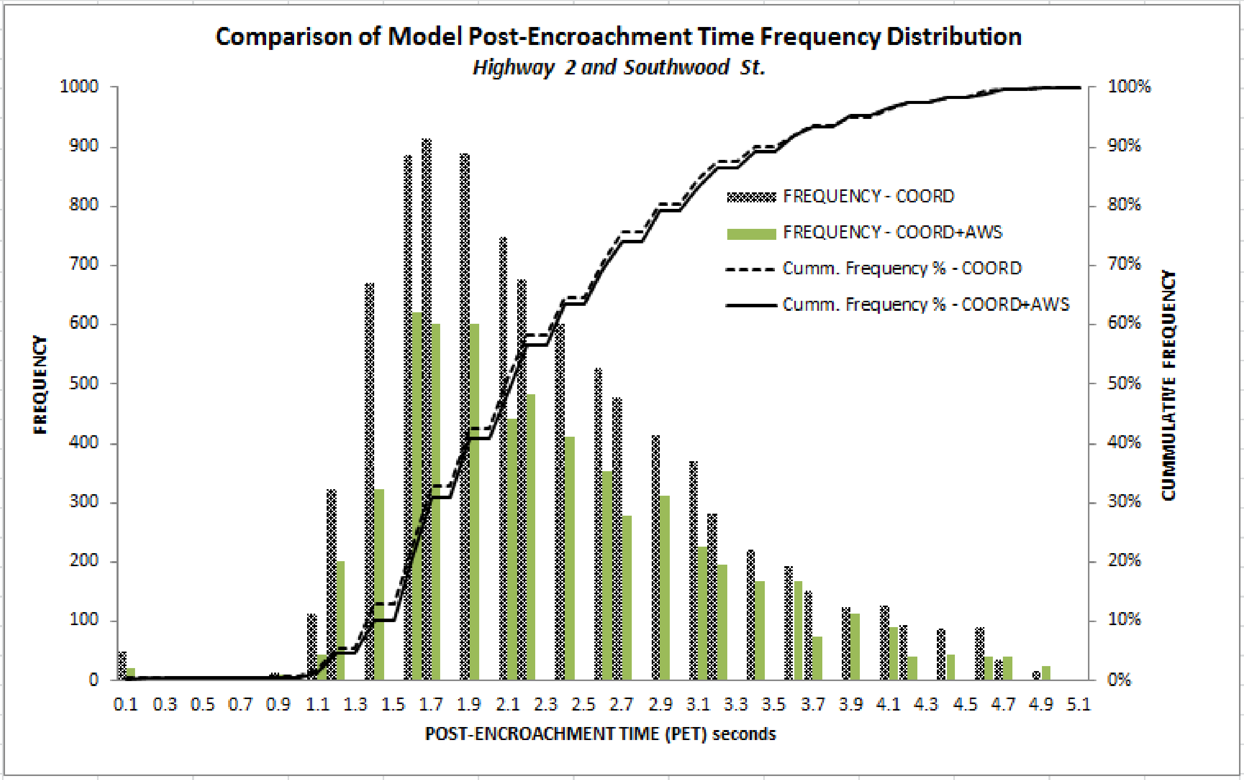



Table B.4.3

| | Conflicts | PET Characteristics | | | |
|---|---|---|---|---|---|
| | | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 9109 | 2.24 | 0.83 | 1.50 | 3.10 |
| Alternate Model (COORD+AWS) | 5938 | 2.10 | 0.80 | 1.55 | 3.15 |

Figure shows that the shape of the cumulative distribution of all conflicts is similar for both models. The cumulative frequency distribution curve for the base model is above that of the alternate model indicating that, in terms of number of conflicts, the alternate model (Coordination + AWS) is safer. The Table shows that both models have similar PET characteristic values.

*33rd Street*

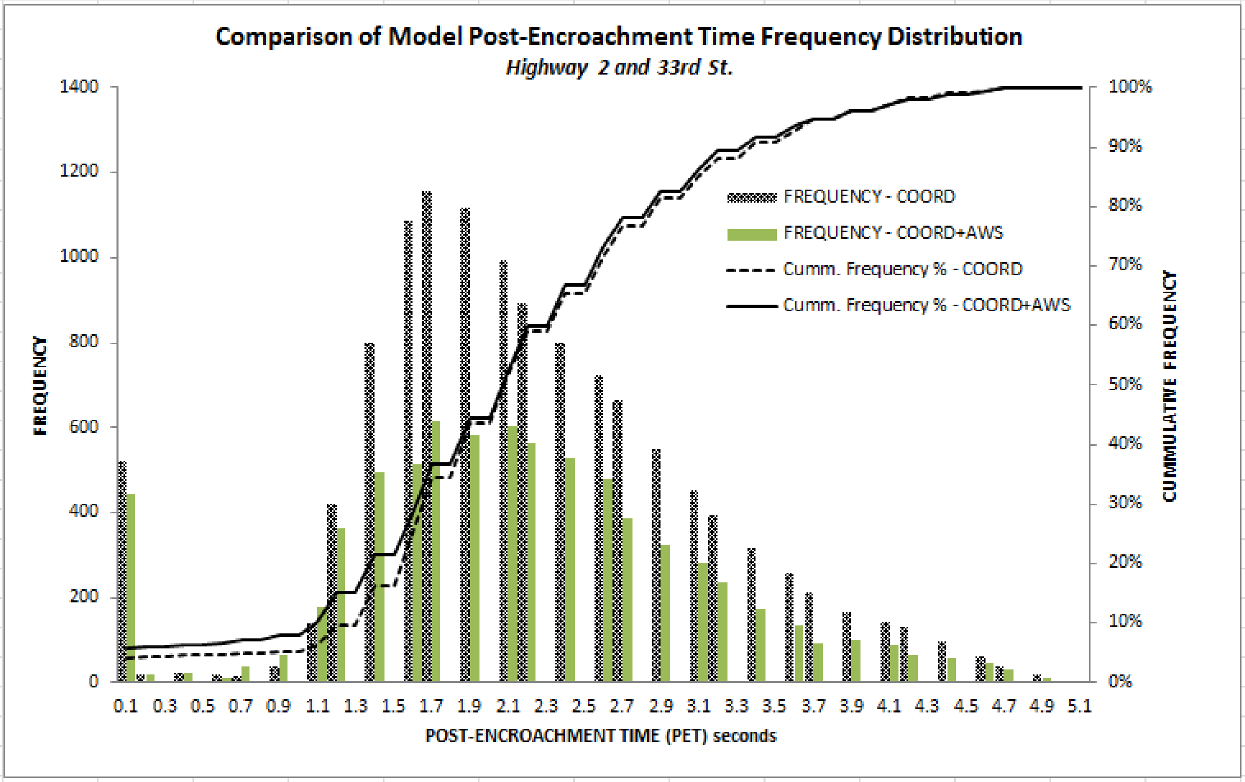



Table B.4.3

| | Conflicts | PET Characteristics | | | |
|---|---|---|---|---|---|
| | | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 12279 | 2.15 | 0.90 | 1.45 | 3.00 |
| Alternate Model (COORD+AWS) | 7541 | 2.08 | 0.95 | 1.15 | 2.95 |

Figure shows that the shape of the cumulative distribution of all conflicts is similar for both models. The cumulative frequency distribution curves for the two models run relatively close to each other. The Table shows that both models have similar PET characteristic values.

*<u>40th Street</u>*

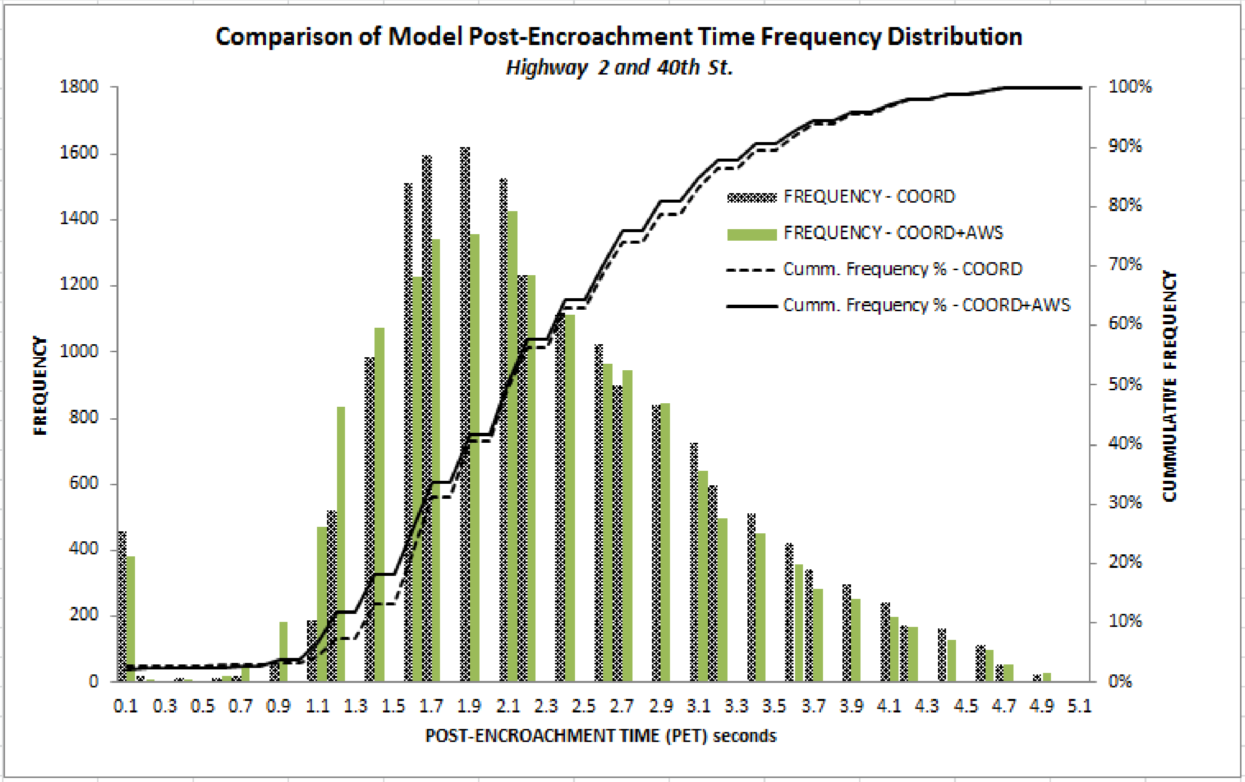



Table B.4.3

| | | PET Characteristics | | | |
|---|---|---|---|---|---|
| | Conflicts | Mean | Std Dev | 15th %ile | 85th %ile |
| Base Model (COORD) | 17429 | 2.23 | 0.88 | 1.50 | 3.00 |
| Alternate Model (COORD+AWS) | 16637 | 2.18 | 0.88 | 1.30 | 3.00 |

Figure shows that the shape of the cumulative distribution of all conflicts is similar for both models. The cumulative frequency distribution curves for the two models run relatively close to each other. The Table shows that both models have similar PET characteristic values.

Appendix C Statistical T-test Results on Conflicts

### Hypothesis

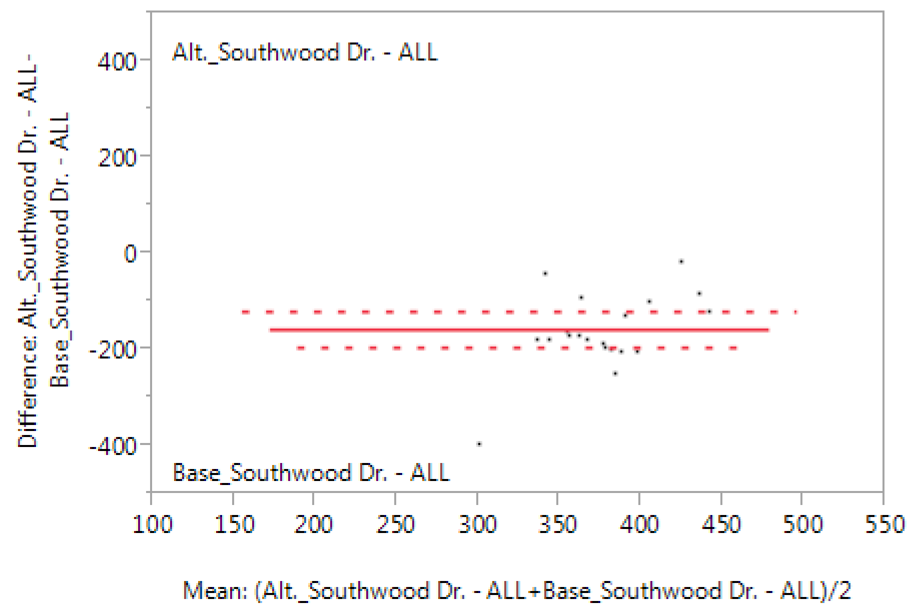
*Ho: number of conflicts from base model = number of conflicts from alternate model*

*Ha: number of conflicts from base model < number of conflicts from alternate model*

Where: conflicts = rear-end, lane change, crossing, and also the total of all three conflicts types.

*<u>Southwood Drive –All Conflict types</u>*

**Difference: Alt._Southwood Dr. - ALL-Base_Southwood Dr. - ALL**

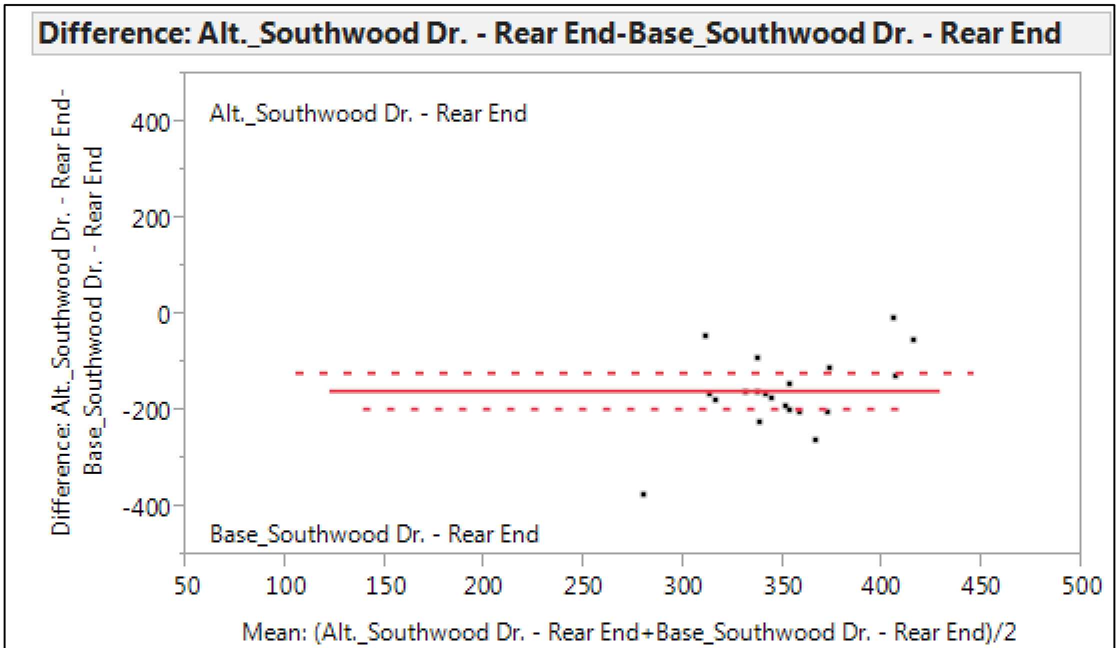



| | | | |
|---|---|---|---|
| Alt._Southwood Dr. - ALL | 296.9 | t-Ratio | -8.80372 |
| Base_Southwood Dr. - AL | 455.45 | DF | 19 |
| Mean Difference | -158.55 | Prob > \|t\| | <.0001* |
| Std Error | 18.0094 | Prob > t | 1.0000 |
| Upper 95% | -120.86 | Prob < t | <.0001* |
| Lower 95% | -196.24 | | |
| N | 20 | | |
| Correlation | -0.1748 | | |

### Conclusion

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result indicates that the numbers of conflicts in the base model are greater than from the alternate model.

*<u>Southwood Drive –Rear-End conflicts</u>*



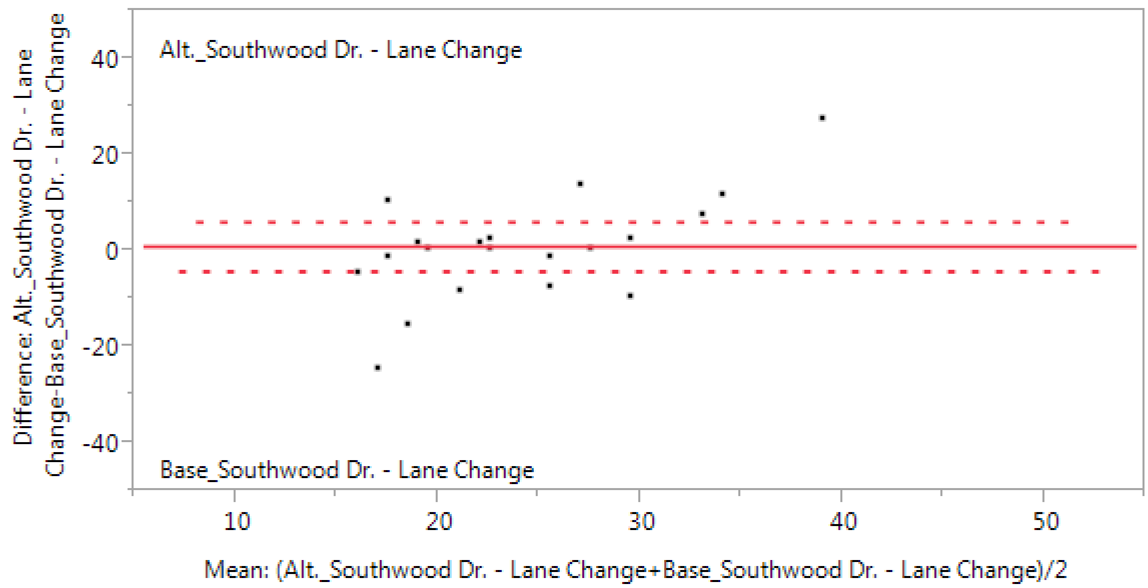

| | | | |
|---|---|---|---|
| Alt._Southwood Dr. - Rear End | 269.8 | t-Ratio | -8.84369 |
| Base_Southwood Dr. - Rear End | 428.85 | DF | 19 |
| Mean Difference | -159.05 | Prob > \|t\| | <.0001* |
| Std Error | 17.9846 | Prob > t | 1.0000 |
| Upper 95% | -121.41 | Prob < t | <.0001* |
| Lower 95% | -196.69 | | |
| N | 20 | | |
| Correlation | -0.1955 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result indicates that the numbers of rear-end conflicts in the base model are significantly greater than from the alternate model.

*Southwood Drive –Lane Change conflicts*

**Difference: Alt._Southwood Dr. - Lane Change-Base_Southwood Dr. - Lane Change**



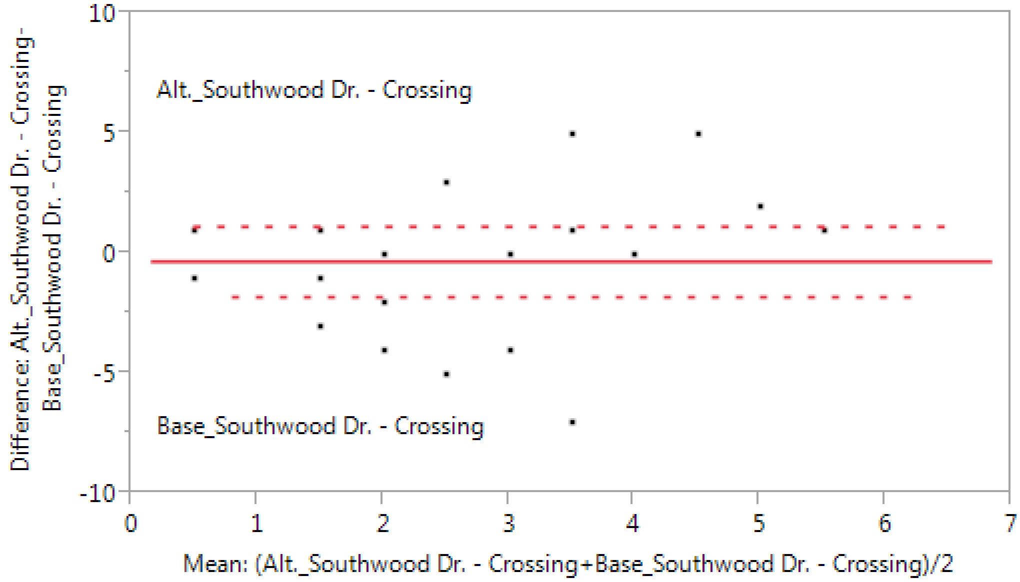

| | | | |
|---|---|---|---|
| Alt._Southwood Dr. - Lane Change | 24.6 | t-Ratio | 0.342786 |
| Base_Southwood Dr. - Lane Change | 23.75 | DF | 19 |
| Mean Difference | 0.85 | Prob > \|t\| | 0.7355 |
| Std Error | 2.47968 | Prob > t | 0.3678 |
| Upper 95% | 6.04003 | Prob < t | 0.6322 |
| Lower 95% | -4.34 | | |
| N | 20 | | |
| Correlation | 0.182 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are greater than 0.05; suggests that at the 95% significance level there is enough evidence not to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are equal. Result also indicates that the numbers of lane change conflicts in the base model are less than from the alternate model.

*Southwood Drive –Crossing conflicts*

**Difference: Alt._Southwood Dr. - Crossing-Base_Southwood Dr. - Crossing**



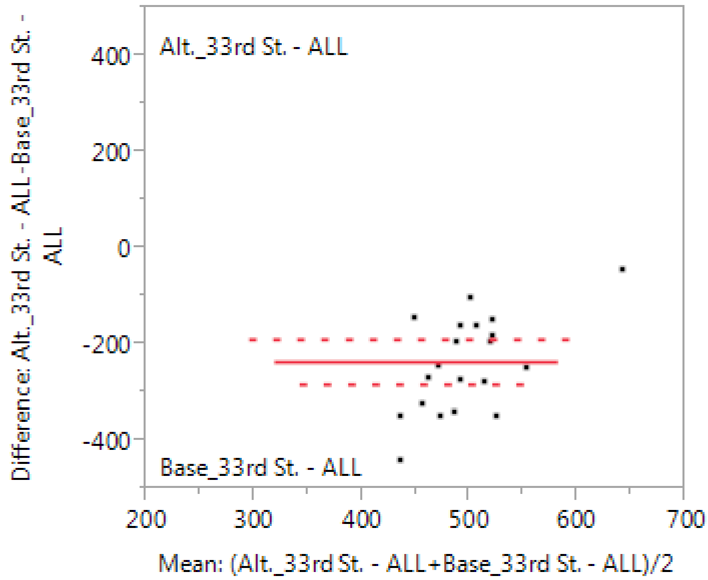

| | | | |
|---|---|---|---|
| Alt._Southwood Dr. - Crossing | 2.5 | t-Ratio | -0.49953 |
| Base_Southwood Dr. - Crossing | 2.85 | DF | 19 |
| Mean Difference | -0.35 | Prob > \|t\| | 0.6231 |
| Std Error | 0.70066 | Prob > t | 0.6884 |
| Upper 95% | 1.11649 | Prob < t | 0.3116 |
| Lower 95% | -1.8165 | | |
| N | 20 | | |
| Correlation | -0.1172 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are greater than 0.05; suggests that at the 95% significance level there is enough evidence not to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are equal. Result also indicates that the numbers of crossing conflicts in the base model are less than from the alternate model.

*33rd Street – All Conflict types*

**Difference: Alt._33rd St. - ALL-Base_33rd St. - ALL**

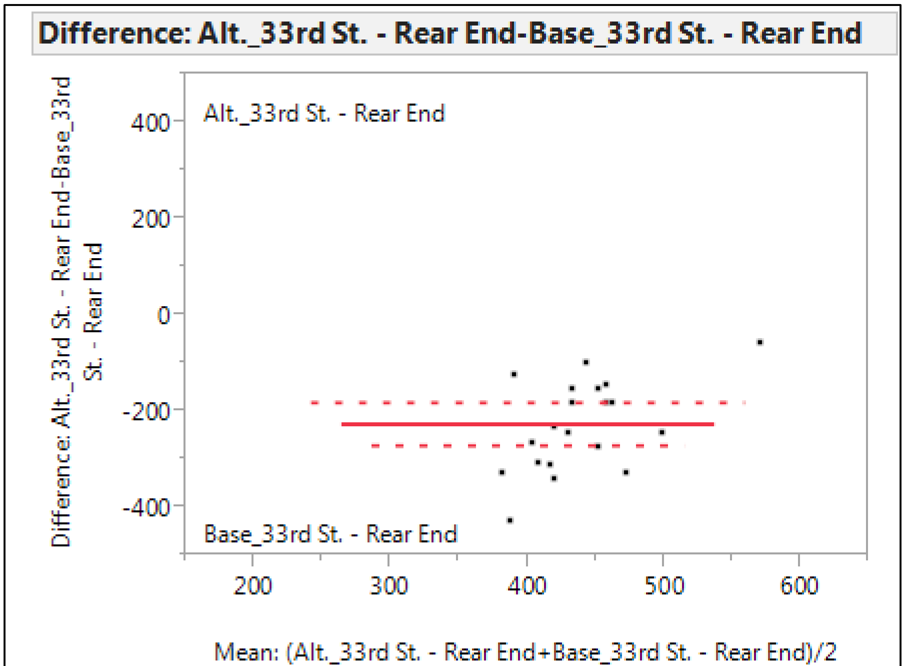



| | | | |
|---|---|---|---|
| Alt._33rd St. - ALL | 377.05 | t-Ratio | -10.5617 |
| Base_33rd St. - ALL | 613.95 | DF | 19 |
| Mean Difference | -236.9 | Prob > \|t\| | <.0001* |
| Std Error | 22.43 | Prob > t | 1.0000 |
| Upper 95% | -189.95 | Prob < t | <.0001* |
| Lower 95% | -283.85 | | |
| N | 20 | | |
| Correlation | -0.0869 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result indicates that the numbers of conflicts in the base model are greater than from the alternate model.

*33rd Street – Rear-End conflicts*



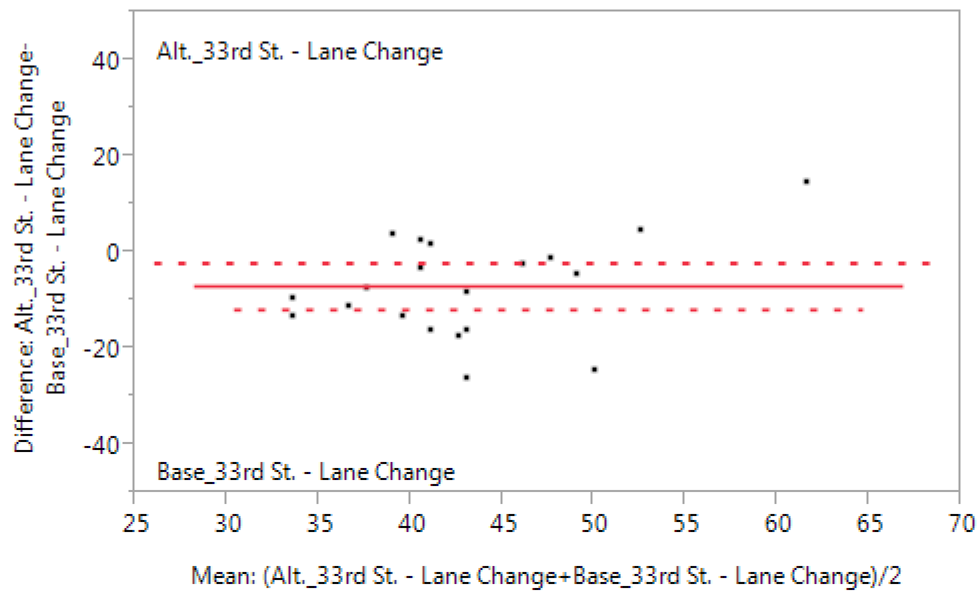

| | | | |
|---|---|---|---|
| Alt._33rd St. - Rear End | 324.85 | t-Ratio | -10.6845 |
| Base_33rd St. - Rear End | 551.4 | DF | 19 |
| Mean Difference | -226.55 | Prob > \|t\| | <.0001* |
| Std Error | 21.2036 | Prob > t | 1.0000 |
| Upper 95% | -182.17 | Prob < t | <.0001* |
| Lower 95% | -270.93 | | |
| N | 20 | | |
| Correlation | -0.1055 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result indicates that the numbers of rear-end conflicts in the base model are greater than from the alternate model.

*33rd Street –Lane Change conflicts*

**Difference: Alt._33rd St. - Lane Change-Base_33rd St. - Lane Change**

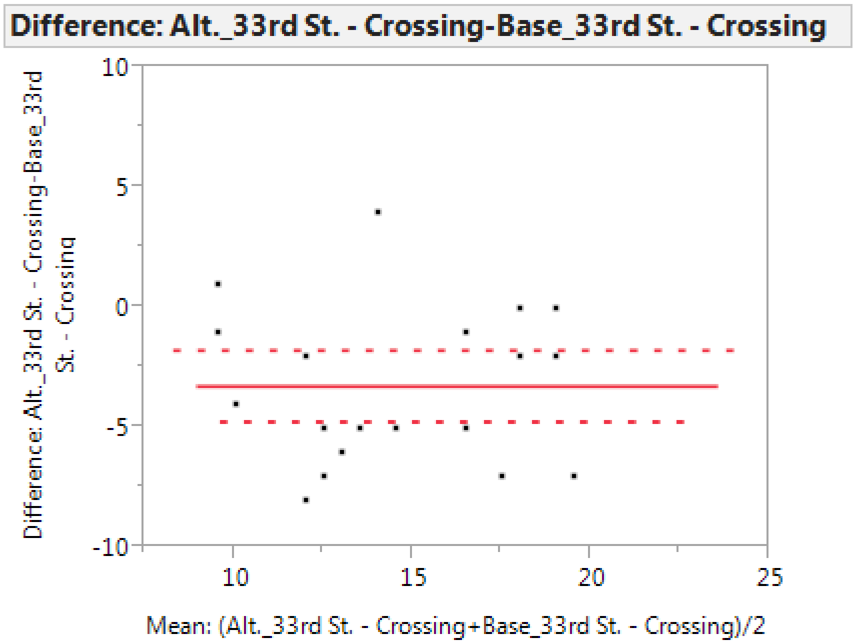



| | | | |
|---|---|---|---|
| Alt._33rd St. - Lane Change | 39.5 | t-Ratio | -3.05705 |
| Base_33rd St. - Lane Change | 46.55 | DF | 19 |
| Mean Difference | -7.05 | Prob > \|t\| | 0.0065* |
| Std Error | 2.30614 | Prob > t | 0.9968 |
| Upper 95% | -2.2232 | Prob < t | 0.0032* |
| Lower 95% | -11.877 | | |
| N | 20 | | |
| Correlation | 0.27396 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result also indicates that the numbers of lane change conflicts in the base model are greater than from the alternate model.

*33rd Street – Crossing conflicts*



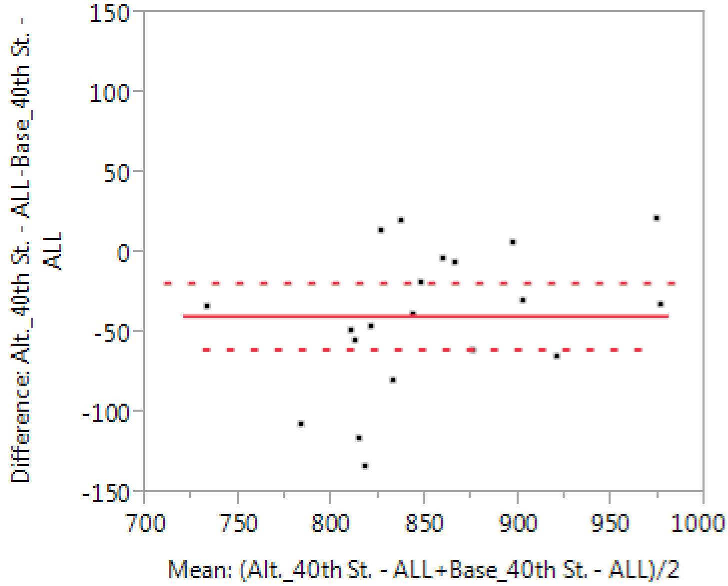

| | | | |
|---|---|---|---|
| Alt._33rd St. - Crossing | 12.7 | t-Ratio | -4.64012 |
| Base_33rd St. - Crossing | 16 | DF | 19 |
| Mean Difference | -3.3 | Prob > \|t\| | 0.0002* |
| Std Error | 0.71119 | Prob > t | 0.9999 |
| Upper 95% | -1.8115 | Prob < t | <.0001* |
| Lower 95% | -4.7885 | | |
| N | 20 | | |
| Correlation | 0.64293 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result also indicates that the numbers of crossing conflicts in the base model are greater than from the alternate model.

*40th Street – All Conflict types*

**Difference: Alt._40th St. - ALL-Base_40th St. - ALL**



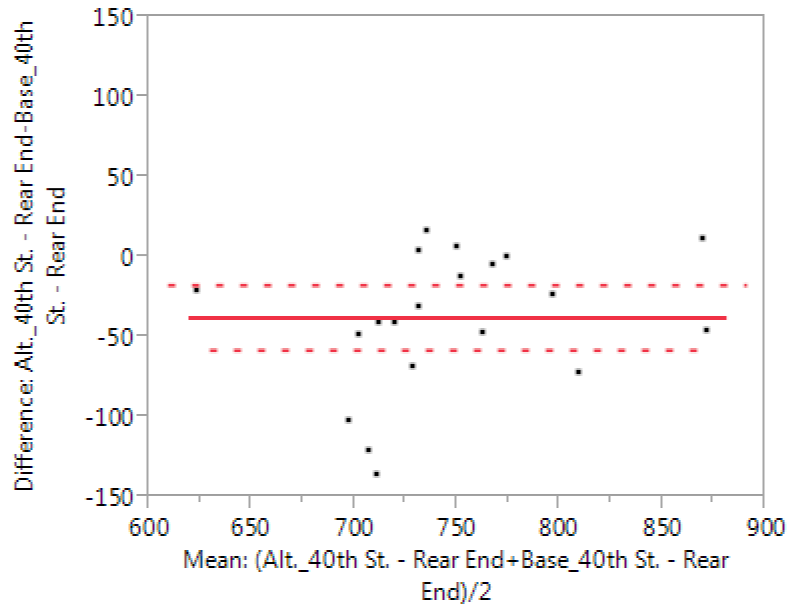

| | | | |
|---|---|---|---|
| Alt._40th St. - ALL | 831.85 | t-Ratio | -3.98733 |
| Base_40th St. - ALL | 871.45 | DF | 19 |
| Mean Difference | -39.6 | Prob > \|t\| | 0.0008* |
| Std Error | 9.93145 | Prob > t | 0.9996 |
| Upper 95% | -18.813 | Prob < t | 0.0004* |
| Lower 95% | -60.387 | | |
| N | 20 | | |
| Correlation | 0.78007 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result indicates that the numbers of conflicts in the base model are greater than from the alternate model.

*40th Street – Rear-End conflicts*

**Difference: Alt._40th St. - Rear End-Base_40th St. - Rear End**

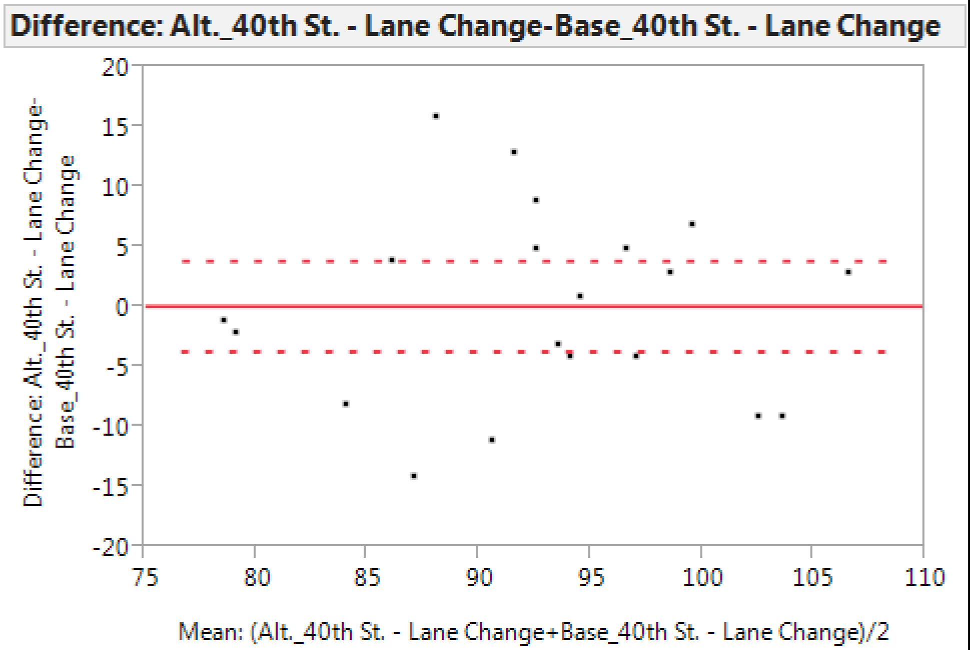



| | | | |
|---|---|---|---|
| Alt._40th St. - Rear End | 727.8 | t-Ratio | -3.90763 |
| Base_40th St. - Rear End | 765.75 | DF | 19 |
| Mean Difference | -37.95 | Prob > \|t\| | 0.0009* |
| Std Error | 9.71176 | Prob > t | 0.9995 |
| Upper 95% | -17.623 | Prob < t | 0.0005* |
| Lower 95% | -58.277 | | |
| N | 20 | | |
| Correlation | 0.76714 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are less than 0.05; suggests that at the 95% significance level there is evidence to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are not equal. Result indicates that the numbers of conflicts in the base model are significantly greater than from the alternate model.

*40th Street – Lane Change conflicts*

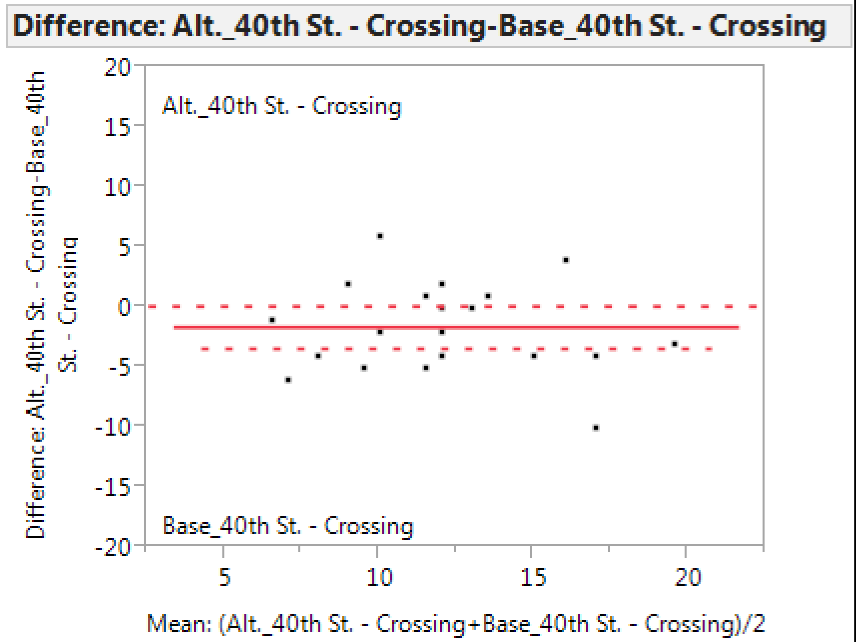



| | | | |
|---|---|---|---|
| Alt._40th St. - Lane Change | 92.8 | t-Ratio | 0.027803 |
| Base_40th St. - Lane Change | 92.75 | DF | 19 |
| Mean Difference | 0.05 | Prob > \|t\| | 0.9781 |
| Std Error | 1.79835 | Prob > t | 0.4891 |
| Upper 95% | 3.814 | Prob < t | 0.5109 |
| Lower 95% | -3.714 | | |
| N | 20 | | |
| Correlation | 0.56094 | | |

**Conclusion**

P-values (Prob > |t| and Prob > t) are greater than 0.05; suggests that at the 95% significance level there is enough evidence not to reject the null hypothesis and conclude that the number of conflicts between the base and alternate models are equal. Result also indicates that the numbers of lane change conflicts in the base model are less than from the alternate model.

*$40^{th}$ Street – Crossing conflicts*




| | | | |
|---|---|---|---|
| Alt._40th St. - Crossing | 11.25 | t-Ratio | -2.00861 |
| Base_40th St. - Crossing | 12.95 | DF | 19 |
| Mean Difference | -1.7 | Prob > \|t\| | 0.0590 |
| Std Error | 0.84635 | Prob > t | 0.9705 |
| Upper 95% | 0.07144 | Prob < t | 0.0295* |
| Lower 95% | -3.4714 | | |
| N | 20 | | |
| Correlation | 0.54538 | | |

**Conclusion**

Two-tailed p-value (Prob > |t|) is marginally higher than 0.05; suggesting that at the 95% significance level there is enough evidence not to reject the null hypothesis and conclude that the number of crossing conflicts between the base and alternate models are equal. Result also indicates that the numbers of crossing conflicts in the base model are less than from the alternate model.

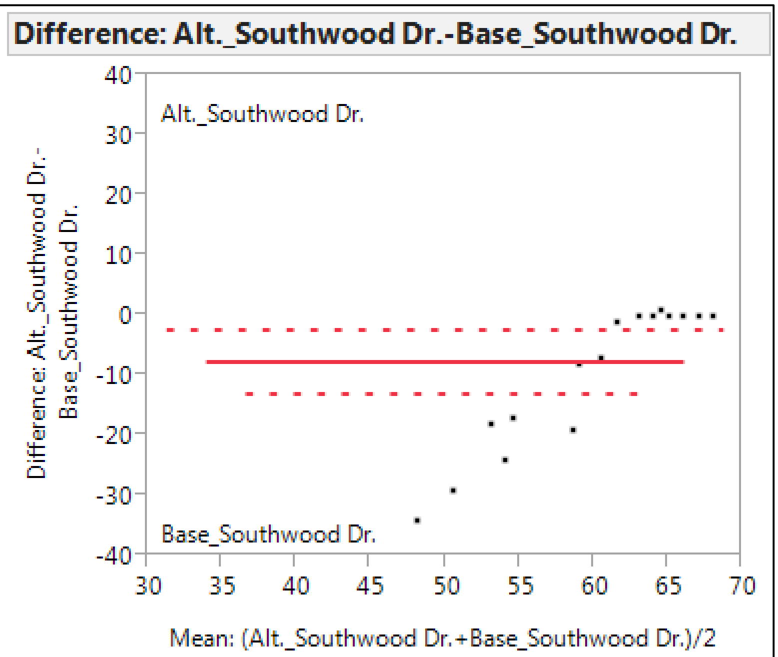
Appendix D Statistical T-test results on Throughput

**Hypothesis**

*Ho: 5-min Av. throughput from base model = 5-min Av. throughput from alternate model*

*Ha: 5-min Av. throughput from base model < 5-min Av. throughput from alternate model*

<u>*Southwood Drive*</u>




| | | | |
|---|---|---|---|
| Alt._Southwood Dr. | 56.85 | t-Ratio | -3.07489 |
| Base_Southwood Dr. | 64.65 | DF | 19 |
| Mean Difference | -7.8 | Prob > \|t\| | 0.0062* |
| Std Error | 2.53668 | Prob > t | 0.9969 |
| Upper 95% | -2.4907 | Prob < t | 0.0031* |
| Lower 95% | -13.109 | | |
| N | 20 | | |
| Correlation | 0.09109 | | |

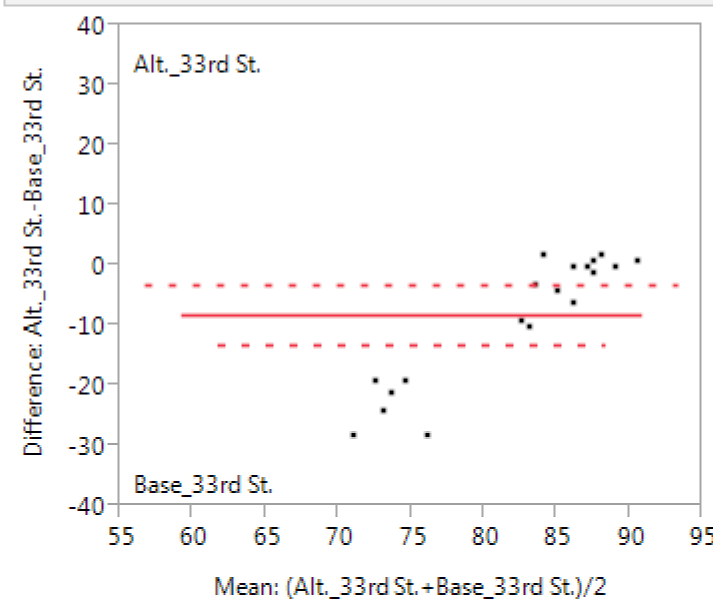
**Conclusion**

Figure shows the output for the paired T-test performed on the 5-minute average throughput in the eastbound direction at Southwood Drive. P-values (Prob > |t| and Prob > t) are less than 0.05;

suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the throughput between the base and alternate models are not equal. Result indicates that there was a statistically significant decrease in throughput when the AAW system was used in addition to signal coordination on the Highway 2 corridor.

*<u>33^rd Street</u>*

Difference: Alt._33rd St.-Base_33rd St.



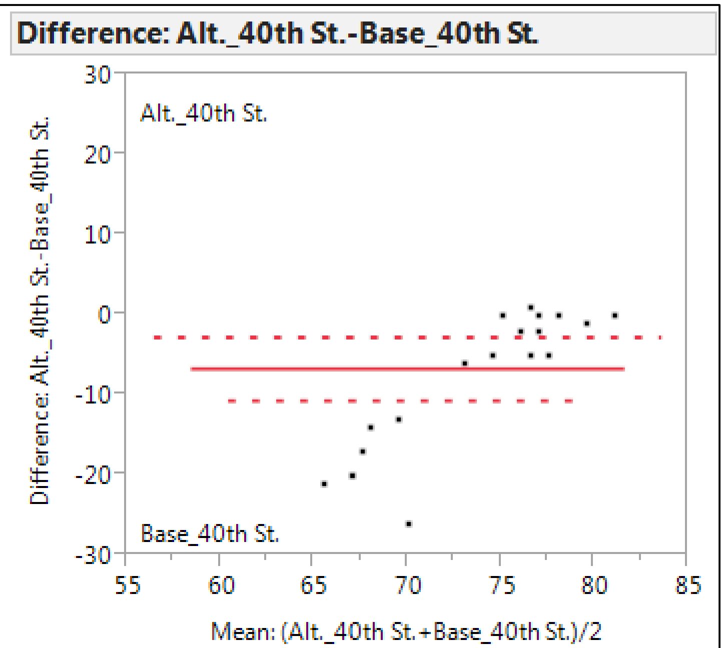

| | | | |
|---|---|---|---|
| Alt._33rd St. | 78.2 | t-Ratio | -3.46356 |
| Base_33rd St. | 86.5 | DF | 19 |
| Mean Difference | -8.3 | Prob > \|t\| | 0.0026* |
| Std Error | 2.39638 | Prob > t | 0.9987 |
| Upper 95% | -3.2843 | Prob < t | 0.0013* |
| Lower 95% | -13.316 | | |
| N | 20 | | |
| Correlation | 0.45829 | | |

**Conclusion**

Figure shows the output for the paired T-test performed on the 5-minute average throughput in the eastbound direction at 33^rd Street. P-values (Prob > |t| and Prob > t) are less than 0.05;

suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the throughput between the base and alternate models are not equal. Result indicates that there was a statistically significant decrease in throughput when the AAW system was used in addition to signal coordination on the Highway 2 corridor.

*40th Street*




| | | | |
|---|---|---|---|
| Alt._40th St. | 70.8 | t-Ratio | -3.58496 |
| Base_40th St. | 77.6 | DF | 19 |
| Mean Difference | -6.8 | Prob > \|t\| | 0.0020* |
| Std Error | 1.89681 | Prob > t | 0.9990 |
| Upper 95% | -2.8299 | Prob < t | 0.0010* |
| Lower 95% | -10.77 | | |
| N | 20 | | |
| Correlation | 0.18268 | | |

## Conclusion

Figure shows the output for the paired T-test performed on the 5-minute average throughput in the eastbound direction at 40th Street. P-values (Prob > |t| and Prob > t) are less than 0.05;

suggests that at the 95% significance level there is enough evidence to reject the null hypothesis and conclude that the throughput between the base and alternate models are not equal. Result indicates that there was a statistically significant decrease in throughput when the AAW system was used in addition to signal coordination on the Highway 2 corridor.