Evaluation of Portable Traffic Signals in Conjunction with Pilot Car Operations at Two-Lane, Two-Way Temporary Rural Work Zones in Kansas

By

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DEDICATION

I would like to dedicate this thesis to my parents who have provided me with everything I ever needed. Thank you for all the sacrifices you have made to help me pursue my dream and supporting me at every step of this wonderful journey. I will always be indebted to you for being the wonderful people you are. I love you with all my heart.

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ABSTRACT

The primary objective of this study was to evaluate the use of Portable Traffic Signal (PTS) systems at long rural two-lane work zones and compare three different conditions for controlling one-lane traffic: flagging only, a PTS system with the presence of a flagger, and a PTS system without the presence of a flagger in conjunction with pilot car operations. The primary measures of effectiveness were determined as Red Light Running (RLR) or noncompliance percentages, vehicle delay estimates, queue lengths, signal timing operations, and general field operations. Data were collected three days per week over a period of four weeks for from August 5, 2014 to August 28, 2014 at four different temporary work zones in Kansas. Two PTS units were used for the purpose of the study in conjunction with pilot car operations.

It was found that only nine vehicles were waived through by a flagger to enter the work zone when flagging only operations were in effect. Additionally, when a PTS was used with a flagger, it was found that for 50 vehicles the flagger used discretion and waved those vehicles through the red light and brought a reduction in the total delay. Also, only two RLR vehicles were observed where the drivers simultaneously disregarded the flagger and the PTS unit. Similarly, 92 red light running (RLR) vehicles were observed when a PTS was used without a flagger. A test of proportions conducted on the three samples at 0.05 level of significance indicated that there was a statistically significant difference in the number of violations when a PTS was used with a flagger and when only flagging operations were used. Also, the difference in the number of violations when a PTS was used without a flagger and when only flagging operations were used was statistically significant. Similarly, there was a statistically significant difference in the number of violations when a PTS was used with a flagger and when a PTS was used without a flagger. The results of the test of proportions indicated that there was no statistically significant difference between the number of RLR vehicles that followed an already departed queue for the ‘PTS with a flagger’ and ‘PTS without a flagger’ conditions. Furthermore, it was also found that there was a statistically significant difference between the number of RLR vehicles that left the queue due to the wait time and the number of vehicles that disregarded the PTS control for both the conditions.

An exploratory delay analysis was conducted to quantify the amount of total delay reduced by the flaggers when they waved the vehicles through the red light. The analysis indicated that the presence of a flagger reduced the total delay by approximately five percent of the total delay that could have occurred during the normal operations. Additionally, equations were developed to determine the volume thresholds at which the PTS system would fail and the appropriate green intervals needed to serve a certain queue length. It was found that based on the existing KDOT policy of a maximum pilot car roundtrip time of 15 minutes, the PTS system would fail at an AADT of approximately 7,083 vehicles per day and at a corresponding maximum green time of approximately 446 seconds.

In conclusion, it was recommended to use a PTS unit without a flagger in conjunction with pilot car operations at long rural two-lane work zones but measures such as engineering studies to more accurately estimate queue lengths, installation of static or dynamic signs indicating the expected wait time, and regular inspections of the PTS units by supervisors or crew members to mitigate excessive delays and monitor for RLR vehicles were suggested.

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CHAPTER 1. INTRODUCTION

1.1 General Background

A Portable Traffic Signal (PTS) system is designed to control one-way traffic at temporary work zones where the adjacent travel lane is closed. Traditionally, a flagger controls operations at each end of such a work zone by stopping and releasing the queue of vehicles. Due to rising costs and the risk of flaggers being struck by noncompliant vehicles, PTS systems are becoming a common tool with contractors and design engineers.

A PTS system consists of two portable trailers with signals attached to a pole and mast arm. Communication between trailers could include fiber, radio, or a synchronized timer. These systems use solar power and can operate as an actuated traffic signal controller allowing for higher directional flows to receive increased travel time through the work zone.

An initial review of the existing literature on PTS systems showed limited research on their use in general. A study conducted by Ullman and Levine in 1987 found that significant labor savings could be achieved with minimal delay to drivers by the use of a temporary traffic signal system when tested at three Texas work zones (*1*). The researchers also indicated that even though noncompliant drivers were found at two of the three sites, it was hypothesized that mass deployment would increase compliance. A follow up study by Daniels et al. in 1999 developed thresholds and limitations of temporary traffic signals at work zones based on three study sites in Texas (*2*). The thresholds addressed issues such as potential cost savings, signal timing recommendations, and wait time as a function of work zone length.

1.2 Research Objective

The primary objective of this research was to determine the effectiveness of the PTS systems at long work zones in conjunction with pilot car operations and the presence of a flagger. Section 6C.13 of the 2009 Manual on Uniform Traffic Control Devices (MUTCD) indicated that a flagger was required to be deployed with a temporary traffic signal (*3*). The research was anticipated to be completed by conducting an operational evaluation, a statistical evaluation, and development of a model to provide guidelines for the use PTS systems at long work zones in conjunction with pilot car operations. The operational evaluation was conducted by investigating and reporting performance measures such as average vehicle wait times, queue lengths, and signal timing operations. The statistical evaluation was conducted by recording and analyzing the number of red light running vehicles and obtaining the estimates of delay reduction. Finally, the research was completed with the development of a model and identification of the volume thresholds at which the PTS systems would fail with recommendations on the use of appropriate green intervals and work zone lengths for corresponding approaching traffic volumes.

1.3 Thesis Organization

This thesis is divided into nine chapters. Chapter 1 introduces a general background with the existing research gap and the research objective. Chapter 2, provides a detailed summary of the literature review relating to PTS systems. Chapter 3 elaborates on the problem statement and introduces the need for this research. Chapter 4 provides a description of the general data collection methodology. Similarly, Chapter 5 provides a detailed description of the test locations where data collection were conducted. Chapter 6 encompasses the data analyses as well as calculations for each of the analyses. Chapter 7 provides findings from the general field observations and data analyses. Chapter 8 provides a detailed description of all the recommendations based on the findings and discusses the limitations of the PTS system and anomalies observed during the research. Finally, Chapter 9 discusses the scope for future research that supplement some of the recommendations made in the previous chapter.

CHAPTER 2. LITERATURE REVIEW

The first step of this research was to conduct a review of the existing literature to determine the findings of previous related studies. The review of the literature is divided by subject. First, a review of literature relating to the PTS is presented. Second, research into the temporary traffic devices is presented followed by research related to pilot car operations and flagger operations. Finally, a short summary on crashes and injury costs concludes the literature review. The chapter ends with a summary of the significant points discovered during this review.

2.1 Portable (or Temporary) Traffic Signals

In 1987, Ullman and Levine conducted a study of a fixed-time portable signal system at three work zone lane closures on two-lane, two-way rural highways (without paved shoulders) in Texas (*1*). The three sites chosen represented traffic volumes varying from 600 to 10,000 ADT (1985) and work zone lengths ranging from 600 to 2,600 feet. Data were collected for traffic volumes, driver noncompliance of the signal, and vehicle stopped delay. Data for delay and compliance were collected for approximately four hours during the day when work was being performed. The researchers found that flaggers had the ability to respond to random vehicle arrivals and gaps in the traffic stream and assign traffic movements through the work zone to minimize vehicle stops and delays. The researchers concluded that fixed-time signals did not respond to random vehicle arrivals, and the vehicle delay under signal control was a function of the signal timing parameters: cycle length and green phase time. At higher traffic volumes, fixed-time signals at a work zone lane closure was found to provide a level of service to drivers comparable to that provided by a flagger. The study also suggested that the potential for vehicle crashes within the work zone may be higher because of driver noncompliance with the PTS. The researchers suggested that the signal validity could be improved by adding a STOP line 50 to 60 feet in advance of the signal and also erecting a temporary 'STOP HERE ON RED' sign next to the stop line enhancing the need for stopping. To control red light running (RLR) for vehicles entering the work zone without stopping, it was recommended by the researchers that the wattage of the signal lamp heads was increased making them more visible in daylight. Table 1 shows that the fixed-time portable signals provided significant cost savings over the use of flaggers.

Table 1. Summary of Portable Signal Costs and Benefits (*1*)

Site	Cost of Additional Motorist Delay ($/hour)[a]	Savings in Labor Costs ($/hour)[b]	Savings Achieved by Portable Signals ($/hour)
1	3.12	12	8.88
3	4.16	18	13.84

[a] Based on recent estimates of value of travel time = $10.40 per vehicle-hour.
[b] Based on typical wages and benefits of approximately $6 per hour for Maintenance Technician I working for the Texas State Department of Highways and Public Transportation.

As shown in Table 1, the costs of additional vehicle delay were based on the estimates on value of travel time by Chui and McFarland available at that time (*4*). The study showed that a substantial savings in flagger labor costs could be achieved by using a portable fixed-time traffic signal system with only a minimal increase in motorist delay cost. The estimates of the cost savings ranged from $9 to $14 per hour. The savings in labor costs were calculated based on the wages and benefits of approximately $6 per hour for a Maintenance Technician I working for Texas State Department of Highways and Public Transportation in 1987.

Daniels et al. explored the use of PTS technology to replace flaggers as a means for improving the efficiency of two-lane rural maintenance operations in Texas (*2*). The study examined critical issues such as determining the applicability of PTS in work zones, collecting data that would assist in assessing the cost effectiveness, driver comprehension of PTS in rural work zones, identifying unique characteristics related to maintenance operations, and recommending guidelines for work zone setup and signal operation parameters. In Texas, PTS systems were used on several two-lane bridge construction projects with work zone lengths ranging from 400 to 1,200 feet and clear end-to-end sight distances but were not used on daily lane-closure type work zones. Field tests were performed for a total of 20 days over a three-month period from June 1998 through August 1998 at three test locations (two hilly and one curving road) in the San Antonio District of TX-DOT. The test sites had similarities in sight distance from beginning to end of each work zone, type of maintenance activities, absence of significant driveways, and absence of significant intersections within the work zone. The complete setup for the signals included a 'STOP HERE ON RED' sign and took approximately 38 to 43 minutes to be fully setup.

The researchers suggested that only one flagger position and not two could be eliminated by the use of this technology. Also, the savings were calculated assuming that one flagger position was eliminated or the flagger was reassigned to another function. Provided that the equipment was put into use eight to ten days per month, it was shown that the return on investment could be realized after two years of operation and were estimated in subsequent years at $20,000 to $30,000 per year (1999-2000). The field test cases advocated that PTS were technically feasible in improving the crew efficiency and flexibility on two-lane rural work zones for maintenance operations. Existing TXDOT guidelines recommended the use of PTS units for long-term stationary work zones of length up to 400 feet. The researchers recommended that a PTS system could be used at short-term stationary work zones of length up to 2,600 feet. They also suggested that the maximum time before driver confusion and a possible violation was four minutes. Therefore, the threshold for maximum wait time was recommended at four minutes and was a function of the yellow clearance time, the red clearance time, and the maximum green time.

A traffic advisory leaflet detailed practices in England, UK for the use of PTS at road and street works (*5*). PTS systems were primarily used for alternating traffic in work zones where one lane of a two-lane facility was closed. The maximum recommended length for the work zones to deploy a PTS system was 300 meters (1,000 feet) due to long all-red times that result in longer queues. It was recommended to control the side roads that were present within the work zone if there was poor visibility of the traffic control on the main road. It was also recommended to use the PTS in vehicle actuated mode to reduce unwanted delays. If a PTS system was going to be operated manually, it was recommended that both ends of the working area be clearly visible to the operator. Proper training was also necessary for personnel who would be setting up the PTSs since poor setups could increase the risk of crashes, additional costs in fuel and time, increased pollution and driver frustration.

Lee et al. studied the effectiveness of a vehicle-actuated signal control system on work zone operations for two-lane highways (*6*). The researchers investigated the dependence of average control delay and number of conflicts on signal control methods for a two-lane highway, taking into account work zone length and traffic volume changes. Pre-timed signal control or time of day (TOD), actuated signal control with fixed all-red (AFAR), and actuated signal control with dynamic all-red (ADAR) were the three signal control methods that were investigated. The average control delay per vehicle was used to evaluate the effectiveness of each control method while the length of the work zone and traffic volume were used to evaluate safety. In the study, VISSIM was used to analyze signal control methods, VisVAP of VISSIM for algorithm embodiment, SYNCHRO 4.0 for TOD signal optimization, and finally surrogate safety assessment model (SSAM) to analyze traffic safety. In terms of safety and mobility for work zones on two-lane highways, the researchers found ADAR to be the most efficient signal control method under most conditions examined, except under certain traffic volumes in a 400 meters (1,200 feet) long work zone. In work zones of length 200 meters (600 feet), the ADAR control method decreased the average control delay per vehicle by a minimum of 16 seconds or more as compared to the other two methods. For work zones of length 400 meters (1,200 feet), the ADAR control method could be operated safely and had less deviation even though vehicle delays were widely distributed from 100 to 712 seconds for all control methods. The signal timings for the ADAR control method (green time and all-red time), were shorter than those for the other control methods in the work zones of length 200 meters (600 feet) and 400 meters (1,200 feet). The results of conflict analysis showed that ADAR had no crossing conflicts and fewer conflicts than other signal control methods, especially for 200 meters (600 feet) long work zones where ADAR had no conflicts. Since the average control delay exceeded 100 seconds for work zones of length 400 meters (1,200 feet), the researcher recommended the construction of a temporary bypass if the traffic volumes exceeded 500 vehicles per hour on two-lane, two-way work zones with length greater than 400 meters (1,200 feet) to reduce delays and increase traffic safety.

Shibuya et al. measured traffic flows at work zones on two-lane roads controlled by flaggers (*7*). To investigate the traffic flow characteristics, traffic flows were observed at six construction sites all being 30 to 80 meters (100 to 200 feet) long work zones on two-lane suburban roads. They developed a computer simulation model based on a microscopic traffic flow theory and using their study data to analyze the traffic behavior, assuming that no heavy vehicles were mixed with the traffic. The delay characteristics were investigated for short work zones less than 200 meters (600 feet) in length. Three methods for estimating the green intervals using flaggers' were presented: nomograph, regression equation, and analytical optimization. The signal timings produced by the nomograph and the regression equation could be installed in pre-timed traffic lights. Also, timings from the analytical optimization could be installed for the actuated traffic lights with detectors as flagger substitutes. The researchers concluded that 35 to

40 percent of the total delay was a sum of the acceleration delay and the speed-decrease delay. Lastly, the researchers also suggested that as the traffic increased, the green intervals obtained from the analytical optimization varied increasingly from the simulated ones.

2.2 Temporary Traffic Control Devices

Li and Bai evaluated the effectiveness of existing temporary traffic control (TTC) measures in highway work zones (*8*). This study quantified the effectiveness of TTC methods: flagger/officer, STOP sign/signal, flasher, no passing zone, and center/edge lines in mitigating work zone crashes and preventing common human errors from causing severe work zone crashes. A total of 655 severe work zone crashes that included 626 injury crashes and 29 fatal crashes in Kansas highway work zones from January 2003 to December 2004 were used for the study. A binary logistic regression technique was used to evaluate the effectiveness of the TTC methods. The Likelihood Ratio test (LR), Score test, and Wald test were used for testing the level of significance of a predictor at a 0.10 level of significance. The effectiveness of the TTC measures were assessed in terms of reducing the severity of the work zone crashes and lowering the probability that a certain severe work zone crash was caused by human error. The researchers concluded that the presence of a flagger or an officer directing traffic lowered the probability of having fatalities by four percent and having flashers or center/edge lines in work zones lowered the probability by six percent. The statistical analysis did not support any close association between the use of STOP signs, no passing zone control in work zone, and the fatality in severe crashes. The study showed that flaggers/officers could considerably lower the probability of severe crashes in work zones by human error such as ‘disregarded traffic control,’ ‘inattentive driving,’ and ‘exceeded speed limit’ while the no passing zone control was effective in lowering the probability of having crashes caused by ‘disregarded traffic control’ by three percent. In addition, having center line/edge lines could lower the probability of having severe work zone crashes by human error such as ‘exceeded speed limit’ and ‘followed too closely’ by five percent and three percent, respectively. Conversely, the study showed that the presence of STOP signs in work zones would increase the probability of having severe crashes by ‘followed too closely’ human error.

In 2006, Pigman et al. performed a study to evaluate the safety operations and issues associated with mobile and short-term work activities (*9*). As a part of the study, speed control measures in work zones: automated flagger devices, aerial lift/elevated platforms, and flashing STOP/SLOW paddles were tested and evaluated at work zones. The researchers also developed policies and guidelines for the use of elevated platforms near traffic. Speed data were collected at 23 locations across eight counties in Kentucky for 100 vehicles at each location evaluating different strategies such as double fine signs within an active work zone, double fine signs and police enforcement within an active work zone, and double fine signs and radar display units within an active work zone. The 50^{th} and 85^{th} percentile speeds were determined and indicated that the largest reduction in speeds were observed when police enforcement was used at the work zone. It was found that the least effective method in controlling the speeds was placement of advisory speed signs in work zones. Furthermore, 80 percent of the survey respondents rated "use police at the work site" very effective as compared to only 12 percent for the "use of advisory speed signs." The study recommended that automated flagger devices should be tested at high speed, high volume locations to assess their feasibility for future use. The study also recommended expanding the use of radar signs displaying the speed of the vehicles in work zones with major maintenance activities and providing the workers with flashing STOP/SLOW paddles during nighttime hours.

Carlson et al. evaluated the various traffic control devices, treatments, and practices for rural high-speed maintenance work zones over two years (*10*). Nine work zones, four two-lane highways with flagger operations and five multilane highway with a single lane closure, were studied at three locations in the Childress District in Texas. Data were collected using two LIDAR, two pairs of piezoelectric sensors with appropriate traffic counter classifiers, and one mobile recording video system with a high-mast camera support in May, June, and August 1999. Speeds, conflicts, driver surveys, maintenance crew surveys, and recorded CB Radio conversations were used to evaluate the devices. The devices evaluated in the "flagger controlled work zones" were fluorescent orange signings, drone radar, fluorescent yellow green vests and hard hat covers, handheld strobe lights attached to flagger vests, visibility improvement attachments and cones, and high visibility retroreflective magnetic strips on flagger vehicles. The devices evaluated at "lane closure work" were high visibility retroreflective magnetic strips on work vehicles, speed display trailers, and advisory speed signing in addition to the ones mentioned above. The speed data were analyzed at a 0.05 level of significance and preliminary analysis indicated that fluorescent orange signing, fluorescent yellow vests, drone radar, and speed display trailers were the most promising devices. Further analyses showed that the drone radar was identified by drivers as a factor influencing them to slow down in flagger operated work zones. In lane closure operations, the speed trailer resulted in the largest reduction in speed at the beginning of the work zone by 2 to 7.5 mph and within the work zone by 3 to 6 mph. The speed trailer was also successful in reducing the percentage of vehicles exceeding the speed limit approaching the taper and within the work zone. The conflict analysis showed that the use of speed trailers increased the conflict rates approaching the work zone and decreased slightly with the use of drone radar.

The second year of the study evaluated the use of seven devices at eight work sites: portable rumble strips, portable variable message signs (VMS), drone radar, fluorescent yellow worker vests, retroreflective vehicle visibility improvements, fluorescent orange signs, and speed display trailers (*11*). Speed data were collected by the LIDAR guns for the free flow speeds throughout the work zones and traffic counters with piezoelectric sensors used to collect speed and vehicle class data for all vehicles in the traffic stream in May and June 2000. The vehicle speeds in the work zones, the ease of installation and removal, the impact of the device on vehicle conflicts, and worker comments on the effectiveness of these devices were assessed. Analysis of the data collected revealed that the speed display trailer had the largest impact on speeds reducing passenger car speeds by 7 to 9 mph and 2 to 3 mph at sites 1 and 2, respectively. Also, the speed display trailer reduced the truck speeds by 2 to 3 mph at both the test sites. The portable rumble strips were found to have no effect on passenger cars, but reduced truck speeds by 2 to 3 mph. The VMS produced speed reductions of 1 to 2 mph within the work zone and had positive benefits in reducing conflicts.

2.3 Pilot Car Related

Rys et al. in phase I of their study tried to determine the most effective method of informing drivers about delay time when approaching a pilot car operation at a two-lane rural highway work zone (*12*). Six notification systems were identified during the preliminary research to provide information to the drivers: highway advisory radio (HAR) with static sign notification, a static sign displaying maximum wait time, a countdown timer displayed on the flagger’s stop paddle, a portable variable message sign (VMS), a countdown timer displayed on the approach sign, and portable message sign with countdown timer. Table 2 provides the feasibility of these different notification systems based on various evaluation criteria (*13*).

Table 2. Summary of Comparison of Information Dissemination Systems used (*12*)

System	Cost[a]	Effectiveness[b]	Integration[a]	Deployment[a]
HAR	High	Low	High	High
Static Sign with Maximum Wait Time	Low	Low	Low	Low
Countdown Timer on Flagger STOP/SLOW Paddle	Low	Low	Low	Low
VMS	High	High	High	High
Countdown Timer on Approach Sign	Low	Low	Low	Low
Portable Message Sign with Countdown Timer	Low	High	Low	Low

[a] For cost, integration, and deployment: high to low (high = 0 and low = 1)
[b] For effectiveness: low to high (high = 1 and low = 0)

As shown in Table 2, all the systems were rated on the basis of the criteria: cost, effectiveness, integration, and deployment. For cost, integration, and deployment, the rating of high to low was defined as high=0 and low=1 and for effectiveness high to low was defined as high=1 and low=0. Therefore, in terms of cost, integration, and deployment, it was found that the "portable message signs with a countdown timer" was the best alternative. Also, this system was found to be the most effective alternative since it was able to provide real-time information to drivers.

After evaluating the systems based on the criteria mentioned earlier, the idea of the "portable message signs with a countdown timer" was chosen for further research. Field testing of the equipment was conducted on a rural highway work zone four to five miles in length with only one sign positioned on the right side of the shoulder near the flagger on September 30, 2004 on US-24 near Riley, Kansas and October 7, 2004 on Route-77 in Riley County, Kansas. The test was run for three hours and 112 public survey questionnaires were distributed. The results indicated that the notification system was vulnerable to strong wind action. The system could not be tested for long periods due to the nature of the work zones and also the test of the autonomous functioning of the system was not performed.

Phase II of the study involved development of a fully workable and deployable prototype based on the concepts and field observations of the system demonstrated in phase I (*14*). An algorithm to estimate the wait time instead of using real-time communication was used to resolve the communication issues related to gaps in coverage. The “mini-trailer” design was tested at an operating pilot car construction zone on a US-24 project west of Silver Lake, KS on October 29, 2008 and a survey was conducted by questioning 30 drivers waiting in the queue. The algorithm kept the displayed wait time within one minute of the arrival of the pilot car. The survey results showed that 100 percent of drivers could understand the sign and 73 percent felt that the sign was helpful.

2.4 Flagger Related

Finley conducted a study on field evaluation of automated flagger assistance devices (AFAD) in work zones on two-lane, two-way farm-to-market and state highways in the Bryan, Lufkin, Paris, and San Antonio districts of Texas (*15*). Field tests were conducted and data were collected at 17 sites in the summers of 2010 and 2011 with survey data collected at six sites during the same period. Two types of AFAD’s were used for this research. First, a remote controlled STOP and SLOW sign to alternate the right of way and, second, a remote controlled red and yellow lenses to alternate the right-of-way with a gate arm. The research findings showed that the violation rate per 100 stop cycles for the STOP/SLOW AFAD without the gate arm was the highest at 6.7 percent and was significantly higher than the violation rate for the red-yellow lens AFAD at 2.2 percent. The addition of supplementary signs increased the drivers understanding that the stop sign would have changed to a slow sign in order to proceed. The overall finding was that the drivers violated the AFAD when the queue of vehicles in the opposite direction was visible to the stopped drivers. Thus, on the basis of this report, the researchers believed that both the AFADs (STOP/SLOW and red-yellow) could be used to control traffic at lane closures on two-lane, two-way roadways.

Trout et al. studied the drivers understanding of the AFADs in work zones (*16*). The researchers surveyed 750 drivers in Texas for the purpose of the study. A chi-square test of homogeneity was used to determine whether the beacon (flashing or steady) affected the drivers’ understanding of the STOP/SLOW Paddle. The results of the chi-square test indicated that the beacon should be continued to be used with the STOP/SLOW Paddle. To determine whether the comprehension percentage was statistically different from the 85 percent criterion, the researchers used a confidence interval test at a 0.05 level of significance. They found that without the "GO ON SLOW" sign, only five percent of the total participants understood that the stop would change to slow when they were allowed to proceed. They also found that with the "WAIT ON STOP" and "GO ON SLOW" signs, only eight percent of the participants stated that they would stop and proceed on slow like a standard STOP sign. For the red-yellow lens AFAD, participants understood the stop phase even though there was evidence of a lack of understanding of the difference between the stop and proceed phases. The researchers recommended that a gate arm should be used with the STOP/SLOW AFAD and also with the red-yellow AFAD to better inform the drivers on when to proceed and when to stop.

El Rayes et al. assessed the effectiveness and essential role of flaggers and spotters in directing traffic for expressway and freeway work zones in Illinois with a posted speed limit greater than 40 mph (*17*). The researchers studied seven highway work zones in 2012 and 2013 to evaluate flagger practices used at work zones in Illinois. Data were collected on the type of construction operations performed at the work zones, layout of the work zones with location of flaggers, and temporary traffic control measures used in the work zone. The researchers collected and analyzed the latest data and reports on work zone crashes in Illinois from 1996-2009 to study the frequency and severity of traffic related work zone crashes. The analysis suggested that the causes of work zone crashes could be mainly classified into six categories: improper driving, distraction, work zone environment, disregarding traffic control, speed, and an unknown cause. The researchers analyzed the effectiveness of existing and new work zone safety measures such as intrusion alarm alert systems, portable changeable message signs (PCMSs), portable speed monitoring displays (PSMDs), temporary rumble strips, drone radar, truck-mounted attenuators (TMAs), mobile barriers, and automatic flagger assistance devices (AFADs).

Two identical online surveys were conducted to gather and analyze feedback from engineers and construction personnel in the Illinois Department of Transportation (IDOT) and other state DOTs on the effectiveness of flaggers and spotters in directing traffic on freeways with a posted speed limit greater than 40 mph. The survey results were analyzed on a scale of 0.0 to 1.0 where 0.0 was 'no need,' 0.25 was 'low need,' 0.5 was 'moderate need,' 0.75 was 'high need,' and 1.0 was 'greatest need.' The average score for the need of flagger to perform various safety and mobility functions in work zones was 0.74 as compared to 0.26 in the national survey indicating that the respondents from states other than Illinois considered the need for a flagger in a work zone to range from ‘no need’ to ‘moderate need.’ The average score for the benefits that could be obtained by using a flagger on freeway work zones was 0.63 and 0.27 in the IDOT survey and the national survey, respectively. Similarly, the average score for the risk and hazards that could be caused by using a flagger were 0.66 and 0.69 in the IDOT survey and the national survey, respectively. The analysis of Illinois crash data from 1996 to 2009 indicated that ‘improper driving’ caused 42.1 percent of fatal crashes, ‘speed’ caused 11.8 percent of fatal crashes, and ‘rear-end collisions’ caused 38.2 percent of fatal crashes in work zones on Illinois freeways/expressways. The IDOT survey acknowledged police patrols, PSMDs, TMAs, and PCMSs as the top four effective measures while the national survey acknowledged TMAs, PCMS, police patrols, and mobile barriers as the top four effective work zone safety measures.

Avrenli et al. studied the effectiveness of flaggers in reducing the likelihood of rear-end collisions for in-platoon vehicles in work zones (*18*). The objective of the study was to explore the efficiency of flaggers in reducing the frequency of factors such as speeding, following too closely, and faster trailing that increase the potential of rear-end collisions. The researchers collected 11 data sets from five single-lane work zones on Interstate highways in Illinois with no lane change opportunities. The time gap and speed data for approximately 4,600 in-platoon vehicles were used. To compare the frequency of short time gaps based on work zone traffic control, contingency tables were prepared and chi-square tests at a 0.05 level of significance were conducted. A binary logistic regression model was also built to quantify the effects of flaggers in reducing the likelihood of short time gaps. The results indicated that for maintaining short time gaps, the probability that a vehicle in platoon would maintain short time gaps did not differ significantly between work zones with no flagger and a 45 mph speed limit and work zones with no flagger and a 55 mph speed limit. For speeding by at least 5 mph at short time gaps, it was found that work zones with no flagger and a 45 mph speed limit were more hazardous. The study concluded that flaggers might be effective in reducing the probability of rear-end collisions as they were able to reduce the probability of speeding and short time gaps.

Cottrell evaluated the AutoFlagger to assist a flagger for short-term lane closures on two-lane highways in Virginia (*19*). Two AutoFlagger units were deployed at the Wytheville

Area Headquarters (AHQ) and the Beach Area Headquarters under the Virginia Department of Transportation. At the Wytheville AHQ, the device was deployed for a total of 59 hours during January and February 2006. The Beach AHQ deployed the device on two occasions in December 2005 on Route 60 in Powhatan County for a total of 16 hours. Data collected were compiled and analyzed to assess the effectiveness of the device. The researcher identified the devices' large size as a potential advantage which made it visible and commanded driver attention. The researcher concluded that the paddle and signal-based AFAD were most effective based on the fact that both were well established and familiar traffic control devices. It was found that the cost of the AFAD could be recouped after 1.7 to 3.4 years depending upon the use of the device. The researcher also indicated that a potential limitation of using AFADs was its inability to provide warnings, instructions, and/or answers to drivers' questions.

The Minnesota DOT had been using the AutoFlagger since 1996 and reviewed the results of a driver survey, flagger comments, field review by traffic engineering staff, and driver behavior videos. The results indicated a positive response for the device from the drivers and the construction workers and flaggers. The observation made from driver videos suggested that only a very small number of drivers failed to interpret the device immediately. Therefore, after reviewing the results, the DOT decided to apply the technique only at two-lane, two-way roadways with one lane closed to traffic with an Average Daily Traffic (ADT) less than 1,500 vehicles per day, lane closure distance of 800 feet or less, and when the operator(s) had an unobstructed view of the Auto-Flagger and approaching traffic in both directions (*20*).

The 2008 KDOT flagger handbook presented operations and guidance for personnel who would be used as flaggers in work zones (*21*). Flaggers help guide traffic, slow traffic, and/or stop traffic to allow safe operations in work zones. Safety was given a prime consideration since flaggers had the highest amount of exposure to fast moving traffic. They also served as safety lookouts for other personnel on the work site by alerting them to potential threats and dangerous situations. Uniformity in operations was considered to be the key in increasing driver safety and compliance. When pilot cars were to be used, flaggers held the traffic until the pilot car was present to guide the traffic through the work zone. The manual also stated that late vehicles should not be allowed to catch up to the platoon after it had embarked.

2.5 Crashes and Injury Costs

Coburn et al. quantified the injury outcomes and developed reliable and comprehensive injury costs for work zone crashes based on the crash type (rear-end and head-on) and crash severity based on the KABCO scale (K, killed; A, incapacitating injury; B, non-incapacitating injury; C, possible injury; O, property damage only) (*22*). Data for the study were collected from WisTransPortal and the Crash Outcomes Data Evaluation System (CODES) data provided by the Center for Health Systems Research and Analysis at the University of Wisconsin-Madison. The researchers used a three step methodology to quantify the crash costs for each severity and manner of collision. The Wisconsin CODES database provided comprehensive injury costs based on injury types and severities suffered by participants in study crashes. The researchers concluded that incapacitating, non-incapacitating, and possible injury crashes were 105 percent, 35 percent, and 50 percent larger than the inflation-adjusted FHWA default values, respectively. The weighted overall injury cost for all work zone crashes was about 25 percent greater than the FHWA cost. Since there was a significant variation in injury crash costs by crash type, the researcher suggested that developing crash-specific costs might result in more accurate cost-benefit analysis for implementing countermeasures.

2.6 Summary of the Literature

- Ullman and Levine's study showed that savings ranging from $9 to $14 per hour in flagger labor costs could be achieved by using a portable fixed-time traffic signal system with only a minimal increase in driver delay cost (*1*). The study also suggested that the potential for vehicle crashes within the work zone might be higher because of driver noncompliance with the PTS system. The researchers suggested that the signal validity could be improved by adding a stop line 50 to 60 feet in advance from the signal and also erecting a temporary "STOP HERE ON RED" sign next to the stop line enforcing the need for stopping. To control RLR for vehicles entering the work zone without stopping, it was recommended that the wattage of the signal lamp heads should be increased so that they were more visible in daylight.
- Daniels et.al studied the use of PTS technology to replace flaggers as a means for improving the efficiency of two-lane rural maintenance operations in Texas (*2*). Their calculations showed that the return on investment in the technology could be realized

after two years of operation and were estimated in subsequent years at $20,000 to $30,000 per year (1999-2000) provided that the equipment was put into use eight to ten days per month. The field test cases advocated that PTS were feasible in improving the crew efficiency and flexibility on two-lane rural work zones for maintenance operations. For the use of PTS in stationary maintenance work activity, the researchers recommended the length of work zone to be increased from 400 to 2,600 feet and the wait time to be a maximum of four minutes.

- In England, the traffic advisory leaflet recommended the use of PTS for alternating traffic in work zones where one lane of a two-lane facility was closed (*5*). The maximum recommended length for the work zones was 300 meters (1,000 feet) due to long all-red times resulting in longer queues. Proper training was also recommended to avoid increase in the risk of crashes, additional costs in fuel and time, increased pollution, and driver frustration.
- Lee et al. studied the effectiveness of a vehicle-actuated signal control system on work zone operations for two-lane highway. In terms of safety and mobility for work zones on two-lane highways, they found the ADAR to be the most efficient signal control method under most conditions examined. They also recommended the construction of a temporary bypass if the traffic volumes exceeded 500 vehicles per hour on two-lane, two-way work zones with length greater than 400 meters (1,200 feet) to reduce delays and increase traffic safety (*6*).
- Rys et al. determined the portable message signs with a countdown timer as the most effective method of informing drivers about delay time when approaching a pilot car operation at a two-lane rural highway work zone in a two-phase study (*12*, *13*, and *14*). After deploying their "mini trailer" design and conducting driver surveys, their results showed that 100 percent of the drivers could understand the sign and 73 percent of the drivers felt that the sign was helpful.

The literature reported herein was useful in development of the research methodology presented in Chapter 4 and also supports some of the recommendations discussed in Chapter 8.

CHAPTER 3. PROBLEM STATEMENT

Lane closures on one-way, two-lane roadways require the use of a control method to regulate the safe and efficient movement of traffic at either ends of the work zone. The 2009 MUTCD indicated that, if traffic on the one-lane roadway was not visible from one end to the other, then flagging procedures, a pilot car in conjunction with a flagger, or a traffic control signal should be used to control opposing traffic flows (*3*). Similarly, Section 805 of the special provision to the KDOT standard specifications for work zone traffic control and safety recommended that pilot car operations could be used to assist and lead traffic during one-way operations, which was over a distance greater than that could be seen between flaggers (*23*). Therefore, for maintenance activities such as asphalt overlay and shoulder repair, using a pilot car in conjunction with flagging operations on two-lane, two-way roadways with one-lane closed for traffic was a widely accepted practice in the state of Kansas at the time of this research.

A report by the National Institute for Occupational Safety and Health (NIOSH) indicated that from 1992 to 1998, 27 flagger fatalities were recorded at highway or street construction work zones, which was approximately 3.86 fatalities per year (*24*). In their analysis of fatal occupational injuries at road construction sites from 2003 to 2010, the Bureau of Labor Statistics (BLS) reported that 442 workers were killed at road construction sites after being struck by a vehicle or mobile equipment (*25*). Of the 442 cases, 92 cases stated that the workers were performing flagging or other traffic control duties and 32 were employed as flaggers. This indicated that whenever the flaggers were used in conjunction with pilot car operations they were operating under the ever-increasing risk of being hit by an erroneous driver. To eliminate the risk of a flagger being struck by noncompliant traffic, PTS systems have become common among contractors at shorter work zones where the ends of the work zone were visible to stopped traffic.

As indicated earlier, the 2009 MUTCD provided guidance regarding the use of pilot car operations in conjunction with flagger operations for controlling one-way traffic at two-lane, two-way work zones. However, there was no direct guidance provided regarding the use of PTS systems in conjunction with pilot car operations and/or flagger operations. Since flagging operations were labor intensive, expensive, and posed hazards for workers, it was important to evaluate new technologies and techniques that had the potential of providing efficient traffic operations and safety at one-lane, two-way work zones. Three conditions were selected in order to provide a clear interpretation of the guidelines stated in the MUTCD and to determine whether these conditions were beneficial in improving the overall operations and safety at two-lane, two-way rural work zones. These were:

- Flagging only operations;
- A PTS system with a flagger; and
- A PTS system without a flagger.

The primary measures of effectiveness were determined as:

- RLR or violation percentages;
- Vehicle delay estimates;
- Queue lengths;
- Signal timing operations (e.g. indications of signal failures); and
- Other field operations.

The KDOT specifications for work zone traffic control and safety were used as guidance regarding issues such as maximum pilot car speed within the work zone and the maximum round trip time for the pilot car. That helped in conducting the data analysis to determine the volume thresholds for the failure of the PTS system and in the estimation of green intervals for corresponding number of vehicles. The Signal/Pilot Car typical and Traffic Control Sign (TE-710) Standard used for this research were provided by KDOT and can be found in Appendix E.

CHAPTER 4. METHODOLOGY

This section is divided into four parts and details the survey of practice, the closed course study, the site selection and data collection methodology, and an overview of the data reduction and data analyses.

4.1 Survey of Practice

A survey of 19 different state DOTs was conducted during May and June 2014. The objective of the survey was to obtain an understanding of the practices followed in the various states regarding the use of PTS systems, pilot car operations, and flagger operations. The survey was conducted via telephone or email depending on the preference of the state officials. Table 3 provides a summary of the responses for all the state DOTs that were surveyed.

Table 3. Summary of Responses for the Survey of Practice

No.	STATE DOT	Pilot Car Operation	Use PTS	PTS		Maximum Length of work zone for PTS (miles)	Guidelines	
				In Conjunction with Pilot Car Operation	In Conjunction with Flagger Operation		MUTCD	Own Standards
1	Arkansas	Yes	Yes	No	No	0.2	Yes	-
2	Conneticut	No	Yes	No	Yes	NS	Yes	-
3	Florida	Yes	Yes	No	No	NS	Yes	-
4	Idaho	Yes	Yes	No	No	5	-	Yes
5	Illinois	No	Yes	No	No	1.5	-	Yes
6	Indiana	Yes	No	NA	NA	NA	-	-
7	Iowa	Yes	Yes	No	No	2.5	-	Yes
8	Kentucky	No	Yes	No	No	0.03	Yes	Yes
9	Maryland	No	Yes	NA	NS	0.4	-	Yes
10	Michigan	Yes	Yes	No	No	2	Yes	-
11	Minnesota	Yes	Yes	No	Yes	NS	Yes	Yes
12	Montana	Yes	Yes	No	Yes	2	Yes	-
13	Nebraska	Yes	Yes	No	No	0.2	Yes	-
14	Nevada	Yes	Yes	No	NS	5	Yes	-
15	Ohio	No	Yes	NA	No	NS	-	Yes
16	Oklahoma	Yes	Yes	No	No	NS	Yes	-
17	Tennessee	No	Yes	No	NS	1.5	Yes	-
18	Texas	Yes	Yes	Yes	No	NS	-	Yes
19	Wyoming	Yes	Yes	Yes	No	NS	Yes	-

Note: “NA”- Not Applicable; “NS”- Not Specified in the survey.

From Table 3, it can be found that at the time of the research, PTS systems were used in 18 of the 19 states that were surveyed. The state of Indiana did not use the PTS system at any of its work zones during the time of the research. It was found that 12 state DOTs used the MUTCD as reference while six state DOTs developed their own guidelines as reference for the use of PTS systems, pilot car operations, and flagger operations. It was also found that two state DOTs used a PTS system in conjunction with pilot car operations and three state DOTs used a PTS system in conjunction with flagger operations. Appendix B provides a detailed description of the responses for all the 19 state DOTs that were surveyed.

4.2 Closed Course Study

A closed course study was performed on August 4, 2014 in the East Lot of the Park and Ride facilities at the University of Kansas. Figure 1 shows a snapshot from the closed course study.

Figure 1. Closed course study at the University of Kansas.

As shown in Figure 1, Mr. Doug Niemerg and Mr. Roger Alexander (John Thomas, Inc.) demonstrated the functioning of the components and described the features of a PTS unit. During this closed course study, instructions were provided for operating the main control box on the PTS unit, lowering and raising of the mast arm and solar panels, operating the handheld remote control, and altering the signal timings. Mr. Garry Olson (KDOT) was also present at the time of this closed course study.

4.3 Site Selection and Data Collection

The next step in the research was to select suitable test locations where data were to be collected. Four locations which were two-lane, two-way long work zones anticipating pilot car operations and flagger operations were identified by working with KDOT and selected for the data collection. Following were the four test locations that were selected for this research:

- US-56 near Burlingame, KS;
- K-31 near Melvern, KS;
- US-24 near Beloit, KS; and
- US-50 near Newton, KS.

Data were collected at these four test locations three days per week for a period of four weeks in August, 2014. A detailed description of all the test locations and data collection is provided in Chapter 5.

4.3.1 Equipment Used

A list of equipment required for the data collection was prepared prior to conducting any field data collection. The following section detailed a general description of the equipment that was used for the research.

Safety

Safety of all the research team members was of paramount importance. All the team members participating in the data collection activity were wearing hard hats and retroreflective vests for the entire duration of the data collection.

PTS Units

John Thomas, Inc. provided two ADDCO Solar PTS units with the Galaxy operating system for the research. A summary of important technical specifications of the PTS unit can be found in Appendix A. Two pickup trucks (Ford F-150) were used to transport the PTS units and the other data collection equipment to every test location.

Video Data Collection

Commonly available equipment was used for the video data collection. The high definition video cameras used for data collection had a battery life of one to two hours, thus needing an extended battery pack to extend the record time of each camera. Also, a custom built camera drum was used to place the video cameras at the time of data collection. Figure 2 shows the video camera used for the research.

Figure 2. Sony HDR CX-220 camera used for video data collection.

As shown in Figure 2, four Sony Handycam HDR-CX 220 cameras were used for collecting video data, two at each end of the work zone. One camera was deployed for collecting the signal data such as start of green interval, end of green interval, red light running vehicles, and pilot car operations for every cycle. The second camera was deployed to record the arrival time of the first vehicle in each queue, length of the queue, and vehicles turning around due to the wait time. Figure 3 shows the battery and the inverters used for the research.

Figure 3. Battery and inverter with the plastic box and connecting wire.

As shown in Figure 3, two large Exide dual purpose batteries along with two Tripp Lite 600 Watt inverters were used to charge the video cameras continuously to ensure that no data were lost due to insufficient charge. The batteries and the inverter were both placed inside a black plastic box to protect them from rain, wind, and for the ease of transportation. A 100 feet long wire was used to connect the inverter to the camera plug-in to allow the batteries to be placed well outside the roadside clear zone during the data collection. Figure 4 shows the custom built drum used to place the video cameras for the research.

Figure 4. Custom built camera drum with orange taping.

Three normal traffic drums were borrowed from Twin Traffic Marketing Corp. for placing the video cameras during the data collection. As shown in Figure 4, a semicircular portion from the face of the drum was replaced with clear plastic for providing visibility to the cameras. A majority of the portion of the plastic glass was taped off with basic orange tape similar to the color of the drum to diminish the visibility of the video cameras to the drivers. It was assumed that the reduced visibility of the cameras would result in unaltered driver behavior. Each drum was designed to support two video cameras on a wire mesh that was fixed inside the drum.

Signage

The four traffic signs used for the purpose of the research were: SIGNAL AHEAD, STOP HERE ON RED, FLAGGER AHEAD, and WAIT FOR PILOT CAR. Figure 5 shows the SIGNAL AHEAD sign used for the research.

Figure 5. Signal Ahead sign used for the research.

As shown in Figure 5, the SIGNAL AHEAD signs were borrowed from C-Hawk's construction office in Eudora, KS. The location of the signage was determined based on the temporary traffic control plan provided by KDOT. At every test location, the contractor was responsible for all the other signage that was to be provided in the work zone as per the traffic control plan. Figure 6 shows the STOP HERE ON RED sign, FLAGGER AHEAD sign, and WAIT FOR PILOT CAR sign used for the research.

Figure 6. Traffic signs used.

As shown in Figure 6, the STOP HERE ON RED signs were borrowed from C-Hawk's construction office in Eudora, KS and the WAIT FOR PILOT CAR signs and the FLAGGER AHEAD signs were borrowed from the contractor at every test location as needed. Similar to the other signs, the location of these signs was determined based on the temporary traffic control provided by KDOT.

4.3.2 Data Collection Methodology

A general data collection and equipment setup methodology was established prior to the field data collection. Figure 7 shows the equipment setup plan that was designed to indicate the location of the PTS unit, video cameras, and the signage during the field data collection.

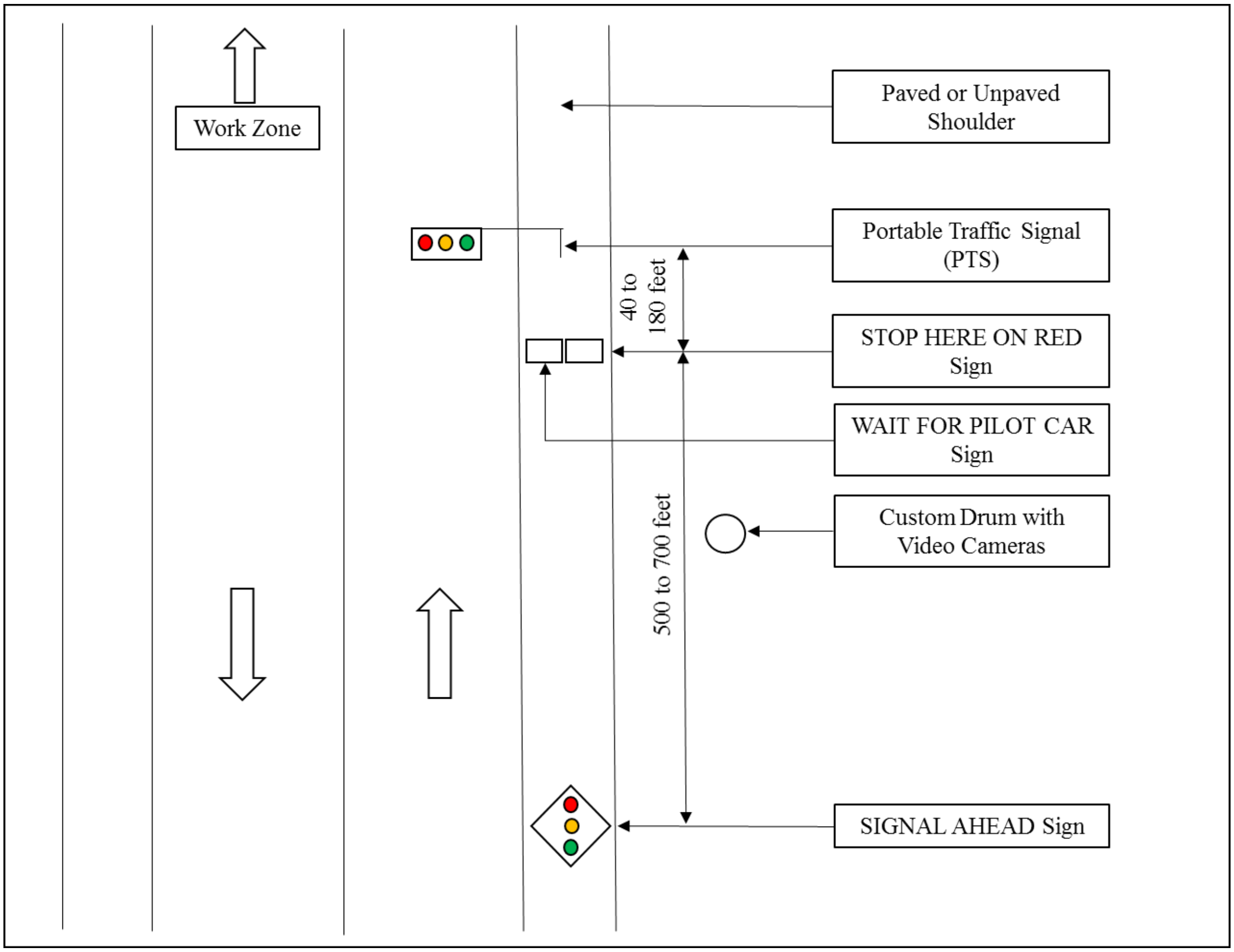

Figure 7. Designed equipment setup plan.

As shown in Figure 7, the 'STOP HERE ON RED' and 'WAIT FOR PILOT CAR' signs were located at the same spot at the test location. Their distance from the PTS unit was approximately 40 to 180 feet and varied depending on the road geometry at each work zone end. The distance of the 'SIGNAL AHEAD' sign from the PTS unit was approximately 500 to 700 feet and varied with the speed of the road. The other work zone signage installed by the contractor was kept unaltered. Also, in the absence of a paved or unpaved shoulder and the presence of a steep foreslope, the test equipment was setup close to the outside edge of the pavement. The following section describes the general procedure that was followed at every test location in regards to equipment setup and video data collection.

Equipment Setup and Video Data Collection

Two research teams were used with one team stationed at either end of the work zone. Each team was responsible for setting up the PTS unit, two video cameras inside the custom drum, an external battery with an inverter, and the signage as per the plan shown in Figure 7. The signage was setup approximately at the same time as the other work zone signage was setup by the contractor. The team periodically checked the PTS units, video cameras, and the signs to ensure data were being collected and the setup was unaltered.

Data collection started as soon as construction activities commenced at the work zone and continued until the end of the day’s activities. Periodically, time was recorded in all the video cameras using a cellphone or a watch by a team member for future reference. A minimum of eight hours of video data per day were set as the target for each team. This minimum duration excluded the time required for the setup of the equipment and the time lost when moving from one location to the other with the work zone. At the end of the day, collected data were immediately transferred to a hard drive to avoid loss of data and rest of the equipment was organized for the following day.

4.4 Data Reduction and Data Analyses

All the data were reduced in the Transportation Engineering and Analysis Laboratory (TEAL) at the University of Kansas. The variables to be considered during data reduction were: arrival and departure time of the first vehicle in the queue, start and end time of the green interval, number and type of vehicles observed in a queue, and number and type of red light running vehicles. Each of these variables and their significance for this study is described in Chapter 6. The analyses of the data were divided into three parts. Each of the analyses are described briefly in the following section.

First, an operational analysis of the different parameters such as the average total wait time, average green interval, and average queue length was conducted.

Second, a statistical analysis was conducted to identify the presence of a statistically significant difference in the number of red light running vehicles for the three conditions:

- Flagger only versus PTS with a flagger;
- Flagger only versus PTS without a flagger, and
- PTS with a flagger versus PTS without a flagger.

A one-tailed two-proportion z-test was used to analyze the two data sets. The test was conducted at a 0.05 level of significance. The null and alternate hypothesis for the test were:

H_o: $p_1 \geq p_2$

H_A: $p_1 < p_2$

Where:

p_1 = proportion of red light running vehicles in the condition 1; and

p_2 = proportion of red light running vehicles in the condition 2.

Additionally, an exploratory delay analysis was conducted to determine whether the presence of a flagger with a PTS unit was beneficial in reducing the total delay. Finally, a model was developed using the available data to identify the volume thresholds at which the PTS system would fail with recommendations on the use of appropriate green intervals for corresponding approaching traffic volumes.

Chapter 5 provides a detailed description of the field data collection conducted at the four test locations.

CHAPTER 5. FIELD DATA COLLECTION

Field data were collected at four locations three days per week for four weeks from August 5, 2014 to August 28, 2014. The test locations were coordinated with the help of Ms. Kristina Ericksen (KDOT) and Mr. Roger Alexander (John Thomas, Inc.). At each of the test locations, data were collected for the following three conditions:

- Flagger only in conjunction with a pilot car operation;
- PTS with a flagger present in conjunction with a pilot car operation; and
- PTS without a flagger in conjunction with a pilot car operation.

Figure 8 shows a map of the four test locations where data were collected for the purpose of this research.

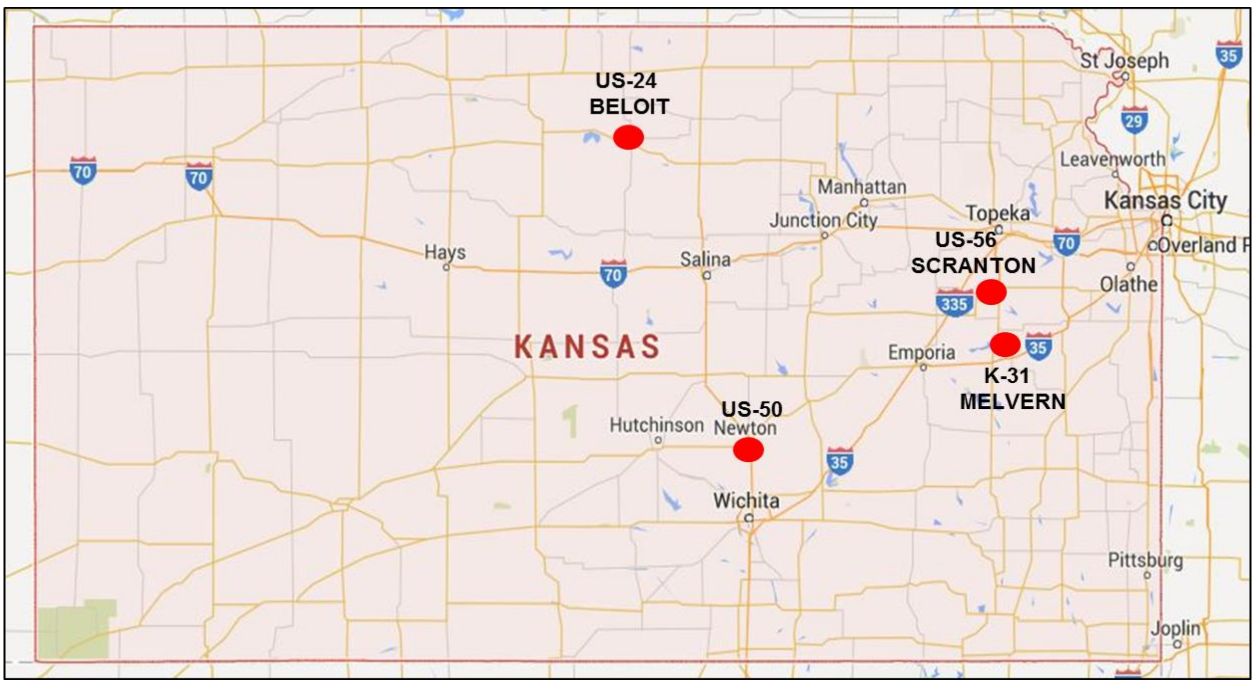

Figure 8. Map showing the test locations for field data collection.

As shown in Figure 8, data were collected at four different test locations for the three conditions mentioned earlier. Table 4 provides a summary of the entire data collection conducted from August 5, 2014 to August 28, 2014.

Table 4. Summary of the Data Collection for All Test Locations

DATE	CONTRACTOR	SITE LOCATION	TOTAL DATA COLLECTED (hours)			
			Flagger Only	**PTS with a Flagger**	**PTS Only**	**Total**
7/30/2014	Dustrol, Inc.	US-56, Burlingame	3.5	NA	NA	3.5
7/31/2014			7.5	NA	NA	7.5
8/5/2014	Dustrol, Inc.	US-56, Burlingame	0	11.5	0	11.5
8/6/2014		US-56, Scranton	0	0	12	12
8/7/2014			0	0	15	15
8/12/2014	Dustrol, Inc.	K-31, Melvern	0	3.5	2	5.5
8/13/2014			0	0	17	17
8/14/2014			7	5.5	5.5	18
8/19/2014	Hall Brothers, Inc.	US-24, Beloit	0	14.5	0	14.5
8/20/2014			0	8.5	8	16.5
8/21/2014			4	0	12	16
8/26/2014	APAC KS-MO	US-50, Newton	0	5	0	5
8/27/2014			0	14	5	19
8/28/2014			NA	NA	NA	0
Total			**22**	**62.5**	**76.5**	**161**

Note: "NA"- Not Applicable because no data were collected.

From Table 4, it can be found that 161 hours of data were collected for the three conditions at each of the test locations. Data were collected for 11 hours for the 'flagger only' condition near Burlingame, KS on July 30 and July 31, 2014. Therefore, no data were collected for that condition from August 5 to August 7, 2014. A detailed description of the test locations is provided in the subsequent sections.

5.1 Test Location 1

Data were collected at a work zone with an ongoing chip seal operation on US-56, a two-way, two-lane rural highway, near Burlingame and Scranton, in Osage County, KS from August 5, 2014 to August 7, 2014. Additionally, data were collected for the 'flagger only' condition on July 30 and July 31, 2014 at the same location. The highway had a posted speed limit of 55 mph and no shoulders outside of the city limits. The highway had a speed limit of 30 mph and eight feet wide paved shoulders within the city. The work zone had an AADT ranging from 1,000 to 3,300 vehicles per day (*26*). The work zone was a long, temporary, and mobile work zone where work activity was not necessarily visible to the traffic stopped at either ends of the work zone. The end-to-end distance was approximately 2 to 2.5 miles for each of the five days when data were collected. The contractors established the work zone in such a way that the maximum round trip time needed for the pilot car was never more than 15 minutes. The green interval on both the PTS units was set to a minimum of 30 seconds and a maximum of 60 seconds. Only one preset (30/60 seconds) was used over the entire data collection period.

Data for the ‘flagger only’ condition were collected on July 30 and July 31, 2014. One team of two research members accomplished this task and collected data for approximately 11 hours over a period of two days. Figure 9 shows a ground view of the data collection setup at the north end of the work zone where data were collected on July 30, 2014.

Figure 9. Southbound traffic data collection for the flagger only condition on July 30, 2014.

As shown in Figure 9, at the north end of the work zone, data were collected over two sessions for the ‘flagger only’ condition. Session 1 started at 12:47 p.m. and ended at 3:10 p.m. while session 2 started at 3:40 p.m. and ended at 4:54 p.m. On July 31, 2014 data were collected over two sessions at one end of the work zone. Session 1 started at 8:10 a.m. and ended at 12:50 p.m. while session 2 started at 1:03 p.m. and ended at 4:03 p.m.

On August 5, 2014 the purpose of the study and the data collection methodology was briefly described to the site supervisor. As a precautionary measure, one of the research team members drove with the pilot car to familiarize the pilot car driver with the handheld remote for the PTS units and verified the correct functioning of all the devices. It was ensured that the procedure was clearly understood by the drivers and all questions were answered. Research team members were stationed in close proximity to the PTS unit for a few cycles to ensure the proper functioning of the system. The relocation of the PTS unit and all the other data collection equipment was required whenever the work zone end stations moved.

On August 5, 2014 data were collected over two sessions for the 'PTS with a flagger' condition. Both ends of the work zone were located on level terrain with adequate sight distances. Figure 10 shows an aerial view of the data collection setup for session 1 at the south end of the work zone on August 5, 2014. At the end of the work zone, data collection started at 8:51 a.m. and ended at 11:54 a.m.

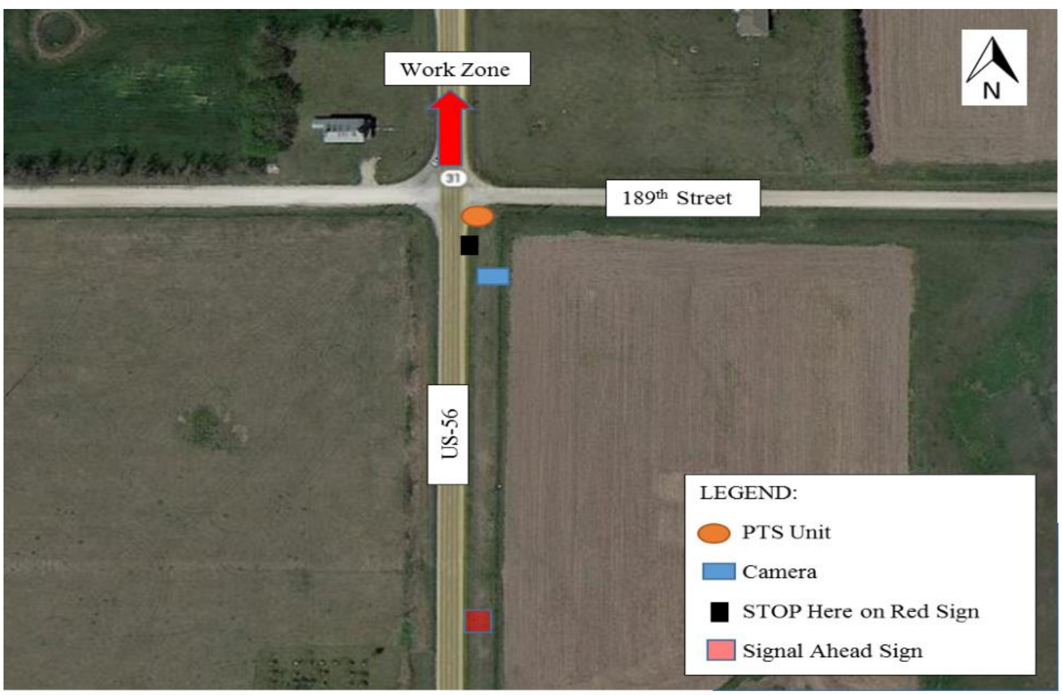

Figure 10. Data collection setup at the south end on day 1 session 1 (Northbound).

As shown in Figure 10, data were collected only at the south end of the work zone since the PTS units were being used for the first time at an actual work zone. Flagger operations were retained at the north end of the work zone. Figure 11 shows a ground view of the data collection setup for session 1 at the south end of the work zone on August 5, 2014.

Figure 11. PTS setup for northbound traffic at the south end on day 1 session 1.

Figure 12 shows an aerial view of the data collection setup for session 2 at the west end of the work zone on August 5, 2014. At the end of the work zone, data collection started at 12:42 p.m. and ended at 5:11 p.m.

Figure 12. Data collection setup at the west end on day 1 session 2 (Eastbound).

Figure 13 shows a ground view of the data collection setup for session 2 at the west end of the work zone on August 5, 2014.

Figure 13. PTS setup for eastbound traffic in Burlingame, KS on day 1 session 2.

As shown in Figure 13, at the west end of the work zone, the PTS was setup inside the city of Burlingame and data were collected for the ‘PTS with a flagger’ condition. During data collection, the Bluetooth connectivity with the handheld remote in the pilot car was lost and had to be reset through the main control box on the trailer. This resulted in a few non-green phases and the ends of the work zone were essentially controlled by the flagger. Additionally, two cases were observed when the green phase restarted after the PTS went into the red phase. This issue is discussed in detail in Chapter 8. Figure 14 shows an aerial view of the data collection setup for session 2 at the east end of the work zone on August 5, 2014. At the end of the work zone, data collection started at 12:48 p.m. and ended at 4:56 p.m.

Figure 14. Data collection setup at the east end on day 1 session 2 (Westbound).

Figure 15 shows a ground view of the data collection setup for session 2 at the east end of the work zone on August 5, 2014.

Figure 15. PTS setup for westbound traffic at the east end on day 1 session 2.

After data were collected for the session 2, the work zone moved again at 5:00 p.m. but work was anticipated to continue till 6:00 p.m. Since, setting up of the PTS unit, video cameras, and the signage accounted for approximately 45 minutes, it was decided to end the data collection. It was also found that the green phase failed to activate a total of nine times during the entire day.

On August 6, 2014 data were collected over one-day long sessions at both ends of the work zone for the ‘PTS without a flagger’ condition. Figure 16 shows an aerial view of the data collection setup for session 1 at the west end of the work zone on August 6, 2014. At the end of the work zone, data collection started at 8:12 a.m. and ended at 2:32 p.m.

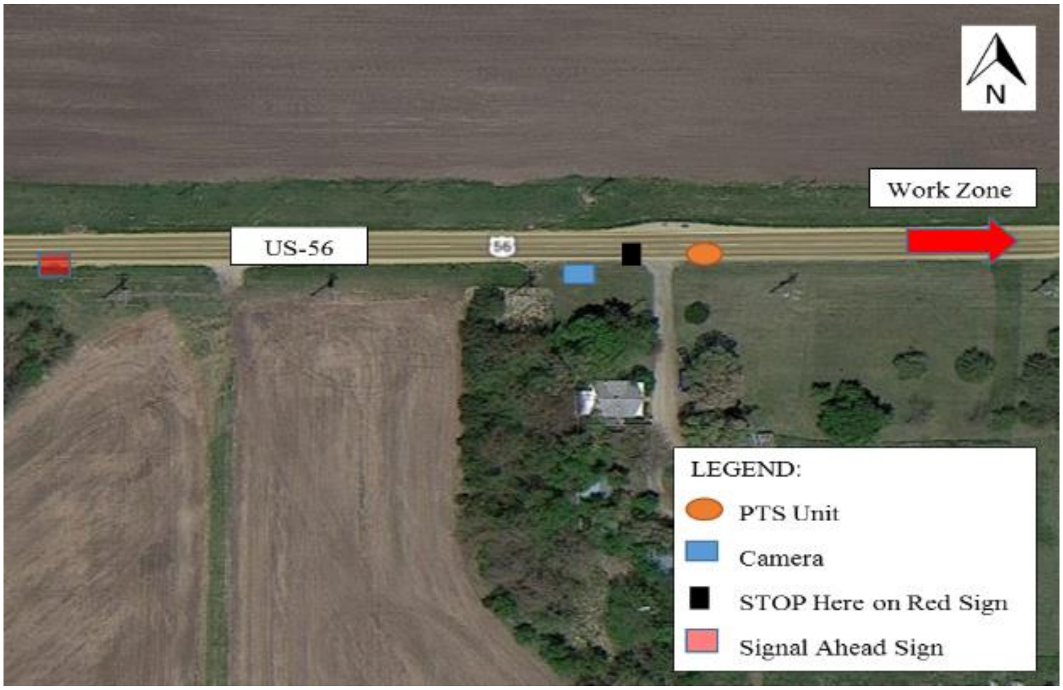

Figure 16. Data collection setup at the west end on day 2 session 1 (Eastbound).

At the west end of the work zone, the pilot car drivers forgot to activate the green phase one time. Also at this end of the work zone, the contractor's official car was parked next to the PTS unit near the flagger station. It was believed that presence of an official vehicle might alter the driver behavior and the compliance rates, the construction crew was requested to park the vehicle further downstream. Figure 17 shows an aerial view of the data collection setup at the east end of the work zone on August 6, 2014. At the end of the work zone, data collection started at 8:52 a.m. and ended at 2:16 p.m.

Figure 17. Data collection setup at the east end on day 2 session 1 (Westbound).

At the east end of the work zone, the pilot car drivers forgot to activate the green phase three times. Also, at this end of the work zone, a flagger was present near the flagger station, but was not interfering with the operations of either the PTS unit or the pilot car. Figure 18 shows a ground view of the data collection setup at the east end of the work zone.


Figure 18. PTS set up for westbound traffic at the east end on day 2 session 1.

Due to rain, work was discontinued after just one session of data collection and, no data were collected thereafter.

On August 7, 2014 data were collected over two sessions at both ends of the work zone for the 'PTS without a flagger' condition. Figure 19 shows an aerial view of the data collection setup for session 1 at the south end of the work zone on August 7, 2014. At the end of the work zone, data collection started at 9:10 a.m. and ended at 12:55 p.m.

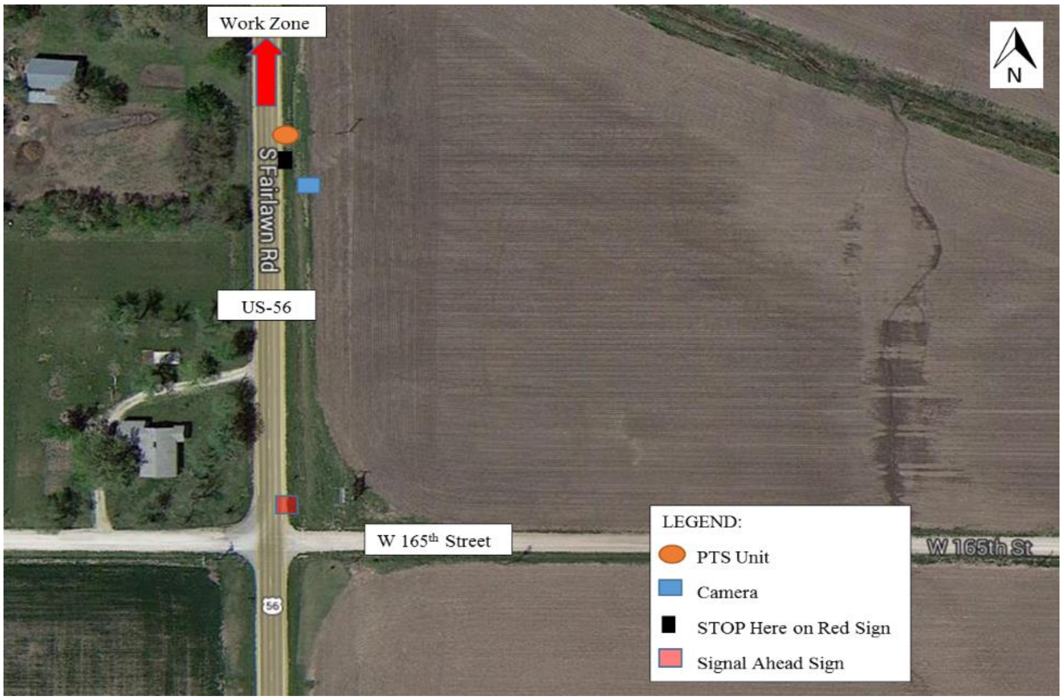

Figure 19. Data collection setup at the south end of on day 3 session 1 (Northbound).

Figure 20 shows a ground view of the data collection setup for session 1 at the south end of the work zone on August 7, 2014.

Figure 20. PTS setup for northbound traffic at the south end on day 3 session 1.

Figure 21 shows an aerial view of the data collection setup for session 1 at the north end of the work zone on August 7, 2014. At the end of the work zone, data collection started at 9:04 a.m. and ended at 12:14 p.m.

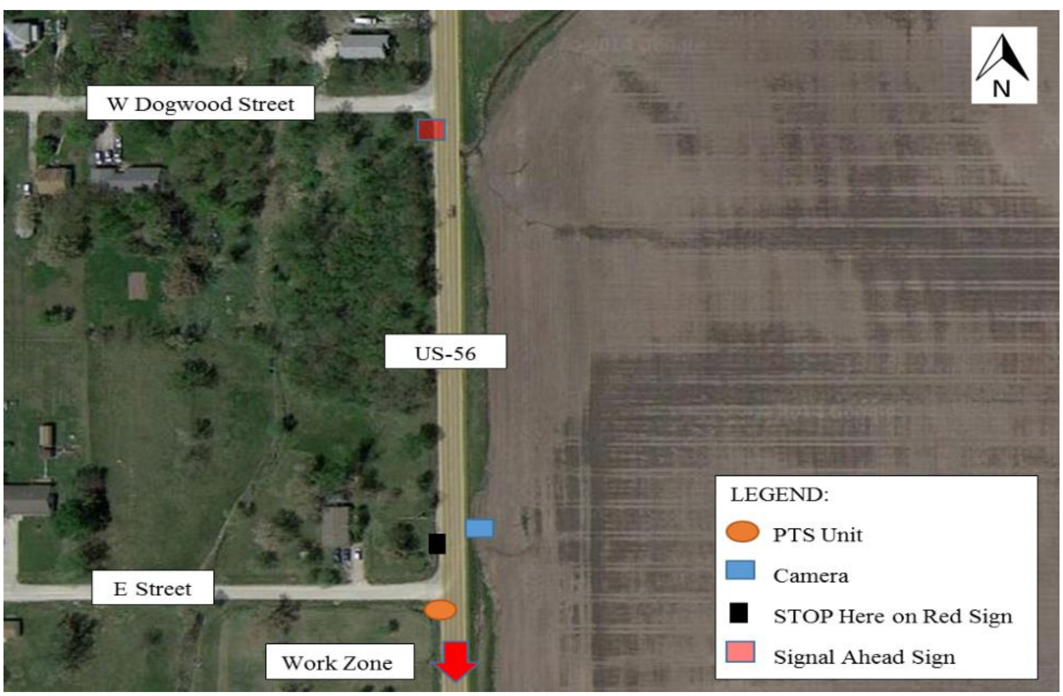

Figure 21. Data collection setup at the north end on day 3 session 1 (Southbound).

Figure 22 shows a ground view of the data collection setup for session 1 at the north end of the work zone on August 7, 2014.

Figure 22. PTS setup for southbound traffic at the north end on day 3 session 1.

Figure 23 shows an aerial view of the data collection setup for session 2 at the west end of the work zone on August 7, 2014. At the end of the work zone, data collection started at 2:00 p.m. and ended at 6:00 p.m.

Figure 23. Data collection setup at the west end on day 3 session 2 (Eastbound).

Figure 24 shows a ground view of the data collection setup for session 2 at the west end of the work zone on August 7, 2014.

Figure 24. PTS setup for eastbound traffic at the west end on day 3 session 2.

As shown in Figure 24, at the west end of the work zone, data were collected at a T-intersection that followed a sharp horizontal curve inside Scranton, KS. The limiting sight distances did not alter the experimental setup and the data collection equipment was setup as per the design plan shown in Figure 23. Figure 25 shows an aerial view of the data collection setup for session 2 at the east end of the work zone on August 7, 2014. At the end of the work zone, data collection started at 1:00 p.m. and ended at 5:35 p.m.

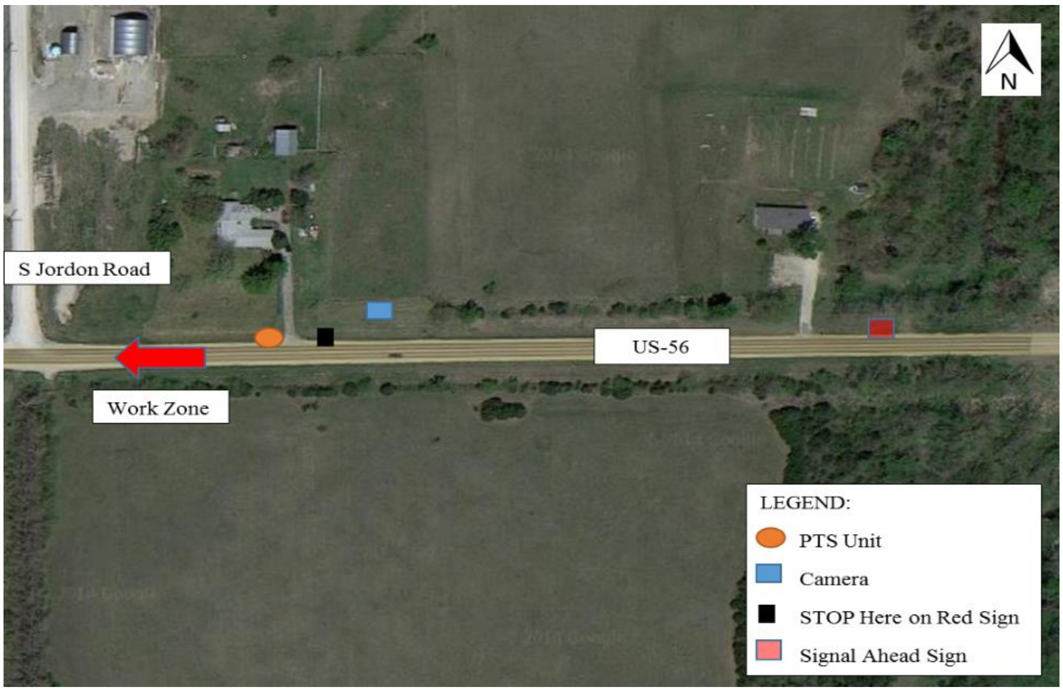

Figure 25. Data collection setup at the east end on day 3 session 2 (Westbound).

Figure 26 shows a ground view of the data collection setup for session 2 at the east end of the work zone on August 7, 2014.

Figure 26. PTS setup for westbound traffic on day 3 session 2.

It was found that the green phase failed to activate only one time at both ends of the work zone during the entire day. A total of 38.5 hours of data were collected over a period of three days.

5.2 Test Location 2

Data were collected on a work zone with an ongoing chip seal operation on K-31, a two-way, two-lane rural highway, outside Melvern, KS from August 12, 2014 to August 14, 2014. The work zone had and an AADT of less than 1,000 vehicles per day (*26*). The highway had no shoulders outside of the city limits and had six feet wide paved shoulders within the city. The work zone was a long, temporary, and mobile work zone where work activity was not necessarily visible to the traffic stopped at either ends of the work zone. The end-to-end distance was approximately 2 to 2.5 miles for each of the three days when data were collected. The contractors established the work zone in such a way that the maximum round trip time needed for the pilot car was never more than 15 minutes. The green interval on both the PTS units was set to a minimum of 30 seconds and a maximum of 60 seconds. Only one preset (30/60 seconds) was used over the entire data collection period.

On August 12, 2014 the purpose of the study and the data collection methodology was briefly described to the site supervisor. As a precautionary measure, one of the research team member drove with the pilot car on the first day to familiarize the pilot car drivers with the handheld remote for the PTS units and verified the correct functioning of the devices. It was ensured that the procedure was clearly understood by the drivers and all questions were answered. Research team members were stationed in close proximity to the PTS unit for a few cycles to ensure the proper functioning of the unit. The relocation of the PTS units and all the other data collection equipment was required whenever the work zone end stations moved.

On August 12, 2014 data were collected for the 'PTS with a flagger' condition at the west end and the 'PTS without a flagger' condition at the east end of the work zone. Figure 27 shows an aerial view of the data collection setup at the west end of the work zone on August 12, 2014. At the end of the work zone, data collection started at 9:30 a.m. and ended at 11:33 a.m.

Figure 27. Data collection at the west end of the test location on day 1 (Eastbound).

Figure 28 shows a ground view of the data collection setup at the west end of the work zone on August 12, 2014.

Figure 28. PTS setup for eastbound traffic at the west end on day 1.

As shown in Figure 28, at west end of the work zone, the PTS unit was located on the crest of a vertical curve with the contractor vehicle parked in close proximity. A flagger was also present (negligibly visible to traffic) at the station with the PTS unit but was not interfering with the pilot car or the PTS operations. Figure 29 shows an aerial view of the data collection setup at the east end of the work zone on August 12, 2014. At the end of the work zone, data collection started at 8:32 a.m. and ended at 12:07 p.m.

Figure 29. Data collection setup at the east end on day 1 (Westbound).

It was found that the green phase failed to activate only one time during the entire day. Figure 30 shows a ground view of the data collection setup at the east end of the work zone on August 12, 2014.

Figure 30. PTS setup for westbound traffic at the east end on day 1.

On August 13, 2014 data were collected over two sessions for the 'PTS without a flagger' condition at both the ends of the work zone. Figure 31 shows an aerial view of the data collection setup for session 1 at the north end of the work zone on August 13, 2014. At the end of the work zone, data collection started at 7:37 a.m. and ended at 12:07 p.m.

Figure 31. Data collection at the north end on day 2 session 1 (Southbound).

Figure 32 shows a ground view of the data collection setup for session 1 at the north end of the work zone on August 13, 2014.

Figure 32. PTS setup for southbound traffic at the north end on day 2 session 1.

As shown in the Figure 32, at the north end of the location, a flagger was present at the flagger station but was not interfering with the pilot car operations or the PTS unit. Figure 33 shows an aerial view of the data collection setup for session 1 at the south end of the work zone on August 13, 2014. At the end of the work zone, data collection started at 8:30 a.m. and ended at 12:16 p.m.

Figure 33. Data collection at the south end on day 2 session 1 (Northbound).

Figure 34 shows a ground view of the data collection setup for session 1 at the south end of the work zone on August 13, 2014.

Figure 34. PTS setup for northbound traffic at the south end on day 2 session 1.

Figure 35 shows an aerial view of the data collection setup for session 2 at the south end of the work zone on August 13, 2014. At the end of the work zone, data collection session 2 started at 12:45 p.m. and ended at 5:00 p.m.

Figure 35. Data collection setup at the south end on day 2 session 2 (Northbound).

Figure 36 shows a ground view of the data collection setup for session 2 at the south end of the work zone on August 13, 2014.

Figure 36. PTS setup for northbound traffic at the south end on day 2 session 2.

As shown in Figure 36, at the south end of the work zone, a highway entrance was located approximately 1,000 feet from the PTS unit towards the work zone that was located beyond the bridge. Vehicles that desired to take the highway could easily get onto it by running the red light and yet without interfering with the activities of work zone. Figure 37 shows an aerial view of the data collection setup for session 2 at the north end of the work zone on August 13, 2014. At the end of the work zone, data collection started at 1:44 p.m. and ended at 5:40 p.m.

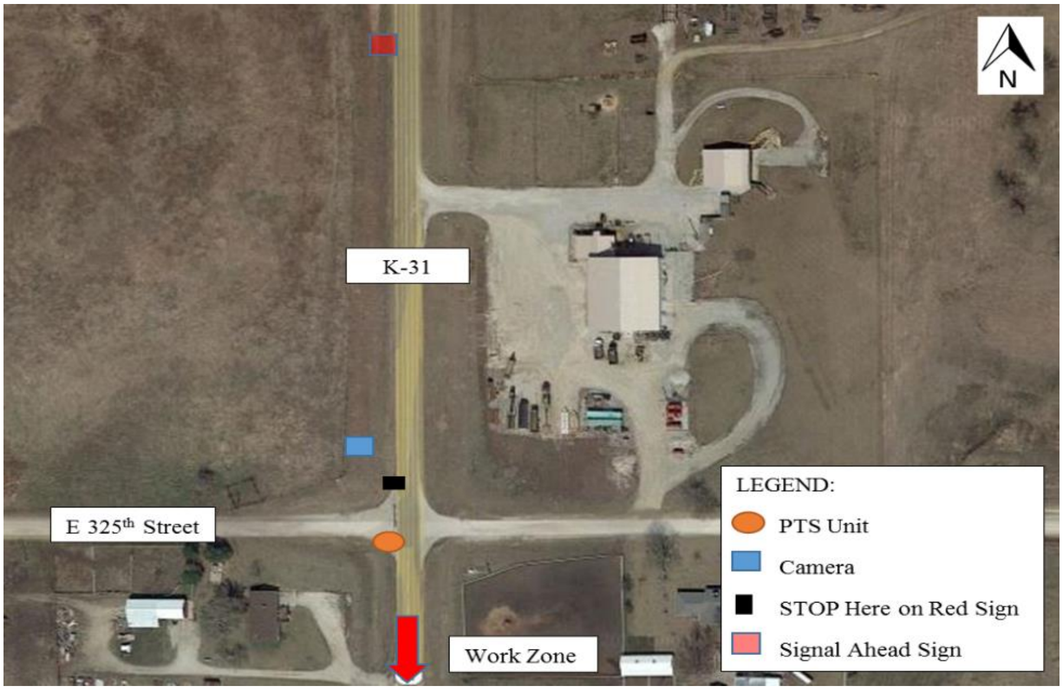

Figure 37. Data collection at the north end on day 2 session 2 (Southbound).

Figure 38 shows a ground view of the data collection setup for session 2 at the north end of the work zone on August 13, 2014.

Figure 38. PTS setup for southbound traffic at the intersection of K-31 and 325th Street.

As shown in Figure 38, no contractor vehicle was parked in close proximity of the PTS unit at the flagger station. The batteries of the handheld remote control were replaced one time since they stopped working approximately five hours after the start of data collection. It was found that the green phase failed to activate a total of three times during the entire day.

On August 14, 2014 data were collected at the same locations from day 2 (August 13, 2014) over two sessions at both ends of the work zone for the ‘PTS without a flagger’ condition and the ‘flagger only’ condition.

As shown in Figure 35 and Figure 36, at the south end of the work zone, data collection for the ‘PTS without a flagger’ condition (session 1), started at 7:21 a.m. and ended at 1:12 p.m. Data collection for the flagging only condition (session 2), started at 2:10 p.m. and ended at 5:18 p.m. At the end of the work zone, it was observed that a few vehicles turned around and left the queue due to the long wait time at the PTS station.

As shown in Figure 37 and Figure 38, at the north end of the work zone near the intersection of E-325th Street and K-31, data collection for the ‘PTS without a flagger’ condition (session 1), started at 7:53 a.m. and ended at 1:35 p.m. Data collection for the flagging only condition (session 2), started at 1:52 p.m. and ended at 5:39 p.m. It was found that the green phase failed to activate a total of five times during the entire day. A total of 40.5 hours of data were collected for all the three conditions over a period of three days.

5.3 Test Location 3

Data were collected on a work zone with ongoing asphalt overlay operation on US-24, a two-way, two-lane rural highway, outside Beloit, KS from August 19, 2014 to August 21, 2014. The work zone had an AADT ranging from 2,500 to 5,000 vehicles per day and eight feet wide paved shoulders (*26*). The work zone was a long, temporary, and mobile work zone where work activity was not necessarily visible to the traffic stopped at either ends of the work zone. The end-to-end distance was approximately 2.2 to 2.8 miles for each of the three days when data were collected. The contractors established the work zone in such a way that the maximum round trip time needed for the pilot car was never more than 15 minutes. The green interval on both the PTS units was set to a minimum of 30 seconds and a maximum of 60 seconds. Only one preset (30/60 seconds) was used over the entire data collection period.

On August 19, 2014 the purpose of the study and the data collection methodology was briefly described to the site supervisor. As a precautionary measure, one of the research team members drove with the pilot car on the first day to familiarize the pilot car drivers with the handheld remote for the PTS units and verified the correct functioning of the devices. It was also ensured that the procedure was clearly understood by the drivers and all questions were answered. Research team members were stationed in close proximity to the PTS unit for a few cycles to ensure the proper functioning of the unit. The relocation of the PTS unit and all the other data collection equipment was required whenever the work zone end stations moved.

On August 19 and August 20, data were collected for the ‘PTS with a flagger’ condition at the west end of the work zone. Figure 39 shows an aerial view of the data collection setup at the west end of the work zone on August 19 and August 20, 2014. On August 19, at the end of the work zone, data collection started at 9:21 a.m. and ended at 5:30 p.m. On August 20, at the end of the work zone, data collection started 8:30 a.m. and ended at 5:30 p.m.

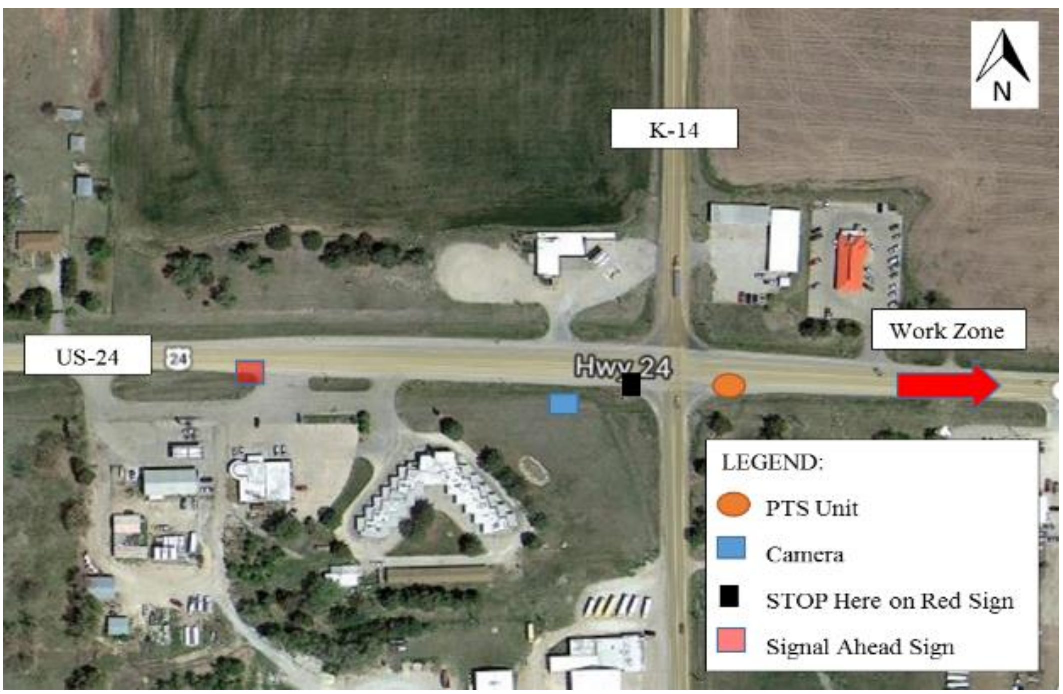

Figure 39. Data collection setup at the west end on day 1 (Eastbound).

Figure 40 shows a ground view of the data collection setup at the west end of the work zone on August 19, 2014.

Figure 40. PTS setup for eastbound traffic at the west end on day 1 and day 2.

As shown in Figure 40, the west end of the work zone was located at an urban intersection with a posted speed limit of 45 mph just outside the city of Beloit, KS. All the approach legs at the intersection had heavy traffic volumes with flaggers stationed at each approach leg to provide appropriate traffic control. Therefore, the presence of a PTS was more of a secondary traffic control to the flagger operation at the intersection. The presence of flaggers made it possible for the vehicles to follow the back of a queue even after the signal turned red when waved through by the flagger. No official vehicle was located in close proximity of the PTS unit and the flagger station. On August 19, 2014 data were collected for the ‘PTS with a flagger’ condition at the southeast end of the work zone. Figure 41 shows an aerial view of the data collection setup at the southeast end of the work zone on August 19, 2014. At the end of the work zone, data collection started at 9:47 a.m. and ended at 5:00 p.m. On August 20, 2014 data were collected for the ‘PTS without a flagger’ condition at the southeast end of the work zone. At the end of the work zone, data collection started 8:50 a.m. and ended at 5:00 p.m.

Figure 41. Data collection setup at the southeast end on day 1 (Northbound).

Figure 42 shows a ground view of the data collection setup at the southeast end of the work zone on August 19, 2014.

Figure 42. PTS setup for northbound traffic at the southeast end on day 1.

On August 19, it was found that the green phase failed to activate a total of four times during the entire day at both ends of the work zone. On August 20, it was found that the green phase failed to activate a total of three times during the entire day at both ends of the work zone.

On August 21, 2014 data were collected for the ‘PTS without a flagger’ condition at the west end of the work zone and for the ‘PTS without a flagger’ condition and the ‘flagger only’ condition at the east end of the work zone. Both ends were located on level terrain with adequate sight distances. Figure 43 shows an aerial view of the data collection setup at the west end of the work zone on August 21, 2014. At the end of the work zone, data collection started 8:25 a.m. and ended at 4:30 p.m.

Figure 43. Data collection setup at the west end on day 3 (Eastbound).

Figure 44 shows a ground view of the data collection setup at the west end of the work zone on August 21, 2014.

Figure 44. PTS setup for the eastbound traffic at the west end on day 3.

As shown in Figure 44, at the west of the work zone, the construction crew observed a few red light running vehicles and wanted to restore the flagging operations. It was decided to restore the flagger at the flagging station but he was not permitted to control the traffic in order to keep the experiment setup unaltered. The flagger was positioned near the PTS unit in such a manner that he was not easily visible to the drivers. Figure 45 shows an aerial view of the data collection setup at the east end of the work zone on August 21, 2014. At the end of the work zone, data collection for the ‘PTS without a flagger’ condition started 8:30 a.m. and ended at 12:30 p.m. Also, data collection for the ‘flagger only’ condition started at 12:30 p.m. and ended at 4:30 p.m.

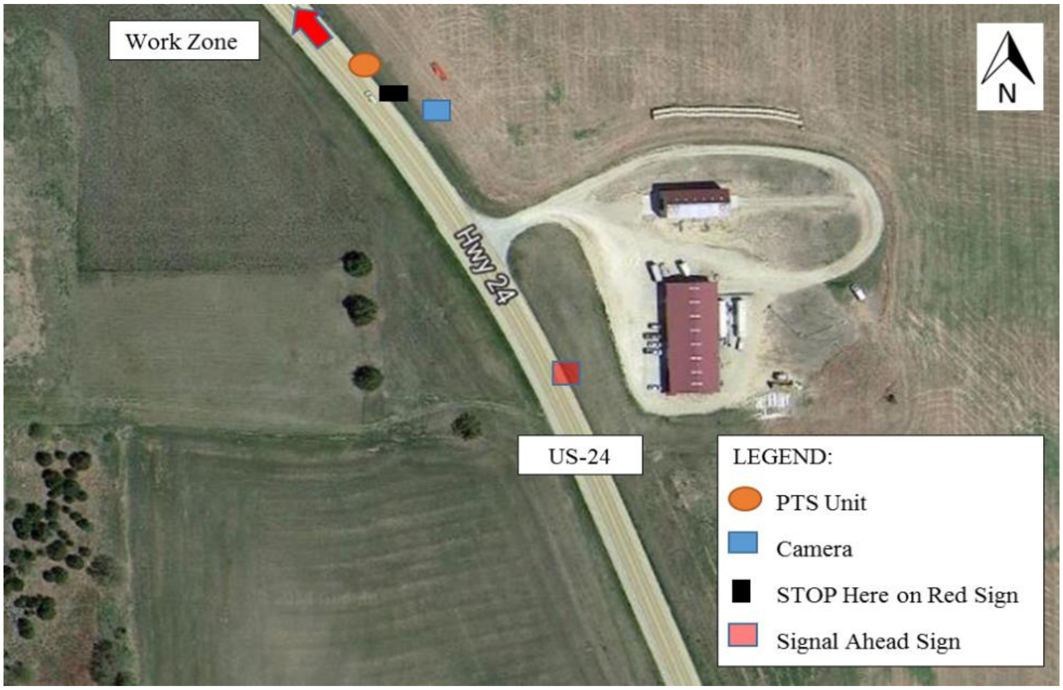

Figure 45. Data collection setup at the east end on day 3 (Westbound).

Figure 46 shows a ground view of the data collection setup at the east end of the work zone on August 21, 2014.

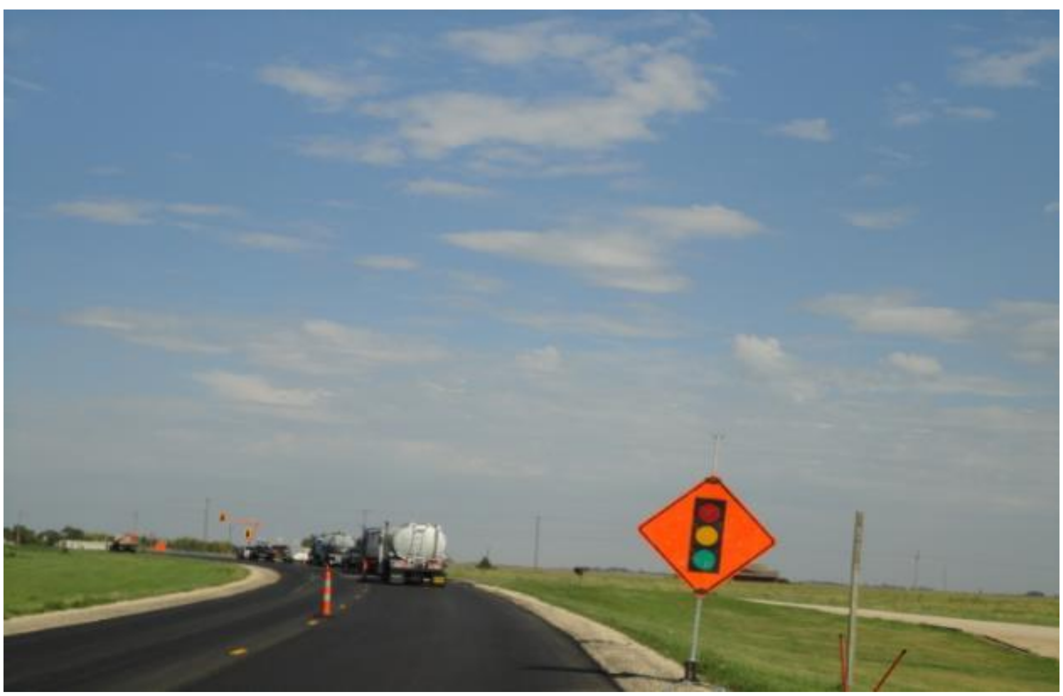

Figure 46. PTS setup for westbound traffic at the east end on day 3.

It was found that the green phase failed to activate just once during the entire day. A total of 47 hours of data were collected for all the three conditions over a period of three days.

5.4 Test Location 4

Data were collected on a work zone with an ongoing chip seal operation on US-50, a two-way, two-lane rural highway, just outside Newton, KS from August 26, 2014 and August 27, 2014. The highway had eight feet wide paved shoulders. The work zone had an AADT ranging from 5,000 to 7,500 vehicles per day with heavy truck traffic (*26*). The work zone was a long, temporary, and mobile work zone where work activity was not necessarily visible to the traffic stopped at either ends of the work zone. The end-to-end distance was approximately 2 miles for the two days when data were collected. The contractors established the work zone in such a way that the maximum round trip time for the pilot car was never more than 15 minutes.

On August 26, 2014 the purpose of the study and the data collection methodology was briefly described to the site supervisor. As a precautionary measure, one of the research team members drove with the pilot car on the first day to familiarize the pilot car drivers with the handheld remote for the PTS units and verified the correct functioning of the devices. It was ensured that the procedure was clearly understood by the drivers and all questions were answered. Research team members were stationed in close proximity to the PTS unit for a few cycles to ensure the proper functioning of the unit. The relocation of the PTS unit and all the other data collection equipment was required whenever the work zone end stations moved.

On August 26, 2014 data were collected for one session at east end of the work zone located on level terrain with adequate sight distances for the ‘PTS with a flagger’ condition. Flagger operations were retained at the west end of the work zone. Figure 47 shows an aerial view of the data collection setup at the east end of the work zone on August 26, 2014. At the end of the work zone, data collection started at 9:56 a.m. and ended at 3:10 p.m.

Figure 47. Data collection setup at the east end on day 1 (Westbound).

The green interval on both the PTS units was set to a minimum of 30 seconds and a maximum of 180 seconds for call 1. Call 2 was set to a minimum of 60 seconds and a maximum of 180 seconds. Call 3 was set to a minimum of 90 seconds and a maximum of 180 seconds. This was the first time when all three presets/calls on the PTS unit were utilized for data collection. At the west end of the work zone, data collection for session 2 started at 4:00 p.m. but the work zone end had to be moved around 4:30 p.m. because the pilot car round trip time was exceeding 15 minutes (*23*). Therefore, no further data were collected for session 2. The green phase failed to activate two times during the entire day. Also, during this session one RLR event in the presence of a flagger was observed. The vehicle completely disregarded the PTS unit and the operating flagger to proceed in the direction of the work zone. Fortunately, that event did not create a safety hazard but frequent occurrences could prove to be a potential safety concern.

On August 27, 2014, owing to the malfunctioning of the PTS unit on the previous day, it was decided to use only one preset for the signal timings. The call 1 preset on the PTS unit was modified to a minimum of 30 seconds and a maximum of 240 seconds for clearing the long queues anticipated to be formed at both ends of the work zone. Figure 48 shows an aerial view of the data collection setup at the east end of the work zone on August 27, 2014. At the end of the work zone, data collection started at 8:18 a.m. and ended at 6:40 p.m.

Figure 48. Data collection setup at the east end on day 2 (Westbound).

Figure 49 shows a ground view of the data collection setup at the east end of the work zone on August 27, 2014.

Figure 49. PTS setup for westbound traffic at the east end on day 2.

Figure 50 shows an aerial view of the data collection setup at the east end of the work zone on August 27, 2014. At the end of the work zone, data collection for the ‘PTS with a flagger’ condition started at 9:00 a.m. and ended at 1:00 p.m. Data collection for the ‘PTS without a flagger’ condition started at 1:00 p.m. and ended at 6:00 p.m.

Figure 50. Data collection at the west end on day 2 (Eastbound).

Figure 51 shows a ground view of the data collection setup at the west end of the work zone on August 27, 2014.

Figure 51. PTS setup for eastbound traffic at the west end on day 2.

It was found that the green phase failed to activate a total of four times during the entire day. On August 28, 2014 due to heavy showers, the site supervisor cancelled all the work activities for the entire day. Therefore, no data were collected. A total of 24 hours of data were collected for all the three conditions over a period of two days.

The collected video data were then reduced and analyzed using the methodology described in Chapter 6.

CHAPTER 6. DATA ANALYSIS

6.1 Data Reduction

All the collected data were analyzed at the KU Transportation Engineering and Analysis Laboratory (TEAL) from September to December 2014. Data were reduced and summarized for each work zone site and then evaluated and compared between sites. The following section provides a description of the different measures of effectiveness that were recorded during the data reduction process.

- First, the arrival and departure times of the first vehicle in the queue were recorded to obtain estimates of the total maximum wait time for the first vehicle in each queue and the total roundtrip time for pilot car operations for each queue. At the time of this research, the KDOT policy did not permit the maximum pilot car round trip time to exceed 15 minutes (*23*). Therefore, recording this information was beneficial in determining whether the KDOT policy was violated at any time during the research when using the PTS systems at the work zones.
- Second, the traffic signal information (start and end of green interval) was recorded for each queue to determine the operational characteristics of the PTS system and record the instances of signal failure/malfunction that were observed during the research.
- Third, the total number of vehicles in each queue were recorded and classified according to their type (motorcycles, passenger car, and trucks) to determine the volume thresholds and appropriate green time by correlating the number of vehicles served with the duration of green time calculated in the second step.
- Finally, the number of red light running (RLR) vehicles or vehicles that violated the traffic control were recorded to conduct the statistical evaluation for comparing between the three conditions (flagger only, PTS with a flagger, and PTS without a flagger).

In addition to the variables mentioned above, the number of vehicles that turned around due to excessive wait time and factors that may have affected the operations of the system (wind, rain, lighting, and signage) were also recorded.

A total of 695 queues were observed during the data reduction process. After reducing all the available data, the following actions were performed:

- First, an operational evaluation and comparison of the three conditions (flagger only, PTS with a flagger, and PTS without a flagger) was conducted by estimating and comparing the average vehicle wait times, queue lengths, and the signal timing operations.
- Second, a statistical evaluation and comparison was conducted by calculating the RLR ratios as a percentage of the total vehicular volumes observed during the corresponding data collection period. RLR events were classified in different types and compared for the three conditions using the test of proportions at a 0.05 level of significance. Furthermore, a delay analysis was conducted to determine the total amount of delay time that was reduced by the presence of flaggers with a PTS unit.
- Finally, a model was developed to determine the traffic volume thresholds and appropriate green time when using the PTS system at two-lane, two-way work zones with pilot car operations. This model would be a practical tool and serve as guidelines for the use of PTS systems in conjunction with pilot car operations at long work zones.

The actions performed would be beneficial in determining the effectiveness of the PTS systems in conjunction with pilot car operations at long work zones. The subsequent sections present a detailed description of each of the evaluations.

6.2 Evaluation of the Operational Parameters

The operational evaluation for the three conditions was conducted by estimating and comparing the parameters such as average vehicle wait times, queue lengths, and the signal timing operations. The following section elaborates the calculations and description of each of the operational parameters.

6.2.1 Average Vehicle Wait Time

The vehicle wait time was calculated by the difference between the arrival time and departure time of the first vehicle in the corresponding queue. The vehicle wait time should not be confused with the all-red time since the all-red time began at the end of the yellow time but the wait time essentially started with the arrival of the first vehicle in the queue. Table 5 provides a summary of the average vehicle wait time calculated for each queue at all the test locations.

Table 5. Summary of the Average Wait Time for All the Three Conditions

Location	Cycles Analyzed			Average Wait Time (seconds)		
	Flagger Only	PTS with a Flagger	PTS without a Flagger	Flagger Only	PTS with a Flagger	PTS without a Flagger
Burlingame	64	53	129	494	546.7	553.0
Melvern	29	14	152	531.3	344.0	354.0
Beloit	15	108	89	697	567.3	618.9
Newton	NA	99	51	NA	605.4	460.9
Total	**108**	**274**	**421**	**574.1**	**515.8**	**496.7**

Note: "NA"- Not Applicable because PTS unit was not used.

From Table 5, it can be found that there was no substantial difference in the average wait time for all the three conditions that were studied. The 'flagger only' condition had the longest average wait time while the 'PTS without a flagger' condition had the least average wait time over the entire duration of the data collection.

6.2.2 Average Queue Length

The approximate length of a queue cleared at the end of each green cycle was calculated. Traffic volumes were divided into three classes for the ease of calculating the queue length: motorcycles, passenger cars, and trucks. For simplicity, school buses and large RV's were also counted as trucks. Vehicles stopped in the queue were assumed to be at a uniform spacing between vehicles of ten feet. For simplicity of the analysis, the lengths of a motorcycle, passenger car and truck were assumed to be 8, 20, and 75 feet, respectively (*27*).

For example, on August 7 at the east end of the test location near Scranton, a queue had one motorcycle, 17 passenger cars and one truck. Therefore, the queue length was calculated as:

Length of the queue cleared = 1*(10+8) + 17*(10+20) + 1*(10+75) = 613 feet

The length of queues were calculated for all the cycles that were reduced during the data reduction. Table 6 provides a summary of the average length of the queue calculated for each of the condition at all the test locations.

Table 6. Summary of the Average Queue Length for All the Three Conditions

Location	Cycles Analyzed			Average Queue Length (feet)		
	Flagger Only	**PTS with a Flagger**	**PTS without a Flagger**	**Flagger Only**	**PTS with a Flagger**	**PTS without a Flagger**
Burlingame	64	53	129	280	252.3	240.1
Melvern	29	14	152	123.3	55.0	59.0
Beloit	15	108	89	528.3	371.2	411.6
Newton	NA	99	51	NA	1328.5	1348.0
Total	**108**	**274**	**421**	**310.5**	**501.7**	**514.7**

Note: "NA"- Not Applicable because PTS unit was not used.

From Table 6, it can be found that there was no substantial difference in the average queue length for all the three conditions that were studied. The 'PTS without a flagger' condition had the longest average queue length while the 'flagger only' condition served the least average queue length over the entire duration of the data collection.

6.2.2 Average Green Time

Only one preset time (call 1) on the PTS unit with a minimum green time of 30 seconds and maximum green time of 60 seconds was used for Test Locations 1, 2, and 3. At Test Location 4, due to higher volumes, call 1 on the PTS unit was changed to a minimum green time of 30 seconds and maximum green time of 180 seconds. Similarly, call 2 was changed to a minimum of 60 seconds and maximum of 180 seconds and call 3 was changed to a minimum of 90 seconds and maximum of 180 seconds. Due to certain anomalies (discussed in Chapter 8), the green time was adjusted to a minimum of 30 seconds and a maximum of 180 seconds for the rest of the day. The following day only one preset (call 1) was used and the green times were changed to a minimum of 30 seconds and a maximum of 240 seconds at both the ends of the work zone. Table 7 provides a summary of the average green time calculated for each of the condition at all the test locations.

Table 7. Summary of the Average Green Time for All the Three Conditions

Location	Cycles Analyzed			Average Green Time (seconds)		
	Flagger Only	PTS with a Flagger	PTS without a Flagger	Flagger Only	PTS with a Flagger	PTS without a Flagger
Burlingame	64	53	129	NA	37.0	38.9
Melvern	29	14	152	NA	30.0	30.7
Beloit	15	108	89	NA	44.2	49.5
Newton	NA	99	51	NA	145.7	138.7
Total	**108**	**274**	**421**	**NA**	**64.2**	**64.5**

Note: "NA"- Not Applicable because PTS unit was not used.

From Table 7, it can be found that there was no substantial difference in the average queue length for the two conditions where the PTS was used. The data reduction indicated that the presence and absence of a flagger did not alter the operations of the PTS system and the operational performance of the two conditions was nearly identical.

6.3 Red Light Running (RLR) or Violation Analysis

RLR or violation was the primary measure used to evaluate the effectiveness of the PTS system. To conduct the statistical evaluation, the number of RLR events or violations for all the three conditions were calculated and then compared between all the test locations.

For the 'flagger only' condition, a violation was defined as, "an event when a vehicle was waived through by a flagger to enter the work zone or move in the direction of the work zone without being escorted by a pilot car." A total of 22 hours of data were collected for the 'flagger only' condition. Table 8 provides a summary of the violations that were observed for the condition.

Table 8. Summary of Violations for the Flagger Only Condition at All the Test Locations

Date	Test Location	Roadway AADT	Traffic Volume (vehicles)	Number of Violations
7/30/2015	US-56 Burlingame, KS	1,000 to 3,300	157	0
7/31/2015	US-56 Burlingame, KS	1,000 to 3,300	363	2
8/14/2014	K-31 Melvern, KS	Less than 1,000	102	7
8/21/2014	US-24 Beloit, KS	2,500 to 5,000	192	0
Total			**814**	**9**

From Table 8, it can be found that a total of 814 vehicles and nine violations were observed for the ‘flagger only’ condition. Therefore, the average percentage of violations for the ‘flagger only’ condition at all the three test locations was approximately 1.1 percent.

When a PTS was used with a flagger or without a flagger, a RLR event was defined as, “an event when a vehicle entered the work zone or traveled in the direction of the work zone when the PTS was displaying a red indication.” Based on field observations and video evidence, RLR events were divided into different categories for the purpose of the study and data were reduced to record each of these following events:

a. RLR when drivers were catching up with a just departed queue;
b. RLR when drivers left a queue due to the wait time;
c. RLR when drivers completely disregarded the PTS system; and
d. RLR when drivers were waived through by the flagger.
   - When the drivers were catching up with a just departed queue; and
   - When the drivers received the flagger’s consent to enter the work zone at another time period.

The number of RLR vehicles were recorded at the time of data reduction under the different categories mentioned earlier. All the four types of RLR events were used to develop the RLR (%) and were compared statistically using a test of proportions described in section 6.3.1. The RLR events of the type ‘d’ were further used in conducting the delay analysis described in Section 6.4.

RLR (%) were calculated by the Eq. 1 given below:

$$\boldsymbol{RLR}\ (\%) = \left(\frac{\boldsymbol{Number\ of\ RLR\ vehicles\ observed\ in\ x\ hours}}{\boldsymbol{Total\ traffic\ volume\ observed\ in\ x\ hours}}\right) * \mathbf{100} \qquad \textbf{Eq. 1}$$

Table 9 provides a summary of the number of RLR vehicles for the ‘PTS with a flagger’ condition.

Table 9. Number of RLR Vehicles for the PTS with a Flagger Condition

Date	Test location	Roadway AADT	Traffic Volumes (vehicles)	RLR Type		
				Follow a Departed Queue	Leave Due to the Wait Time	Disregarded the Traffic Control
8/5/2014	Burlingame	1,000 to 3,300	413	4	0	0
8/6/2014	Scranton		NA	NA	NA	NA
8/7/2014	Scranton		NA	NA	NA	NA
8/12/2014	Melvern	less than 1,000	20	0	0	0
8/13/2014	Melvern		NA	NA	NA	NA
8/14/2014	Melvern		NA	NA	NA	NA
8/19/2014	Beloit	2,500 to 5,000	642	53*	13*	0
8/20/2014	Beloit		300	12*	5*	0
8/21/2014	Beloit		NA	NA	NA	NA
8/26/2014	Newton	5,000 to 7,500	503	1	0	1
8/27/2014	Newton		2,471	3	0	1
8/28/2014	Newton		NA	NA	NA	NA
Total			**4,349**	**73**	**18**	**2**

Note: "NA"- Not Applicable because no data collected for PTS with flagger condition; "*"- Four-leg intersection.

From Table 9, it can be found that a total of 4,349 vehicles and 93 (73+18+2) violations were observed at all test locations for the 'PTS with a flagger' condition. It was found that the average percentage of RLR vehicles for the 'PTS with a flagger' condition at all the three test locations was two percent. From Table 9, it can be found that the RLR vehicles for the type when vehicles were waived through by the flagger to follow a departed queue were higher than the other two types. This was because on August 19 and 20, 2014, the PTS unit was located at the intersection of US-24 and K-14 just outside the city of Beloit, KS as shown in Figure 40. As described in section 5.3, the intersection geometry and traffic operations at that work zone end did not comply with the design of the research. Therefore, it was decided to exclude the data collected at that end of the work zone for the purpose of conducting the test of proportions. Table 10 provides a summary of the number of RLR vehicles for the 'PTS with a flagger' condition when data for the intersection at Beloit, KS were excluded.

Table 10. Number of RLR Vehicles for the PTS with a Flagger Condition Excluding the Intersection at Beloit, KS

Date	Test location	Roadway AADT	Traffic Volumes (vehicles)	RLR Type		
				Follow a Departed Queue	Leave Due to the Wait Time	Disregarded the Traffic Control
8/5/2014	Burlingame	1,000 to 3,300	413	4	0	0
8/6/2014	Scranton		NA	NA	NA	NA
8/7/2014	Scranton		NA	NA	NA	NA
8/12/2014	Melvern	less than 1,000	20	0	0	0
8/13/2014	Melvern		NA	NA	NA	NA
8/14/2014	Melvern		NA	NA	NA	NA
8/19/2014	Beloit	2,500 to 5,000	372	39	3	0
8/20/2014	Beloit		NA	NA	NA	NA
8/21/2014	Beloit		NA	NA	NA	NA
8/26/2014	Newton	5,000 to 7,500	503	1	0	1
8/27/2014	Newton		2,471	3	0	1
8/28/2014	Newton		NA	NA	NA	NA
Total			**3,779**	**47**	**3**	**2**

Note: “NA”- Not Applicable because no data collected for PTS with flagger condition.

From Table 10, it can be found that the RLR vehicles for the type when vehicles were waived through by the flagger to follow a departed queue were higher than the other two types. It was found that after the exclusion of the intersection, the total number of violations reduced to 52 (47+3+2) from 93 and the average percentage of the RLR vehicles reduced to 1.3 percent.

Table 11 provides a summary of the number of RLR vehicles for the ‘PTS without a flagger’ condition. It can be found that a total of 2,944 vehicles and 92 violations were observed at all test locations when the PTS was used without a flagger. It was also found that the number of RLR vehicles for the type when vehicles left the queue due to the wait time was higher than the other two types.

Table 11. Number of RLR Vehicles for the PTS without a Flagger Condition

Date	Test Location	Roadway AADT	Traffic Volumes (vehicles)	Follow a Departed Queue	Leave Due to the Wait Time	Disregarded Signal
8/5/2014	Burlingame	1,000 to 3,300	NA	NA	NA	NA
8/6/2014	Scranton		343	0	4	3
8/7/2014	Scranton		660	19	7	1
8/12/2014	Melvern	less than 1,000	17	0	0	0
8/13/2014	Melvern		157	0	9	5
8/14/2014	Melvern		87	0	2	0
8/19/2014	Beloit	2,500 to 5,000	NA	NA	NA	NA
8/20/2014	Beloit		333	7	1	0
8/21/2014	Beloit		553	10	21	2
8/26/2014	Newton	5,000 to 7,500	NA	NA	NA	NA
8/27/2014	Newton		794	0	0	1
8/28/2014	Newton		NA	NA	NA	NA
Total			**2,944**	**36**	**44**	**12**

Note: “NA”- Not Applicable because no data were collected.

Table 12 provides a summary of the percentages of the number of RLR vehicles for the ‘PTS without a flagger’ condition.

Table 12. Percentage of RLR Vehicles for the PTS without a Flagger Condition

Date	Test Location	Roadway AADT	Follow a Departed Queue (percent)	Leave Due to the Wait Time (percent)	Disregarded Signal (percent)
8/5/2014	Burlingame	1,000 to 3,300	NA	NA	NA
8/6/2014	Scranton		0	0.9	0.9
8/7/2014	Scranton		2.9	1.1	0.2
8/12/2014	Melvern	less than 1,000	0	0	0
8/13/2014	Melvern		0.6	4.4	3.2
8/14/2014	Melvern		0	1.2	1.2
8/19/2014	Beloit	2,500 to 5,000	NA	NA	NA
8/20/2014	Beloit		2.1	0	0
8/21/2014	Beloit		1.8	3.8	0.4
8/26/2014	Newton	5,000 to 7,500	NA	NA	NA
8/27/2014	Newton		0	0	0.1
8/28/2014	Newton		NA	NA	NA

Note: “NA”- Not Applicable because no data were collected.

From Table 12, the percentages of the number of RLR vehicles for the ‘PTS without a flagger’ condition at all the test locations can be found. It also found that the average percentage of RLR vehicles for the ‘PTS without a flagger’ condition at all the three test locations was 3.1 percent.

6.3.1 Test of Proportions

A test of proportions was conducted to determine whether there was statistically significant difference between the number of RLR vehicles and/or violations for each of the condition: flagger only, PTS with a flagger, and PTS without a flagger (*28*). For conducting the analysis, the total number of vehicles observed for the condition were used as sample sizes and the number of RLR vehicles were used as population proportions.

The test of proportions was conducted for evaluating the following three cases:

Case 1: Flagger only versus PTS with a flagger;
Case 2: Flagger only versus PTS without a flagger; and
Case 3: PTS with a flagger versus PTS without a flagger.

A one-tailed two-proportion z-test was used to analyze the two data sets. The test was conducted at a 0.05 level of significance. The variables used for the analysis were:

n_1 = Sample size 1 (total number of vehicles observed for the condition);

n_2 = Sample size 2 (total number of vehicles observed for the condition);

p_1 = Proportion of RLR vehicles/violations to the sample size 1; and

p_2 = Proportion of RLR vehicles/violations to the sample size 2.

The null hypothesis was to be rejected if the proportion of RLR vehicles for one condition (p_1) was sufficiently smaller than the proportion of RLR vehicles for the other condition (p_2). The null and alternate hypotheses for the test were:

H_o: $p_1 \geq p_2$

H_A: $p_1 < p_2$

The pooled sample proportion (*p*), the standard error (*SE*), and the test statistic (*z*) were calculated using the following equations:

$$\boldsymbol{Pooled\ Sample\ Proportion\ (p) = \left(\frac{p_1 + p_2}{n_1 + n_2}\right)} \qquad \textbf{Eq. 2}$$

$$\boldsymbol{Standard\ Error\ (SE) = sqrt\left\{p * (1 - p) * \left[\left(\frac{1}{n_1}\right) + \left(\frac{1}{n_2}\right)\right]\right\}} \qquad \textbf{Eq. 3}$$

$$\boldsymbol{Test\ Statistic\ or\ z - score\ (z) = \left(\frac{p_1 - p_2}{SE}\right)} \qquad \textbf{Eq. 4}$$

Since a one-tailed test was selected, the p-value was the probability that the z-score was less than the calculated test statistic and was found using the Normal Distribution table.

Due to bad weather conditions, no data were collected for 'flagger only' condition at the test location 4. Therefore the test of proportions was conducted using the data for Test Locations 1, 2, and 3 for Case 1 and Case 2. Table 13 provides the results of the test of proportions for the Case 1.

Table 13. Results of the Test of Proportion for Case 1

Test Location	**Traffic Volumes**		**Number of Violations**		**p-value**	**Null Hypothesis**
	Flagger Only	**PTS with a Flagger**	**Flagger Only**	**PTS with a Flagger**		
1	520	413	2	4	0.179	Do Not Reject
2	102	20	7	0	0.999	Do Not Reject
3	192	372	0	42	0.00003	Reject
Total	**814**	**805**	**9**	**46**	**0.00003**	**Reject**

From Table 13, it can be found that for Test Locations 1 and 2, the p-values were greater than 0.05. Therefore, the null hypothesis could not be rejected for the locations 1 and 2, meaning there was no significant difference in the number of violations for the 'flagger only' condition to the number of RLR vehicles for the 'PTS with a flagger' condition. From the overall result, it was also concluded that the number of RLR vehicles when a PTS was used with a flagger were statistically significant and higher than the number of violations when only a flagger was used to control work zone traffic. Table 14 provides the results of the test of proportions for the Case 2.

Table 14. Results of the Test of Proportion for Case 2

Test Location	Traffic Volumes		Number of Violations		p-value	Null Hypothesis
	Flagger Only	PTS without a Flagger	Flagger Only	PTS without a Flagger		
1	520	1,003	2	35	0.00009	Reject
2	102	261	7	16	0.6016	Do Not Reject
3	192	886	0	40	0.00135	Reject
Total	**814**	**2,150**	**9**	**91**	**0.00003**	**Reject**

From Table 14, it can be found that for Test Location 2, the p-value was greater than 0.05. Therefore, the null hypothesis could not be rejected for the Test Location 2, meaning there was no significant difference in the number of violations for the 'flagger only' condition to the number of RLR vehicles for the 'PTS without a flagger' condition. From the overall result, it was concluded that the number of RLR vehicles when a PTS was used without a flagger were statistically significant and higher than the number of violations when only a flagger was used to control work zone traffic. Table 15 provides the results of the test of proportions for the Case 3.

Table 15. Results of the Test of Proportion for Case 3

Test Location	Traffic Volumes		Number of Violations		p-value	Null Hypothesis
	PTS with a Flagger	PTS without a Flagger	PTS with a Flagger	PTS without a Flagger		
1	413	1,003	4	35	0.0042	Reject
2	20	261	0	16	0.127	Do Not Reject
3	372	886	42	40	0.999	Do Not Reject
4	2,974	794	6	1	0.6703	Do Not Reject
Total	**3,779**	**2,944**	**52**	**92**	**0.00003**	**Reject**

From Table 15, it can be found that for Test Locations 2, 3, and 4, the p-value was greater than 0.05. Therefore, the null hypothesis could not be rejected, meaning there was no significant difference in the number of RLR vehicles for the ‘PTS with a flagger’ condition to the number of RLR vehicles for the ‘PTS without a flagger’ condition. The overall result indicated that the number of RLR vehicles when the PTS was used without a flagger were statistically significant and higher than the number of RLR vehicles when the PTS was used with a flagger. Therefore, the PTS unit with a flagger was statistically more effective than a PTS unit without a flagger in reducing the number of RLR violations.

A more in-depth statistical analysis was conducted to determine whether there was a statistically significant difference between the different types of RLR events for the conditions ‘PTS with a flagger’ and ‘PTS without a flagger.’ Since the amount of data collected for the ‘flagger only’ condition were less compared to the other two conditions, no further analysis was conducted for the condition. Table 16 provides the results of the test of proportions that compared the RLR events where vehicles followed a departed queue.

Table 16. Results of the Test of Proportion for the RLR Events where Vehicles Followed a Departed Queue

Test Location	Traffic Volumes		Follow a Departed Queue		p-value	Null Hypothesis
	PTS with a Flagger	PTS without a Flagger	PTS with a Flagger	PTS without a Flagger		
Burlingame	413	1,003	4	19	0.106	Do Not Reject
Melvern	20	261	0	0	0.519	Do Not Reject
Beloit	372	886	39	17	0.999	Do Not Reject
Newton	2,974	794	4	0	0.849	Do Not Reject
Total	**3,779**	**2,944**	**47**	**36**	**0.530**	**Do Not Reject**

From Table 16, it can be found that there was no statistically significant difference between the number of RLR vehicles for the two conditions. This meant that the number of vehicles following a departed queue at a PTS unit were statistically equal in the presence and absence of a flagger. Table 17 provides the results of the test of proportions that compared the RLR events where vehicles left the queue due to wait time.

Table 17. Results of the Test of Proportion for the RLR Events where Vehicles Left the Queue Due To the Wait Time

Test Location	Traffic Volumes		Leave Due to the Wait Time		p-value	Null Hypothesis
	PTS with a Flagger	PTS without a Flagger	PTS with a Flagger	PTS without a Flagger		
Burlingame	413	1,003	0	11	0.016	Reject
Melvern	20	261	0	11	0.175	Do Not Reject
Beloit	372	886	3	22	0.026	Reject
Newton	2,974	794	0	0	0.500	Do Not Reject
Total	**3,779**	**2,944**	**3**	**44**	**< 0.001**	**Reject**

Table 18 provides the results of the test of proportions that compared the RLR events where vehicles disregarded the traffic control.

Table 18. Results of the Test of Proportion for the RLR Events where Vehicles Disregarded the Traffic Control

Test Location	Traffic Volumes		Disregarded the Traffic Control		p-value	Null Hypothesis
	PTS with a Flagger	PTS without a Flagger	PTS with a Flagger	PTS without a Flagger		
Burlingame	413	1,003	0	4	0.099	Do Not Reject
Melvern	20	261	0	5	0.266	Do Not Reject
Beloit	372	886	0	2	0.179	Do Not Reject
Newton	2,974	794	2	1	0.301	Do Not Reject
Total	**3,779**	**2,944**	**2**	**12**	**< 0.001**	**Reject**

From Table 17, it can be found that there was a statistically significant difference between the number of RLR vehicles for the two conditions. This meant that the drivers were more likely to leave a queue due to the wait time at a PTS unit in the absence of a flagger. From Table 18, it can be found that there was a statistically significant difference between the number of RLR vehicles for the two conditions. This meant that the PTS system was more susceptible to being disregarded by drivers in the absence of a flagger. All results obtained from the test of proportions were used to make suitable conclusions and recommendations described in Chapters 7 and 8.

6.4 Delay Analysis

On August 19, 2014 the PTS unit was located at the intersection of US-24 and K-14 outside Beloit, KS and data were collected for 'the 'PTS with a flagger' condition.' Figure 52 presents a ground view of the intersection and the data collection setup at Beloit, KS.

Figure 52. Ground view of the eastbound PTS leg of the intersection at Beloit, KS.

As shown in Figure 52, the PTS unit was located on the eastbound leg of the intersection of K-14 and US-24 near Beloit, KS. Due to the high volumes observed at the intersection the presence of a flagger was deemed necessary by the site supervisor. Therefore, flaggers were stationed on all the three approach legs to the intersection. It was observed that during the pilot car operations, the upstream end of the queue on the eastbound PTS leg of the intersection on US-24 was followed by the vehicles stopped at the other two approach legs of the intersection. By the time the other two legs on K-14 (northbound and southbound) were cleared completely, a few vehicles reappeared on the upstream PTS leg of the intersection. Therefore, the flagger had to make an informed judgment and waived the first few newly-stopped vehicles to follow the back of the queue even though the PTS was displaying red. It was also found that in three cases the flagger provided his/her consent to the stopped vehicles to enter the work zone at a later time without being escorted by a pilot car. These operations resulted in a reduction of the total delay time observed for the 'PTS with a flagger' condition which is discussed in the following section.

To determine the total delay that was reduced by the presence of a flagger, an exploratory delay analysis was conducted for all 31 cycles where RLR by type, when waived through by a flagger, were observed. For the simplicity of the research, the following assumptions were made prior to conducting the analysis:

- All the vehicles arrived at a uniform rate at the start of the red interval;
- The last vehicle in the queue arrived exactly at the start of the green interval;
- The start and end of the green interval were retained from the actual observed data;
- The additional time anticipated to clear the vehicles in the queue that were allowed by a flagger to enter the work zone on red indication was calculated by assuming a uniform discharge rate for all vehicles during the green interval; and
- All the vehicles traveled at constant speeds and there was no start-up lost time.

One cycle was selected from the data for August 19, 2014 that had six RLR vehicles waived through by a flagger. Note that, if these vehicles were not allowed by the flagger then these six vehicles would have been a part of the following cycle. Two scenarios were compared to obtain an estimate of the total reduction in vehicular delay. First, the actual scenario where ten vehicles were a part of the pilot car cycle and second, a hypothetical scenario where all the 16 vehicles were assumed to be a part of the cycle if the flagger had not waived those vehicles to join the pilot car queue in the previous cycle. The following values were extracted from the actual data on August 19, 2014, and used to develop Table 19 and Table 20.

- End of green interval for Cycle 1 = 11:02:18 a.m.
- Start of all-red interval for Cycle 1 = 11:02:22 a.m.
- Start of green interval for Cycle 2 = 11:12:56 a.m.
- End of green interval for the Cycle 2 = 11:13:51 a.m.

Where:

Cycle 1 = the pilot car cycle where six violations of the type, waved through by a flagger, were observed; and

Cycle 2 = the pilot car cycle for which the reduction in total delay was estimated.

The total maximum wait time for the first vehicle in the queue was calculated as the time difference between the start of the green interval for the cycle to be analyzed (Cycle 2) and the start of the all-red interval for the previous cycle (Cycle 1). Therefore, the total maximum wait time was found to be 638 seconds.

The queue could have had a total of 16 vehicles if six of the vehicles were not waived through by the flagger to enter the work zone. Therefore, the uniform arrival rate was calculated as a function of the total maximum wait time for all 16 vehicles and not for ten vehicles observed in the actual scenario. The arrival rate was found to be 40 seconds and was used in the developing the values in Table 19 and Table 20.

The length of the green interval for Cycle 2 was calculated as the difference between the start and the end of the green interval and was found to be 55 seconds. Since a uniform discharge rate was assumed for both the scenarios, the length of green interval for hypothetical scenario with 16 vehicles was calculated by interpolation and found to be 88 seconds. The start of the green interval for the hypothetical scenario was same as the actual scenario (11:12:56 a.m.). Therefore, the end of green interval for the hypothetical scenario was found to be 11:14:24 a.m.

Table 19 provides the arrival time for all the vehicle positions in the queue considered in the actual scenario. From Table 19, it can be found that a uniform arrival rate of 40 seconds was used to develop the arrival times for the actual scenario. The vehicle position at 11:06:16 a.m. indicated that no vehicle had arrived at the PTS unit. The vehicle position at 11:13:51 a.m. indicated that the queue had completely cleared and the end of the green interval.

Table 19. Arrival Times for the Actual Scenario

Arrival time (a.m.)	i^{th} Vehicle
11:06:16	0
11:06:56	1
11:07:36	2
11:08:16	3
11:08:56	4
11:09:36	5
11:10:16	6
11:10:56	7
11:11:36	8
11:12:16	9
11:12:56	10
11:13:51	0

Table 20 provides the arrival time for each of the vehicle position in the queue considered in the hypothetical scenario.

Table 20. Arrival Times for the Hypothetical Scenario

Arrival time (a.m.)	i^{th} Vehicle
11:02:16	0
11:02:56	1
11:03:36	2
11:04:16	3
11:04:56	4
11:05:36	5
11:06:16	6
11:06:56	7
11:07:36	8
11:08:16	9
11:08:56	10
11:09:36	11
11:10:16	12
11:10:56	13
11:11:36	14
11:12:16	15
11:12:56	16
11:14:24	0

From Table 20, it can be found that similar to the exisintg scenario a uniform arrival rate of 40 seconds was used to develop the arrival times. The vehicle position at 11:02:16 a.m. indicated that no vehicle had arrived at the PTS unit. The vehicle position at 11:14:24 a.m.

indicated that the queue had completely cleared and the end of the green interval. As indicated previously, the final value in the Table 20 corresponding to the end of green cycle for the hypothetical scenario was calculated by assuming a uniform discharge rate for both the scenarios. Figure 53 shows the chart generated by plotting the values for vehicle position against the arrival times using the data from Table 19 and Table 20.

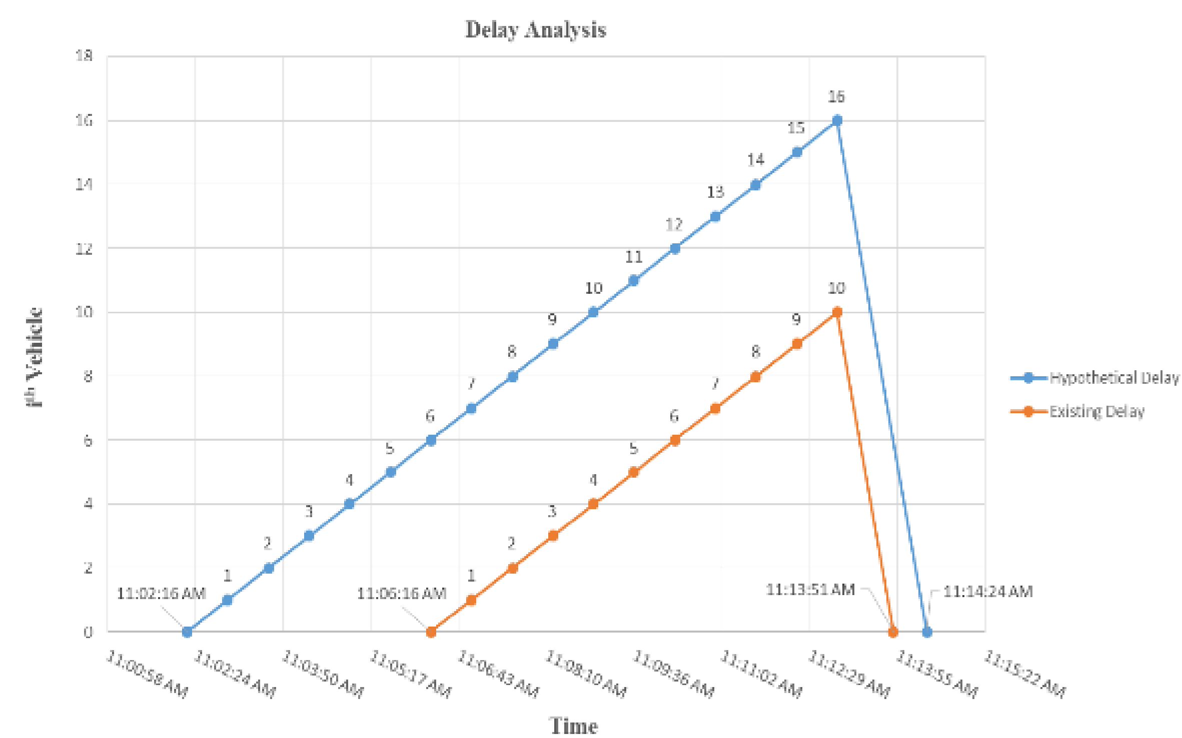

Figure 53. Graph illustrating a sample delay analysis.

As shown in Figure 53, a chart was developed using the values from Table 19 and Table 20. Time was represented on the X-axis and the position of the arriving i^{th} vehicles were listed on the Y-axis. This plot was used to calculate the total delay for the actual and the hypothetical scenarios and then to estimate the amount of delay that was reduced by the presence of a flagger. The following Eq. 5 was used to compute the total delay for each of the conditions:

$$\boldsymbol{Total\ Delay} = (\boldsymbol{Area\ of\ triangle}) = \mathbf{0.5} * \boldsymbol{Base} * \boldsymbol{Height} \qquad \textbf{Eq. 5}$$

The value for the ‘base’ corresponded to the difference in time measured in seconds when the entire queue cleared to when there was no vehicle in the queue.

Base for the hypothetical scenario = 11:14:24 a.m. – 11:02:16 a.m. = 728 seconds

Base for the actual scenario = 11:13:51 a.m. - 11:06:16 a.m. = 455 seconds

The value of the ‘height’ corresponded to the number of vehicles in the queue for each of the scenarios.

Height for the hypothetical scenario = 16 vehicles

Height for the actual scenario = 10 vehicles

The total delay for the hypothetical and the actual scenarios were calculated using Eq. 5 mentioned previously.

The total delay for the hypothetical scenario (a) = 0.5 * 728 * 7 = 5,824 vehicle-seconds

The total delay for the actual scenario (b) = 0.5 * 455 * 4 = 2,275 vehicle-seconds

The total delay reduced by flagger (c) = a – b = 5824 – 2275 = 3,549 vehicle-seconds

Percentage of total delay reduced by the flagger = $\frac{c}{a}$ = $\frac{3{,}549}{5{,}824}$ = 0.609 = 60.9 percent

The percentage of total delay reduced by the presence of a flagger for this one queue was around 61 percent which meant that a flagger could bring substantial reduction in total vehicle delays by making informed judgements and allowing vehicles to enter the work zone. Table 21 provides a summary of the total delay that were calculated for all 31 cycles analyzed for all the test locations.

From table 21, it can be found that the total delay reduced by the presence of a flagger for all the test locations was approximately 16.8 hours. This total reduction in delay was compared to the total delay observed in the presence of a flagger to obtain the percentage of delay reduced by a flagger over the entire duration of the research.

Table 21. Summary of the Delay Analysis when a PTS was used with a Flagger

Date	Number of Cycles Analyzed	Reduction in Delay Due to Presence of a Flagger		
		vehicle-seconds	vehicle-minutes	vehicle-hours
8/5/2014	2	2,953	49.2	0.8
8/19/2014	19	44,090	717.0	12.3
8/20/2014	7	11,247	187.5	3.1
8/26/2014	1	905	15.1	0.3
8/27/2014	2	1,323.5	22.1	0.4
Total	**31**	**60,518.5**	**1,008.64**	**16.8**

The total delay observed for the 'PTS with a flagger' condition was calculated by the Eq. 6

$$\boldsymbol{Total\ Delay = 0.5 * Wait\ time\ for\ first\ vehicle * Number\ of\ vehicles} \qquad \textbf{Eq. 6}$$

Table 22 provides a summary of the total delay observed when a flagger was present with a PTS unit calculated using the Eq. 6.

Table 22. Summary of the Total Delay Observed when a PTS was used with a Flagger

Date	Location	Total Delay (vehicle-seconds)	Total Delay (vehicle-minutes)	Total Delay (vehicle-hours)
8/5/2014	Burlingame	119,588.5	1,993.1	33.2
8/6/2014	Scranton	-	-	-
8/7/2014	Scranton	-	-	-
8/12/2014	Melvern	4,097.5	68.3	1.1
8/13/2014	Melvern	-	-	-
8/14/2014	Melvern	-	-	-
8/19/2014	Beloit	189,926.5	3,165.4	52.7
8/20/2014	Beloit	88,903	1,481.7	24.7
8/21/2014	Beloit	-	-	-
8/26/2014	Newton	175,554	2,925.9	48.8
8/27/2014	Newton	569,317	9,488.6	158.1
8/28/2014	Newton	-	-	-
Total		**1,147,386.5**	**19,123.1**	**318.7**

From Table 22, it can be found that approximately 318.7 vehicle-hours of delay was observed at all the test locations when a flagger was present with a PTS unit. It was found previously that the presence of a flagger reduced approximately 16.8 vehicle-hours of vehicle delay. On comparison of this total vehicle delay reduced by the presence of a flagger to the total vehicle delay observed over the entire duration of the study for the 'PTS with a flagger' condition, it was found that the presence of a flagger was beneficial in reducing approximately five percent of the total vehicle delay.

6.5 Model Development for Volume Thresholds and Appropriate Green Time

The video data reduction provided information on individual green intervals and the number of vehicles that were served in each of the intervals. With the help of this information, a model was developed based on the ongoing KDOT policy that would provide guidance to the contractor and KDOT prior to the application of the PTS units on two-lane, two-way work zones with pilot car operations. The following section provides a description of the methodology and the calculations involved.

6.5.1 Saturation Headway and Start-up Lost Time

To develop the model for determining the appropriate green time that needs to be allotted for a given AADT or a queue of vehicles at a PTS station, the saturation headway (h_s) and start-up lost time (t_s) were necessary to be calculated. These terms were defined using the 2010 Highway Capacity Manual (HCM) and were provided in this section (*29*):

Saturation headway (h_s) = at a signalized intersection, the average headway between vehicles occurring after the fourth vehicle in the queue and continuing until the last vehicle in the initial queue clears the intersection.

Start-up lost time (t_s) = the additional time consumed by the first few vehicles in a queue at a signalized intersection above and beyond the saturation headway because of the need to react to the initiation of the green phase and to accelerate.

Saturation flow rate (s) = the equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all times and no lost times are experienced.

The 2010 HCM indicated that a minimum of 15 vehicular queues were required to obtain a statistically significant result with each of the selected queue having a minimum of eight vehicles (*29*). It was found from the data reduction that all the four test locations had varying AADT, peak hour volumes, truck percentages, and length of the longest queues. Therefore, to obtain an unbiased and all-encompassing result, the ten longest queues were selected from Test Locations 1, 3, and 4, respectively. Test Location 2 (K-31 near Melvern, KS) did not have any queues that served more than eight vehicles in one cycle. Therefore, data for Test Location 2 were not included in the calculations. Finally, a total of 30 queues that served a minimum of eight vehicles each were used as a part of the model development analysis. The calculated values for h_s and t_s were then used to obtain a better understanding of the green interval needed to clear a queue of vehicles at the PTS station.

Two different cases were compared to determine the h_s and t_s for the selected vehicular queues:

- Case 1 included the vehicles that were cleared in the green interval of the corresponding queue and the queue position for the beginning of the saturation flow was determined using the charts developed to calculate the values for h_s and t_s (referred to as Graphical Method);
- Case 2 included the vehicles that were cleared in the green interval of the corresponding queue and the methodology indicated in the Highway Capacity Manual (HCM) was used to calculate the values for h_s and t_s (referred as HCM Method).

The following assumptions were made during the data reduction for each of the selected queues:

- All types of vehicles (motorcycles, passenger cars, trucks) were to be considered to determine h_s;
- It was not necessary for the vehicle to be a part of the standing queue when calculating h_s. Vehicles that joined the standing queue after the signal had turned green were also included in the analysis;
- Only the vehicles that were cleared in the green interval were considered for the calculations. The vehicles that entered the work zone at the onset of the yellow indication and the RLR vehicles were excluded from the calculations;
- For the first vehicle, the headway was calculated as the time duration from the start of the green interval to the time when the vehicle's rear axle crossed the STOP line. The vehicle's rear axle was chosen as the reference because a number of the vehicles that

were the first vehicle in the queue stopped partially beyond the STOP line and it was not feasible to calculate their start-up time with the front axle as reference;

- From the second vehicle onwards, individual vehicle headways were calculated as the duration from the time when a vehicle's rear axle crossed the STOP line to the time when the rear axle of the next vehicle had crossed the STOP line;
- The effective green time was assumed to be equal to the actual green time but the lost time at the end of the phase was not considered in the analysis; and
- The starting response time was a part of the headway for the first vehicle and was not calculated separately.

To determine h_s and t_s for the selected queues, data for vehicle position were plotted against average vehicle headways for each corresponding position. It was observed that the number of data points that represented each of the vehicle positions decreased as the vehicle position increased. The coefficient of determination (R^2) was defined as, "the proportion of the variability in the dependent variable that is accounted for by the independent variable" (*30*). Therefore, the R^2 value indicated the strength of the linear relation between the two variables which were average headway and vehicle position in our case. Towards the end of the data set, the vehicle positions were represented by as few as one data point which impacted the R^2 value significantly. To mitigate this issue, two different plots were generated to determine the best possible value for the h_s and the t_s. Figure 54 shows the chart presenting the raw data for all the 30 queues for vehicle positions against the corresponding average vehicle headways.

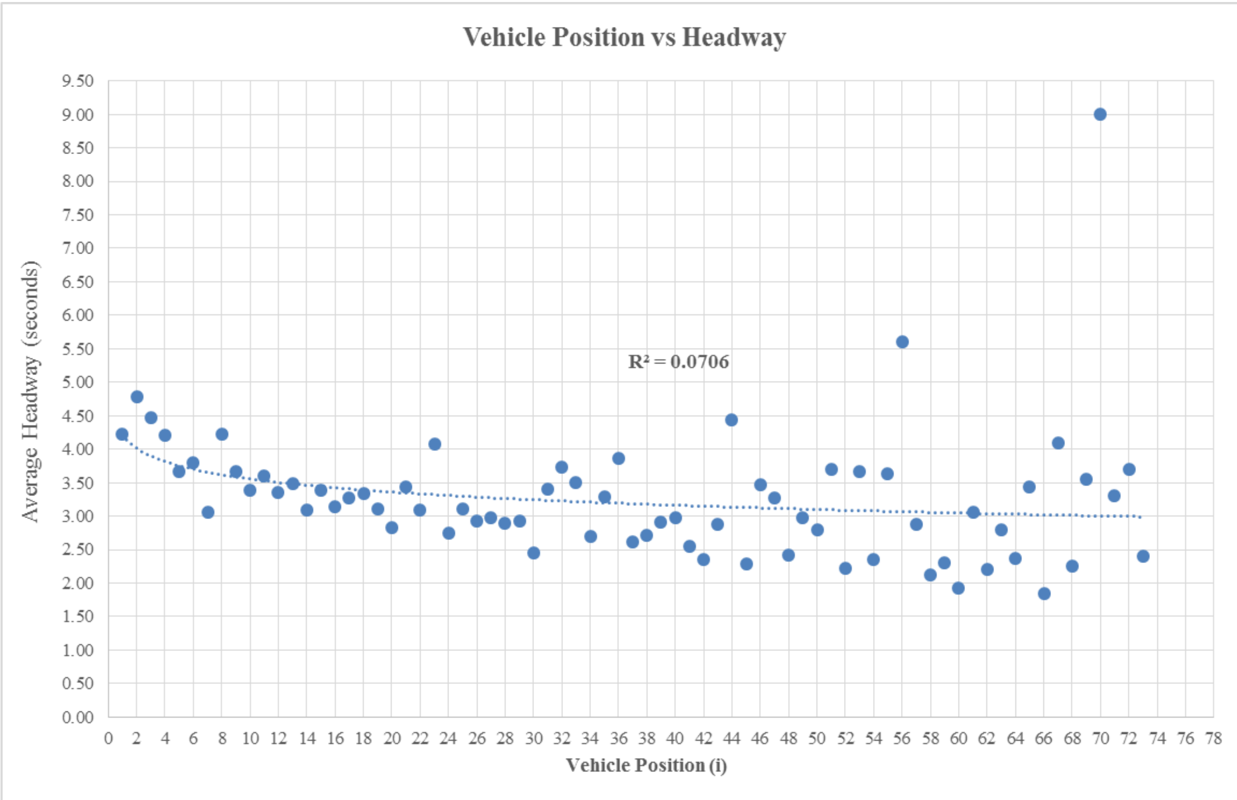

Figure 54. Plot of the vehicle headway data against vehicle position for all the 30 queues.

As shown in Figure 54, the average vehicle headways were plotted against the vehicle positions to obtain the estimates of h_s and t_s. It was found that beyond the 20th vehicle position, the number of data points representing the corresponding vehicle positions were less than 15 resulting in over-representation of the data for those vehicle positions. Therefore, a dispersed nature of the plot was observed beyond the 20th vehicle position as the number of vehicles representing a particular position started decreasing. Video data reduction also indicated that the dispersed nature of the plot was due to the presence of heavy vehicles and late addition of vehicles to the standing queue in the green interval or gap time. The ability of outliers to affect the values of the mean diminish for larger sample sizes. Also, the shape of a t-distribution begins to resemble a normal distribution for larger sample sizes as the number of degrees of freedom increase. Therefore, to obtain a result least affected by the presence of outliers and small sample sizes, it was decided to consider the vehicle positions that were represented by a minimum of 15 vehicles. Figure 55 shows the chart for the average vehicle headways against the vehicle positions represented by a minimum of 15 vehicles.

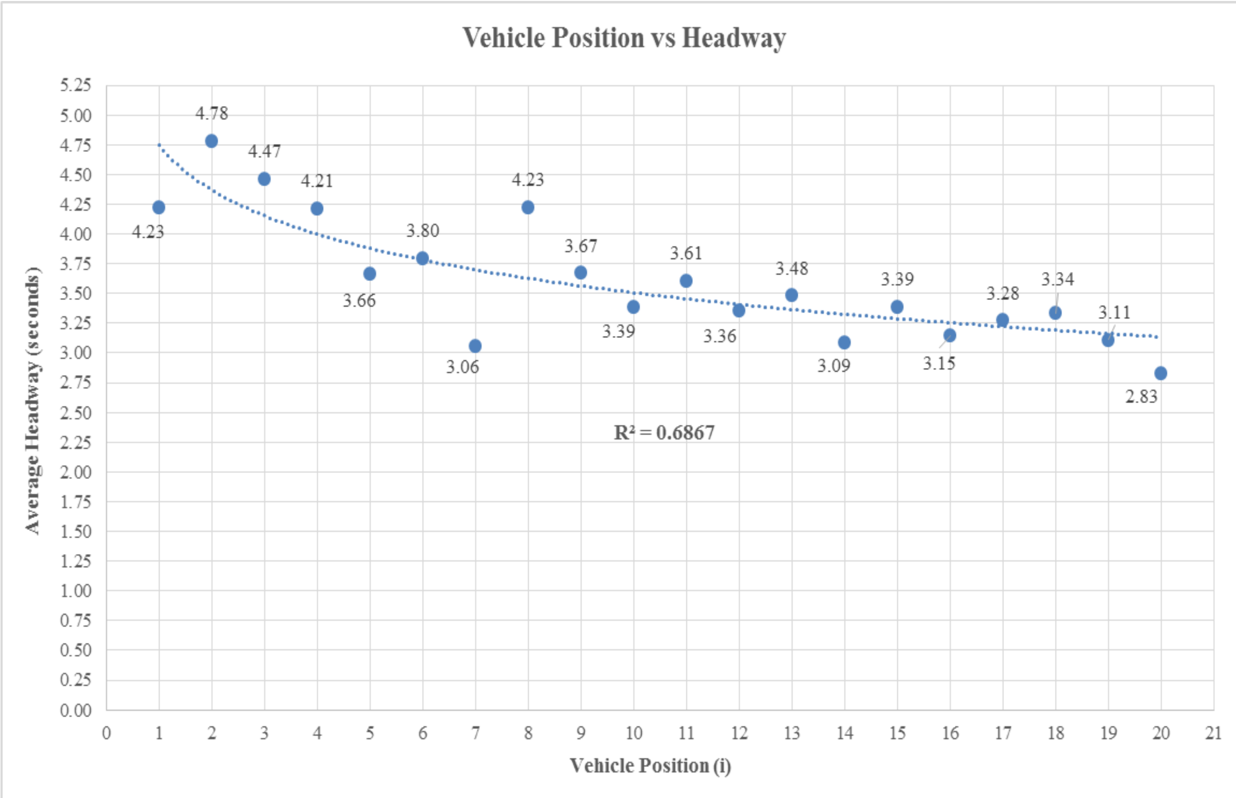

Figure 55. Plot for the vehicle headway data against first 20 vehicle positions.

As shown in Figure 55, the average headways were plotted against the first 20 vehicle positions. It was found that this plot had eliminated the dispersed nature observed earlier and also had an improved R^2 value by reducing the over-representation of the data for some vehicle positions. Therefore, it was decided to calculate the h_s and t_s by the Graphical Method and the HCM Method using the plot shown in Figure 55. Although from Figure 55 it was found that the average vehicle headways dropped sharply after the fourth vehicle, saturated headway conditions (stable headway) were not observed beyond that position and average vehicle headways varied irregularly. From the Graphical Method, it was observed that the stable headway conditions did not start until the ninth vehicle position. Therefore, it was concluded that the eight vehicle was the position beyond which the values for the headways started exhibiting a stable nature. The values for h_s were calculated as the average of the headways between the first vehicle, where the saturation was assumed to start, and the last vehicle in the queue and the values for t_s were calculated as the sum of difference between the individual vehicle headways and h_s.

$$\boldsymbol{Saturation\ Headway\ (h_S) = \left[\frac{h(i) + h(i+1) + \cdots + h(n)}{n - i + 1}\right]} \quad \textbf{Eq. 7}$$

$$\boldsymbol{Saturation\ Flow\ Rate\ (s) = \left[\frac{3600}{h_S}\right]} \quad \textbf{Eq. 8}$$

$$\boldsymbol{Startup\ Lost\ Time\ (t_S) = \left[\sum_{1}^{(i-1)} (h - h_S)\right]} \quad \textbf{Eq. 9}$$

Where:

i = Vehicle position where the saturation headway is assumed to start;

h = Individual headway of the vehicle; and

n = Position of the last vehicle in the queue.

Table 23 provides a summary of the calculated values of h_s, t_s, and s by the Graphical Method and the HCM Method.

Table 23. Summary of Values of h_s and t_s by the Graphical Method and the HCM Method

No. of Queues Analyzed	Variable	Method Used	
		Graphical	HCM
30	Position for start of h_s	9	5
	h_s (seconds/vehicle)	3.31	3.40
	t_s (seconds)	5.98	4.08
	s (vehicles/hour/lane)	1,088	1,059

From Table 23, it can be found that the results for the values of h_s for both the cases were not vastly different. On the contrary, the t_s calculated by the Graphical Method was approximately 2.5 seconds higher than the t_s calculated by the HCM method. The HCM Method was used for the determination of h_s at signalized intersections and not work zones (*29*). Although the nature of the data were similar, it was believed that using the values from the HCM method would not be a true representation of the data collected since the research involved work zones and not intersections. Therefore, the values for h_s and t_s from the Graphical Method were used in the subsequent sections for calculating the green time. To determine the effects of the presence of heavy vehicles on the h_s and t_s, the average headways were plotted against the vehicle positions excluding the trucks from the dataset. Figure 56 shows the chart for the average vehicle headways against the vehicle positions represented by a minimum of 15 vehicles and excluding the data for the trucks and heavy vehicles.

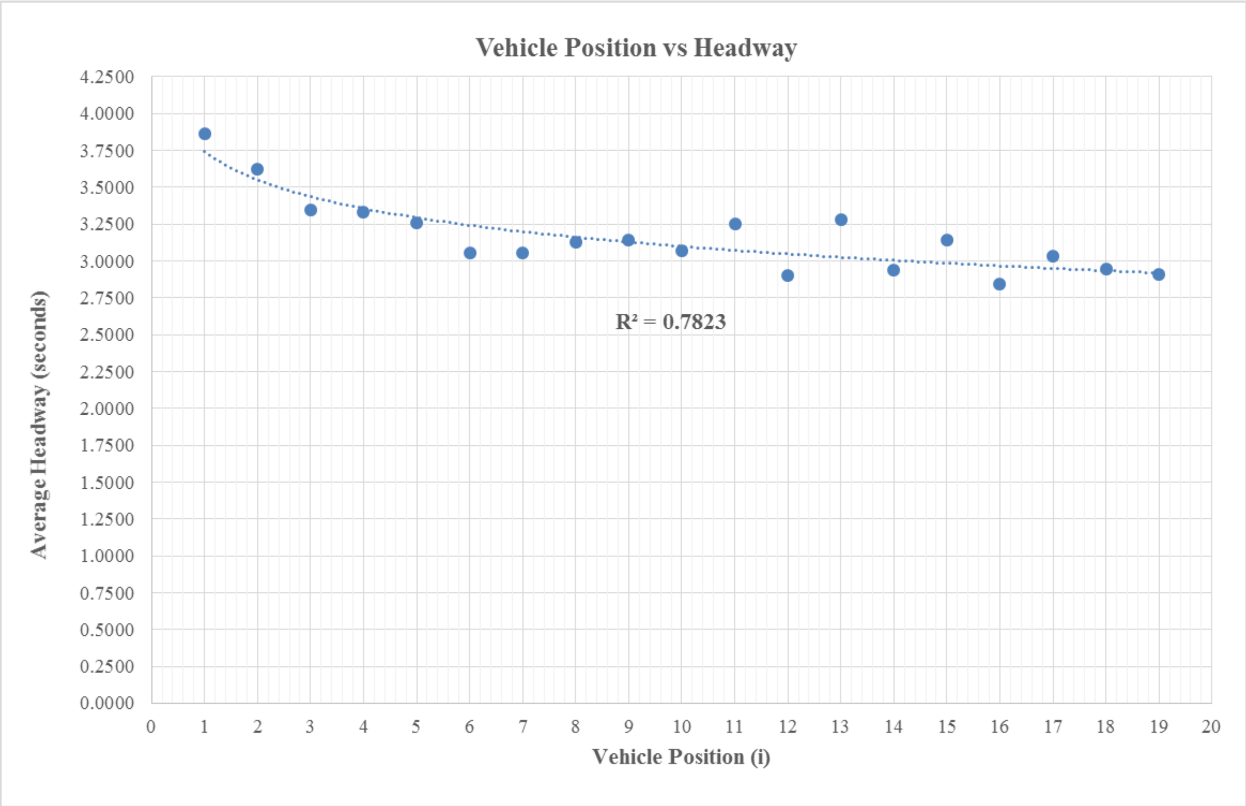

Figure 56. Plot for the headway data against vehicle position excluding the trucks and heavy vehicles.

As shown in Figure 56, the average headway data were plotted against the vehicle positions excluding the data for the trucks and heavy vehicles. It was found that the h_s values, when the heavy vehicles were excluded from the dataset, using the HCM Method and the Graphical Method were approximately 3.06 and 3.04 seconds, respectively. The video data reduction indicated that on an average 3.75 trucks or heavy vehicles represented each vehicle position in all the 30 queues considered for the analysis. Therefore, it was decided to use the values calculated from Table 23 by the Graphical Method as they incorporated the effects of the presence of heavy vehicles on the values of h_s and t_s and were a true representation of the site conditions.

6.5.2 Platoon Clearance Time

The platoon of vehicles escorted by the pilot car at the onset of the green interval from one end required a certain clearance time at the other end of the work zone before the pilot car could turnaround and begin escorting the queue back. This time will be referred to as the Platoon Clearance Time (P_t) in the following sections.

30 queues were considered in the calculation of h_s and t_s it was found that P_t varied significantly for all the three test locations and no significant correlation could be determined. Video data reduction indicated that the P_t was affected by the number of driveways in the work zone, connecting major roads, and the proximity to the city/town. The test locations that had a major connecting road within the work zone absorbed a majority of the traffic from the discharged queue resulting in a shorter P_t at the opposite work zone end. Presence of multiple driveways and the proximity of the work zone to a city/town reduced the number of vehicles that were initially a part of the queue. Due to a small sample size it was difficult to determine the number of vehicles that left a discharged queue to use a driveway or another road. Therefore, P_t was assumed to be equal to the green interval provided at the opposite end of the work zone for simplicity. Table 24 provides a summary of the P_t and the turnaround time.

Table 24. Summary of Average Platoon Clearance Time and Turnaround Time

Test Location	Roadway AADT	Average Green Time (second)	Average P_t (second)	Percent Difference	Average Turnaround time (second)
US-56	1,000 – 3,300	65	64	1.54	12
US-24	2,500 – 5,000	64	52	18.75	24.8
US-50	5,000 – 7,500	203.9	174	14.66	37.1
Total		**112.55**	**97.68**	**13.20**	**25**

From Table 24, it can be found that the average values for P_t at each location varied significantly. At Test Locations 3 and 4, the P_t was significantly less than its corresponding green interval. The turnaround times at these locations were longer than Test Location 1. As indicated previously, Test Locations 3 and 4 had a number of driveways and connecting roads within the work zone ends which reduced the length of the departed queue. Since the P_t was directly related to the number of vehicles in the queue, the greater percent difference at Test

Locations 3 and 4 were attributed to the presence of multiple driveways, inter-connecting roads, and proximity to the town.

6.5.3 Development of the Model to Determine the Green Interval

After calculating the values for h_s and t_s, a model was developed to calculate the amount of green time and volume threshold based on the roadway AADT, speed of the pilot car, and the length of the work zone. The following section list the assumptions made prior to the development of the model:

- P_t included the turnaround time for the pilot car at the work zone ends. The sum of these two times was assumed to be equal to the green interval (G) which was utilized at the opposite end of the work zone during the same cycle.
- The total lost time was equal to the start-up lost time calculated earlier in section 6.5.1.

Figure 57 shows a general end-to-end layout of the work zone and the different variables that were used in the initial development of the model.

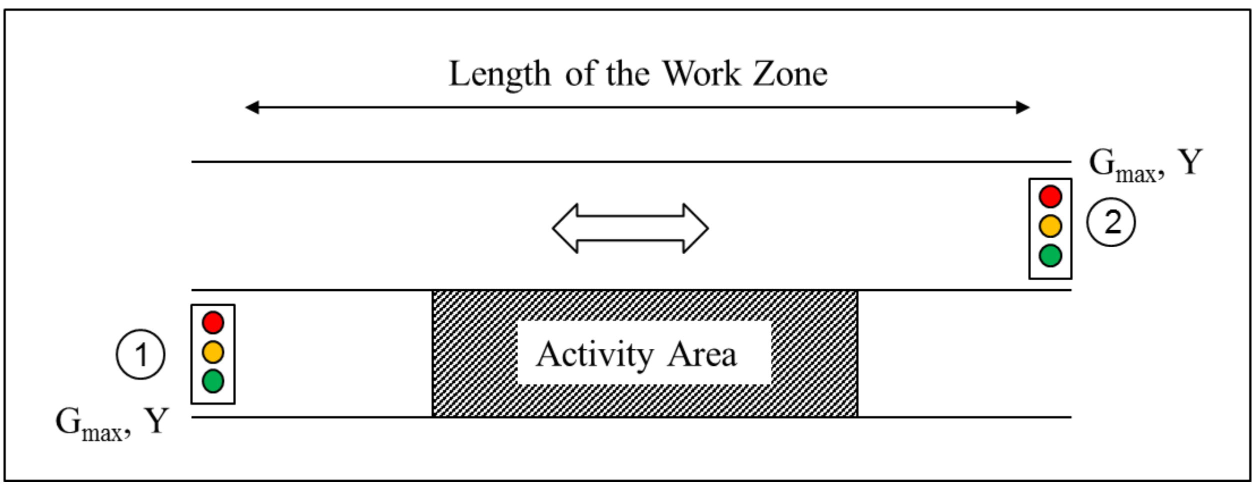

Figure 57. General end-to-end layout of the work zone at all test locations.

As shown in Figure 57, the end-to-end distance or the length of the work zone was the distance in miles between the PTS units stationed at ends 1 and 2, respectively. Therefore, the total round trip time for a pilot car was a sum of the time needed to travel the end-to-end distance or length of the work zone, the green interval, and the yellow interval utilized on the PTS unit. For the simplicity of the model, it was assumed that the green and yellow interval at both the ends were equal. Therefore, the total round trip time for a pilot car for end 1 or end 2 was the sum of the time in minutes required to travel the length of the work zone twice, the green and yellow intervals at end 1, and the green and yellow intervals at end 2. Using this concept and the assumptions listed earlier Eq. 10 and Eq. 11 were developed to calculate the total round trip time in minutes:

$$\boldsymbol{T_r = \left[\left\{2 * \left(\frac{L_w}{S_p}\right) * 60\right\} + \left\{2 * \left(\frac{G_{max} + Y}{60}\right)\right\}\right]} \qquad \textbf{Eq. 10}$$

$$\boldsymbol{T_r = \left[\left\{120 * \left(\frac{L_w}{S_p}\right)\right\} + \left(\frac{G_{max} + Y}{30}\right)\right]} \qquad \textbf{Eq. 11}$$

Where:

T_r = Pilot car round trip time (minutes);

L_w = Length of work zone/end-to-end distance (miles);

S_p = Pilot car speed (mph);

G_{max} = Maximum feasible green interval (seconds); and

Y = Yellow interval (seconds).

Eq. 12 and Eq. 13 for calculating the maximum feasible green interval and the length of work zone were obtained by rearranging the terms from Eq. 11:

$$\boldsymbol{G_{max} = \left[30 * \left\{T_r - \left(\frac{120 * L_w}{S_p}\right)\right\}\right] - Y} \qquad \textbf{Eq. 12}$$

$$\boldsymbol{L_w = \left[\left\{T_r - \left(\frac{G_{max} + Y}{30}\right)\right\} * \left(\frac{S_p}{120}\right)\right]} \qquad \textbf{Eq. 13}$$

Eq. 14 was developed to calculate the number of vehicles cleared in a certain green interval and was a function of h_s and t_s.

$$V_{max} = \left[\frac{(G_{max} - t_S)}{h_S}\right] \quad \textbf{Eq. 14}$$

Where:

V_{max} = Maximum number of vehicles that could be served per round trip (vehicles per round trip);

t_s = Start-up lost time (seconds); and

h_s = Saturation headway (seconds).

The 2010 HCM defined capacity as, "the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions" (*29*). Therefore, the capacity per hour per direction was calculated as a function of the number of vehicles and the number of round trips the pilot car could make in any given hour. Eq. 15 given below was developed for calculating the capacity in vehicles per hour per direction.

$$C = (V_{max} * Number\ of\ Round\ Trips\ per\ hour) \quad \textbf{Eq. 15}$$

Where:

C = Capacity (vehicles per hour per direction).

The number of round trips per hour was calculated as the number of round trips in 60 minutes since the *Tr* was calculated in minutes using Eq. 11.

$$C = \left[V_{max} * \left(\frac{60}{T_r}\right)\right] \quad \textbf{Eq. 16}$$

Substituting the value of V_{max} from Eq. 14 in Eq. 16:

$$\boldsymbol{C = \left[\frac{(G_{max} - t_S)}{h_S}\right] * \left(\frac{60}{T_r}\right)} \qquad \textbf{Eq. 17}$$

The 2010 HCM defined the AADT as, "the total volume of traffic passing a point or segment of a highway facility in both directions for one year divided by the number of days in the year" (*29*). Assuming the Peak Hour Volume (PHV) to be 15 percent of the AADT and a 50/50 directional distribution of the traffic volume, Eq. 18 was developed for calculating the capacity:

$$\boldsymbol{C = (0.15 * 0.5 * AADT)} \qquad \textbf{Eq. 18}$$

Where:

AADT = Average Annual Daily Traffic (vehicles per day)

The terms in Eq. 18 were rearranged to obtain the equation for calculating the *AADT* given in Eq. 19.

$$\boldsymbol{AADT = \left[2 * \left(\frac{C}{0.15}\right)\right]} \qquad \textbf{Eq. 19}$$

Substituting the value of *C* from Eq. 17 in Eq. 19:

$$\boldsymbol{AADT = \left[\frac{(G_{max} - t_S)}{h_S}\right] * \left(\frac{60}{T_r}\right) * \left(\frac{2}{0.15}\right)} \qquad \textbf{Eq. 20}$$

Simplifying the Eq. 20:

$$\boldsymbol{AADT = \left[\frac{(G_{max} - t_S)}{h_S}\right] * \left(\frac{800}{T_r}\right)} \qquad \textbf{Eq. 21}$$

Using the value of h_s = 3.31 seconds and t_s = 5.98 seconds obtained from section 6.5.1 in Eq. 21:

$$\boldsymbol{AADT = \left[\frac{(G_{max} - 5.98)}{T_r}\right] * 241.7} \qquad \textbf{Eq. 22}$$

The terms in Eq. 22 were rearranged to obtain the final equation for calculating the maximum feasible green interval given in Eq. 23.

$$\boldsymbol{G_{max} = \left[\left(\frac{AADT * T_r}{241.7}\right) + 5.98\right]} \qquad \textbf{Eq. 23}$$

If the variables: *AADT*, the desired round trip time, and the pilot car speed were known and/or assumed, the maximum feasible green interval, volume threshold for failure of the system, length of the work zone, the number of vehicles served, and the capacity could be easily estimated using the equations developed in Section 6.5.3.

Using the equations mentioned earlier, three charts shown in Figures 58, 59, and 60 were developed for values of *AADT*, G_{max}, and L_w based on the ongoing KDOT policy of a T_r = 15 minutes and a pilot car speed of 40mph to determine the volume thresholds and other corresponding values (*23*). Other charts that were developed for different pilot car speeds can be found in Appendix F. With the help of the model developed in this research, several charts could be developed for values of T_r and other relevant combinations. Figure 58 shows a plot of the *AADT* against the maximum feasible green interval.

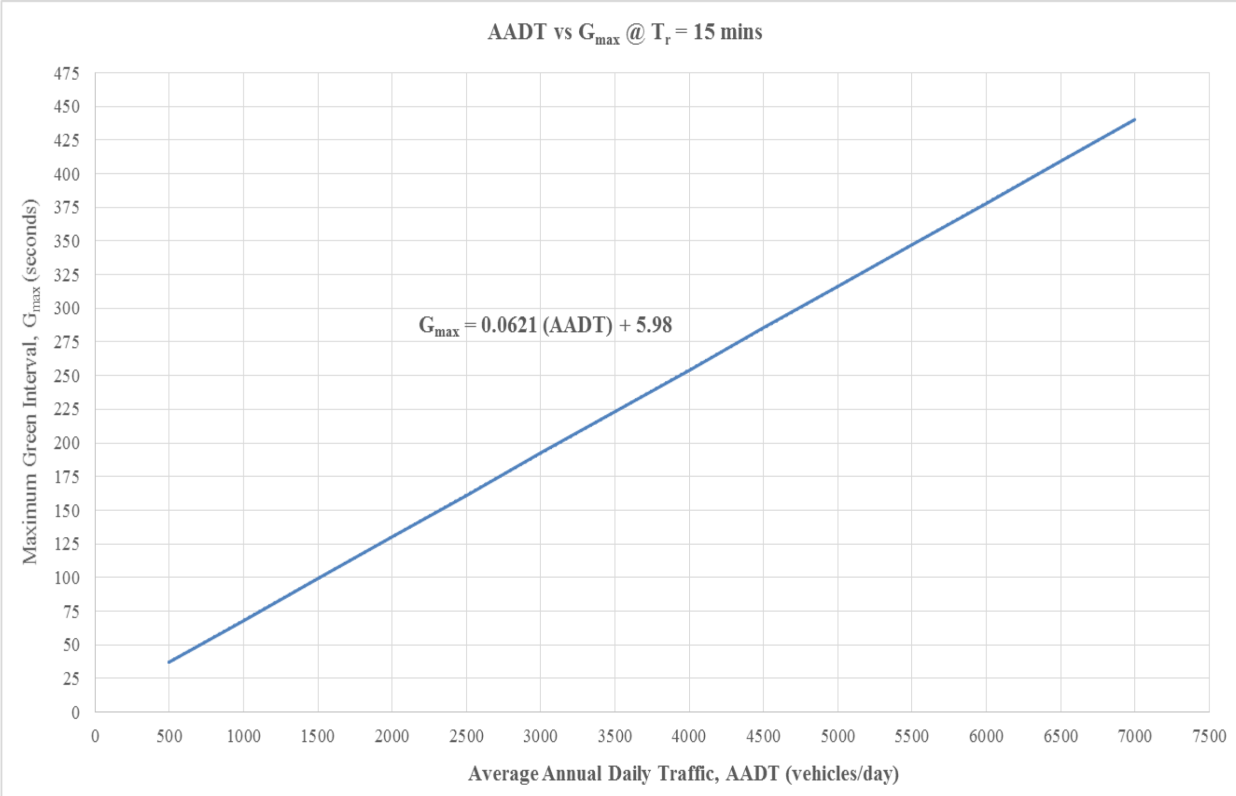

Figure 58. Plot for the *AADT* against the maximum green interval.

As shown in Figure 58, the *AADT* values were plotted against the maximum feasible green interval for a constant T_r of 15 minutes and using the Eq. 23. It was found that at a constant T_r, the *AADT* varied linearly with the maximum feasible green interval. This chart could be used as the first step in determining the feasibility of a PTS system at the work zone. *AADT* values could be used to obtain an estimate of the maximum feasible green interval that could be set on the PTS unit. Figure 59 shows a plot of the maximum feasible green interval against the number of vehicles that could be cleared in that corresponding green interval.

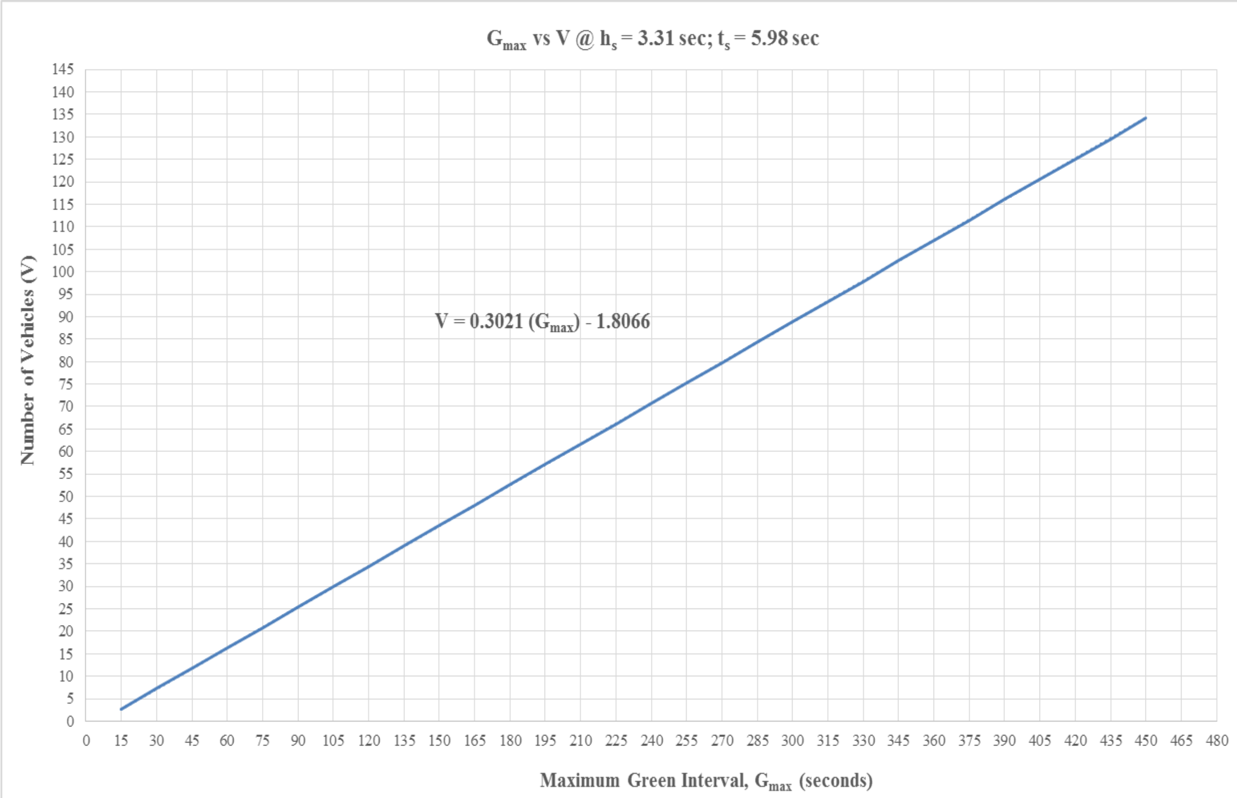

Figure 59. Plot for maximum green time against number of vehicles.

As shown in Figure 59, the maximum feasible green interval was plotted against the number of vehicles that could be cleared in that corresponding green interval using the Eq. 14. It was found that at any given values of h_s and t_s, the number of vehicles that could be cleared varied linearly with the corresponding maximum feasible green interval. Figure 60 shows the plot for the maximum feasible green interval against the maximum feasible length of the work zone.

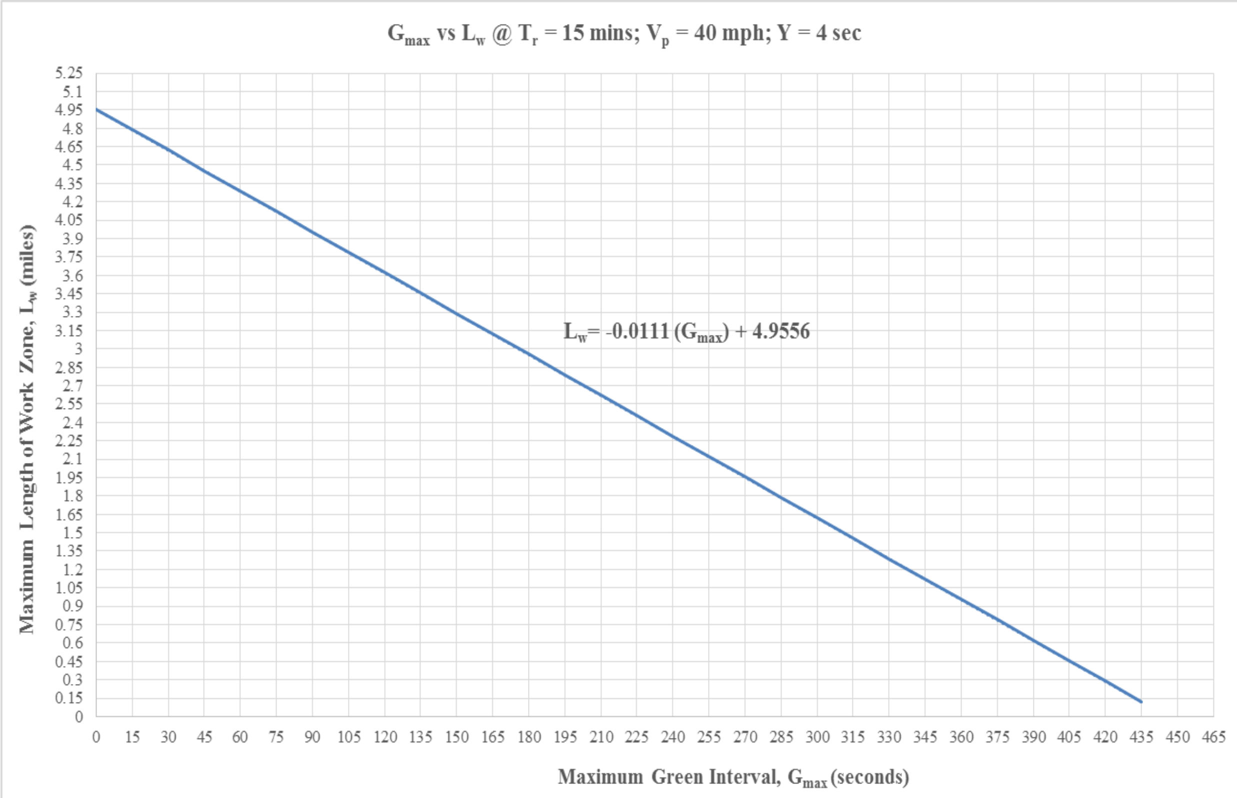

Figure 60. Plot for maximum green interval against maximum length of work zone.

As shown in Figure 60, the maximum feasible green interval was plotted against the maximum feasible length of the work zone using the Eq. 13. It was found that at a constant pilot car speed and round trip time, the maximum feasible length of the work zone varied linearly with the maximum feasible green interval. This chart could be used to determine the maximum feasible length of the work zone corresponding to the maximum feasible green interval calculated earlier using Figure 58. Chapter 7 presents a detailed description of the use of the charts shown in Figure 58, 59, and 60. Table 25 provides the calculated values for the maximum feasible length of the work zone, maximum feasible green interval, and number of vehicles cleared in the corresponding green interval based on the ongoing KDOT policy for pilot car round trip time and speed and calculated using Eq. 13, Eq. 14, Eq. 16, and Eq. 19.

Table 25. Table showing the Maximum Feasible Length of Work Zone and Maximum Feasible Green Interval Based on Current KDOT Policy

T_r = 15 minutes			
S_p = 40 mph			
***AADT* (vehicles per day)**	**L_w (miles)**	**G_{max} (seconds)**	***V* (number)**
< = 1000	4.20	70	19
1000 to 2000	3.51	130	38
2000 to 3000	2.82	195	56
3000 to 4000	2.13	255	75
4000 to 5000	1.44	320	94
5000 to 6000	0.75	380	113
6000 to 7000	0.06	440	131
S_p = 35 mph			
< = 1000	3.70	70	19
1000 to 2000	3.07	130	38
2000 to 3000	2.47	195	56
3000 to 4000	1.86	255	75
4000 to 5000	1.26	320	94
5000 to 6000	0.66	380	113
6000 to 7000	0.05	440	131
S_p = 30 mph			
< = 1000	3.15	70	19
1000 to 2000	2.63	130	38
2000 to 3000	2.12	195	56
3000 to 4000	1.60	255	75
4000 to 5000	1.08	320	94
5000 to 6000	0.56	380	113
6000 to 7000	0.05	440	131

From Table 25, it can be observed that as the maximum feasible green time increased the length of the work zone decreased. It was also found that for a T_r of 15 minutes there would be no length of work zone available if the *AADT* increased beyond 7,000 vehicles per day. Using the equations listed earlier it was found that the PTS system would fail at an *AADT* of 7,083 vehicles per day at a maximum green interval of 446 seconds.

From the results obtained from the RLR analysis, delay analysis, and the signal timings and operations, the effectiveness of the PTS system at two-lane, two-way work zones in conjunction with pilot car operations for all the three conditions was evaluated. The findings, recommendations, and areas that need additional research can be found in Chapter 7, Chapter 8, and Chapter 9.

CHAPTER 7. RESEARCH FINDINGS

A Portable Traffic Signal (PTS) system is designed to control one-way traffic at temporary work zones where the adjacent travel lane is closed. Traditionally, a flagger controls operations at each end of such a work zone by stopping and releasing the queue of vehicles. Due to rising costs and the risk of flaggers being struck by noncompliant vehicles, PTS are becoming a common tool with contractors and design engineers. The 2009 MUTCD indicated that, if traffic on the one-lane roadway was not visible from one end to the other, then flagging procedures, a pilot car in conjunction with a flagger or a traffic control signal should be used to control opposing traffic flows. However, there was no guidance provided regarding the use of PTS systems in conjunction with pilot car operations and/or flagger operations. Since, flagging operations were labor intensive, expensive, and posed hazards for workers, it was important to evaluate new technologies and techniques that had the potential of providing safe and efficient traffic operations at one-lane, two-way work zones.

The objective of this study was to evaluate and compare three conditions for controlling one-lane, two-way work zone traffic in conjunction with pilot car operations: flagging only operations, a PTS system with a flagger, and a PTS system without a flagger. Four locations which were two-lane, two-way long work zones anticipating pilot car operations and flagger operations were identified by working with KDOT and selected for the data collection. A total of 161 hours of field data were collected at all the test locations.

After all the data were reduced, three different analyses were performed to evaluate and comment on the effectiveness of the PTS systems in monitoring one-lane, two-way traffic at long work zones. First, an operational evaluation and comparison of the three conditions (flagger only, PTS with a flagger, and PTS without a flagger) was conducted by estimating and comparing the average vehicle wait times, queue lengths, and the signal timing operations. Second, a statistical evaluation and comparison was conducted by calculating the RLR ratios as a percentage of the total vehicular volumes observed during the corresponding data collection period. RLR events were classified in different types and compared for the three conditions using the test of proportions at a 0.05 level of significance. Furthermore, an exploratory delay analysis was conducted to determine the total amount of delay time that was reduced by the presence of flaggers with a PTS unit. Finally, a model was developed to determine the traffic volume thresholds and appropriate green time when using the PTS system at two-lane, two-way work zones with pilot car operations. This model would be a practical tool and serve as guidelines for the use of PTS systems at long and temporary rural work zones.

7.1 Summary of Findings

7.1.1 Safety and Visibility

In comparison to a flagger, the PTS units were highly visible from a long distance when observed from the upstream end. Therefore, vehicles at the upstream end of a queue would be made more aware of the presence of a work zone downstream. Although, in some cases visibility could be diminished by the presence of an oversized truck or a semi-trailer ahead of a passenger car or motorcycle, providing adequate signage and informing the drivers well in advance would provide information to drivers regarding the presence of a PTS unit and a work zone. It is suggested (although not directly studied in this thesis) that use of a PTS system could minimize the ever-increasing risk of flaggers being victims of inattentive and rash driving at work zones.

7.1.2 Ease of Installation and Operation

The PTS system was found to be easy to install with setup and teardown time approximately to be seven to ten minutes each. The units did not involve a complicated process to operate and were also easily operated by the pilot car drivers using a handheld remote. Signal timings such as: green interval, yellow interval, and gap time were easily entered, stored, and adjusted on the PTS units. On the contrary, the pilot car remote did not operate correctly resulting in inactivation of the green phase on a few occasions during this research. Such situations potentially cause driver confusion and increase the probability of noncompliance events.

7.1.3 Evaluation of Operational Parameters

An operational evaluation for the three conditions was conducted by estimating and comparing the parameters such as average vehicle wait times, queue lengths, and the signal timing operations. Following were the three key findings from the comparison of the operational parameters:

- The ‘flagger only’ condition had the longest average wait time while the ‘PTS without a flagger’ condition had the least average wait time over the entire duration of the data collection.
- The ‘PTS without a flagger’ condition served the longest average queue length while the ‘flagger only’ condition served the least average queue length over the entire duration of the data collection.
- The ‘PTS with a flagger’ condition and the ‘PTS without a flagger’ condition had a negligible difference in the average duration of the green interval over the entire duration of the data collection.

Since the three conditions did not differ substantially in the values of average total wait time, average queue length, and average green interval it was concluded that all the three conditions provided the same operational efficiency to monitor traffic at two-lane, two-way work zones with pilot car operations.

7.1.4 RLR or Violation Analysis

Based on field observations and video evidence, RLR events were divided into different categories for the purpose of the study and data were reduced to record each of these following events:

a. RLR when drivers were catching up with a just departed queue;
b. RLR when drivers left a queue due to the wait time;
c. RLR when drivers completely disregarded the PTS system; and
d. RLR when drivers were waived through by the flagger.
    - When the drivers were catching up with a departed queue; and
    - When the drivers received the flagger’s consent to enter the work zone at another time period.

Nine violations were observed for the ‘flagger only’ condition and all the nine violations were in the absence of a vehicle queue ahead and solely based on the judgment of the flagger. These were the type of violations where the drivers talk to the flagger and obtained his/her consent to enter the work zone unguided by a pilot car. Such events are possible when a flagger is stationed at the work zone end and not when only a PTS unit is used. The results of the test of proportions indicated that the number of violations when a PTS was used with a flagger and when a PTS was used without a flagger were both statistically higher than the condition when flagger only operations were used. This result could suggest that using only flagging operations was the most suitable method of providing work zone traffic control. Keeping in mind the potential risk of flaggers being hit by errant vehicles and other advantages of using the PTS systems, it is recommended that reduction in the number of RLR vehicles or violations should not be the only criteria for evaluation of the effectiveness of these traffic control devices. Furthermore, it was believed that since the data collected for 'flagger only' condition were small compared to the data collected for the other two conditions, more data needs to be collected to make better comparisons of the flagging conditions to the other traffic control measures.

The number of RLR vehicles for the 'PTS without a flagger' condition was found to be 92 and the number of RLR vehicles for the 'PTS with a flagger' condition was found to be 93. Since the test location of Beloit was an outlier in terms of roadway geometry and operations, it was excluded from the calculations for the RLR ratios and analysis. Therefore, after the exclusion of the data for Beloit, the total number of violations when a PTS was used with a flagger were 52. The test of proportions indicated that the number of violations when a PTS was used without a flagger were statistically higher than the number of violations when a PTS was used with a flagger.

Data reduction indicated that when a PTS unit was used without a flagger, there were a total of 92 RLR vehicles where 36 vehicles followed an already departed queue, 44 vehicles left the queue due to the extensive wait time to move in the direction of the work zone, and 12 vehicles disregarded the PTS control. Also it was found that when a PTS unit was used with a flagger, there were a total of 52 RLR vehicles where 47 vehicles followed an already departed queue, 3 vehicles left the queue due to the extensive wait time to move in the direction of the work zone, and 2 vehicles disregarded the PTS and flagger control. The results of the test of proportions indicated that there was no statistically significant difference between the number of RLR vehicles that followed an already departed queue for both the conditions. Furthermore, it was also found that there was a statistically significant difference between the number of RLR vehicles that left the queue due to the wait time and the number of vehicles that disregarded the PTS control for both the conditions.

7.1.5 Delay Analysis

When a PTS was used with a flagger, the total delay was determined based on the information available for arrival and departures time of the vehicles in each of the queues. It was found that the presence of a flagger reduced approximately five percent of the total delay that occurred at all the test locations. It was believed that a five percent reduction would not be sufficient to entirely advocate the use of a flagger with a PTS unit. The reduction in delay was brought about by disregarding another traffic control (PTS unit). Reduction in vehicle delay should not be considered a valid justification for disregarding an actual traffic control. Also the 2008 KDOT Flagger Handbook indicated that late vehicles should not be allowed to join a vehicle platoon that has already embarked. The use of a single traffic control (a flagger or a PTS unit) would demand greater respect from the drivers towards the traffic control and eliminate the effect of contradiction produced by the use of a multiple traffic control devices.

7.1.6 Model for Volume Thresholds and Appropriate Green Interval

A model was developed to provide guidance to the contractor and KDOT prior to the application of the PTS units on two-lane, two-way work zones with pilot car operations and obtain estimates of the volume thresholds and appropriate green intervals that need to be allotted to serve a certain queue length. The three charts shown in Figure 58, 59, and 60 could be used as reference prior to setting up a work zone on a two-lane, two-way roadway with pilot car operations. From Figure 58, the AADT of a roadway could be used to determine the maximum feasible green interval that could be set on a PTS unit. From Figure 59, the maximum feasible green interval calculated earlier could be used to determine the number of vehicles that could be cleared in the corresponding green interval in a single round trip. Finally, from Figure 60, the corresponding length of the work zone or end-to-end distance could be determined. It is noteworthy to mention that Figure 60 and Figure 59 could be used in a reverse order if a certain length of the work zone is desired to be established by the contractor. Based on the model, it was found that use of a PTS system would fail at an AADT of approximately 7,083 vehicles per day if 15 minutes of delay is the maximum delay threshold allowed. Also, the maximum green time that could be set on the PTS is approximately 446 seconds. Using several combinations of the equations provided in the model, various signal timings, lengths of work zone, and traffic volume information could be obtained as desired.

Chapter 8 provides a detailed description of all the recommendations based on the findings of this research and discusses the limitations of the PTS system and anomalies observed during the research.

CHAPTER 8. RECOMMENDATIONS

This chapter covers a detailed description of all the recommendations that were based on the findings of the general field observations and data analysis. First, the chapter discusses recommendations for the use of a PTS system with a flagger or without a flagger followed by a list of recommendations and measures that needed to be adopted in possible signal failure scenarios. The chapter concludes with a description of the different limitations and anomalies of a PTS system observed during the research.

8.1 PTS with a Flagger or PTS without a Flagger

Based on field observations and data analyses, it was found that the most appropriate location to use a PTS system without a flagger would be a two-lane, two-way rural highway with an AADT less than 7,000 vehicles/day and having a limited number of driveways between the work zone ends. Since not every location will have similar topography and roadway geometry, the following are a few recommendations and measures that could be adopted for better efficiency and operations.

A major part of the five percent reduction in delay was at the intersection outside Beloit, KS where the roadway geometry was a contributing factor. It is strongly recommended that a PTS unit should never be used without a flagger at intersections and locations with heavy cross-traffic. At such locations, a PTS unit should be used as a secondary traffic control device for increased driver visibility and driver understanding. Also, the PTS unit could be placed in the flashing yellow mode providing the drivers with additional information regarding the presence of a traffic control device. Furthermore, in cases when a flagger is used to monitor traffic at long work zones, the flagger might not be visible to the vehicles in the queue. Complex situations and road geometry coupled with a considerable percentage of truck traffic could affect the proper flagger operations. Provision of a PTS unit would inform the drivers of the presence of a traffic control and reduce driver anxiety.

All of the work zones investigated were long and mobile where the far end of the work zone was not visible to the traffic stopped at the flagger stations. It was evident from the data that the round trip time for the pilot car was a maximum of 15 minutes and an approximate end-to-end distance of the work zone was between two to three miles. It is believed that installation of a static sign indicating the end-to-end distance and maximum wait time to drivers could reduce their anxiety and lessen the likelihood of RLR events.

It is recommended that proper spacing should be provided between a PTS unit, work zone channelizers, and the STOP line. If a PTS unit is stationed improperly, pilot car drivers will find it difficult to turn around to begin their subsequent operation and be unable to identify if the signal turned green. If the signal was not in the green phase, it will cause driver confusion and drivers approaching the STOP line might entirely disregard the signal creating a safety issue within the work zone. A simple solution for this issue will be to provide ample spacing between the PTS unit and the STOP line and preferably locating the PTS unit close to a driveway so that a pilot car driver could easily perform the turnaround maneuver and keep themselves informed on the correct functioning of the PTS system.

It is recommended to conduct a short engineering study every time prior to the use of the PTS to obtain an understanding about the site characteristics such as topography and maximum peak hour traffic volumes. Using the model developed in this research provided, the site superintendent can estimate the maximum feasible green interval and length of the work zone needed at any particular pilot car speed and round trip time.

During the data collection, the work crew and vehicles were allowed to enter and exit the work zone at any time and were not restricted by the presence of the PTS. Interestingly, it was observed the drivers had a tendency to follow the work vehicle that entered the work zone assuming that it was the pilot car. It is recommended that in the absence of a flagger, a sign should be installed on the back of all the work vehicles indicating that those were not the pilot car and discourage drivers at the end stations from following them into the work zone.

As per the KDOT specifications, speed within the work zone was to be a maximum of 40 mph (*23*). Therefore, pilot car operations prove to be effective as they were able to guide traffic at a consistent and safe speed through the entire work zone. In 2000, Meyer evaluated the effectiveness of removable orange rumble strips and found significant reductions in the mean and 85th percentile speeds downstream from the rumble strips for cars and trucks (*31*). In 2011, Sun et al. investigated the effectiveness of non-adhesive portable rumble strips in improving safety in highway work zones and found that the portable rumble strips were effective in increasing the percentage of braking vehicles by an average of 10.5 percent and an increase in speed compliance by 2.9 percent (*32*). In 2011, Wang et al. found that the portable plastic rumble strips were effective in significantly reducing the speeds of cars by 4.6 to 11.4 mph, and for trucks 5.0 to 11.7 mph (*33*). Therefore, for RLR vehicles, a potential safety measure could be the use portable rumble strips enforcing the need for a reduction in speeds within the work zone. Reduction in speed of RLR vehicles could assist in reducing the severity of potential crashes and provide the work crew and other drivers some additional time to react to the situation.

Since rural roads and highways are generally free from vertical and horizontal obstructions, such as a flyover bridge, oversize vehicles could be found in rural environments and could be a matter of concern when deploying a PTS unit. Figure 104 in Appendix G shows an oversize vehicle passing around the PTS unit observed during the data collection. When a PTS unit is deployed without a flagger, it is recommended to indicate the clearance height on the mast arm to avoid driver confusion and ensure that oversize loads are able to pass under or around the structure. Generally, the PTS units should be stationed on the roadway shoulder in such a manner that the mast arm does not extend beyond the centerline. The mast arm might protrude beyond the roadway centerline wherever shoulders are not available and having a sign indicating the maximum clearance height would provide the drivers some additional guidance.

It is recommended that if a PTS unit is desired to be used without flagging operations, a signal controller is used who operated the signal but did not engage in the flagging procedure. However, it would also be beneficial to have the controller trained as a flagger so that he/she could conduct flagging operations in case of an emergency. Although, this might not be a suitable alternative in terms of reducing the costs or making additional manpower available, it could improve the safety of flaggers by moving them away from the flagger station.

8.2 Measures to Adopt for Potential Problems Due to Signal Failure

Signal failure events could occur at any point during the work activity. Therefore, it is recommended to be prepared in case of a malfunction or a potentially hazardous situation. The following are some measures believed to minimize effects of undesirable scenarios and maintain high levels of safety within the work zone:

It is recommended to deploy a flagger at only one end of the work zone with live video feed from the other end (PTS end) of the work zone. This would provide the work crew with an additional crew member to assist them in the work area by eliminating one flagger position. Also, the provision of live feed would enable the flagger at one end to identify a potential system failure at the other end or occurrence of noncompliance events, and anomalous driver behavior.

Similarly, instead of a flagger the site supervisor could be provided with a continuous live video feed for both the ends of the work zone. The site supervisor could then monitor both ends from one location and inform his work crew of potential dangers and unsafe events. If a PTS unit was to be used without a flagger, it is recommended that regular inspection trips be done by the work crew to overlook the PTS functioning and report immediately to the site supervisor about any potential system failures. If live video feed was not feasible, radio communication could be used and a crew member could be stationed near the work area explicitly to inform the pilot car of a possible RLR event and alert the pilot car driver to slow down by the time the crew member mitigated with the violator. Although, both the alternatives could add additional costs, it is believed that they would provide supplementary information to the work crew and assist in avoiding a potentially hazardous situation.

8.3 PTS Limitations and Anomalies

At every test location for a few phases the green phase on the PTS unit failed to activate. It was believed that these occurrences were a consequence of one of the following situations:

- Pilot car drivers forgot to turn on the green phase i.e. unfamiliarity of the pilot car drivers with the PTS device;
- The PTS remote was low on battery or discharged completely; and
- The Bluetooth connectivity of the remote was lost with the PTS main control box.

It was believed that as the pilot car drivers get familiar in operating the PTS remote, the probability of them failing to activate the green phase will diminish. It is also recommended to periodically check the battery units in the PTS remote control to ensure correct operations.

At three test locations during the research, only one preset on the PTS unit was used for green time and one of the research team member rode in the pilot car for the first few cycles to familiarize the drivers with the system and to avoid confusion. Even then there were situations when the pilot car drivers forgot to activate the green phase. Also, whenever the pilot car driver forgot to press the 'Red Rest' button that activated the maximum green phase on the PTS unit, the signal never provided the maximum green time but kept the green phase activated until the Bluetooth connectivity was lost with the PTS unit. It is recommended to use only one preset so that pilot car drivers find it easy to continue their operation and to avoid the possibility of an incorrect selection of green time.

At Newton (US-50), all the three presets offered on the PTS handheld remote were used. Unfortunately, for unknown technical reasons the PTS unit did not function properly and resulted in unusual situations. On August 26, 2015 the green phase activated for only 35 seconds and continued into the yellow phase and the all-red phase for four cycles in continuation even though there were vehicles still present in the queue. During the same cycles, the PTS reverted back to the green interval after a few seconds causing driver confusion and improper traffic control. Fortunately, the presence of a flagger aided the scenario who took charge and stopped drivers appropriately at the STOP line. The importance of a flagger with a traffic control device was reiterated by such incidences where a flagger was able to resolve the situation. In the absence of a flagger, the situation might have resulted in vehicles entering the work zone without the pilot car and provided a potential threat to the crew members as well as fellow road users. The situation subsided after a few cycles and normal operations resumed after a few settings were reset on the main control box.

It was observed that a few times the green cycle time extended beyond the maximum value. The vendors were informed of this unusual incident with the system. According to them, it was believed to be a function of the gap time. For the first three Test Locations, the gap time was five seconds and if a vehicle arrived in the very last second of the maximum green interval then the PTS unit would allow for an additional five seconds and extend the green cycle. This sounded practical since the PTS unit at a work zone was responsible for mono-directional traffic unlike a traffic signal in a town or an urban environment. Thus, extending the green time in some way aided in reducing vehicular delay, and minimized the likelihood of RLR by the vehicle which triggered the time extension. Similar situations were observed when the gap time was set to 12 seconds on US-50 at Newton, KS. The maximum green times were observed to be 192 seconds and 252 seconds for green cycle length of 180 seconds and 240, seconds respectively.

It was also found from the video data that a total of 36 vehicles turned around and left the queue heading the opposite direction. Although there was no direct evidence to support this, but it was believed that the occurrence of such events was a function of: the wait time at a PTS or a flagger station and driver impatience. It is possible that these drivers took an alternate route parallel to the work zone and joined the mainline road a few miles downstream. These vehicles did not interfere with any of the work activity, and therefore, they were termed harmless but they provided an interesting perspective that suggested the driver's aversion to be halted by a traffic signal or by a flagger especially in a rural environment.

Like any engineered system, there are always things that can be done for improvement. Chapter 9 provides a few areas for future research that could help in improving the overall effectiveness of the system.

CHAPTER 9. FUTURE RESEARCH

The chapter discusses areas of future research that might supplement some of the recommendations made in the previous chapter and improve the overall guidelines available on the topic.

From the data collected, it was observed that a total of 44 vehicles over the entire data collection period did not comply with the PTS unit in the absence of a flagger due to the extended wait time. To mitigate with this issue of RLR due to excessive wait times, it was recommended to display the expected wait time with the help of an appropriate sign. This could be done in either of two ways. First, the contractor could install a portable dynamic changeable message sign that informed the drivers of the expected wait in real time. Also, these dynamic message signs could be synchronized with the PTS handheld remote control and an algorithm could be developed that provided the drivers with a more precise wait time. It could be effective in reducing the driver anxiety and minimize the urge to run the light due to extended wait times. It is KDOT policy that the long rural work zones in Kansas with pilot car operations avoid a pilot car round trip time more than 15 minutes. Thus, a second alternative to the dynamic message sign would be to install a static sign informing drivers of the total wait time. This would be a cheaper alternative and could be effective in reducing the noncompliance rates that occurred due to extended wait times. A scope for potential future research would be to conduct a study wherein noncompliance rates in presence of a static message sign or a dynamic changeable message sign could be compared with the noncompliance rates in their absence.

The volume thresholds designed and recommended in the research included all vehicle types i.e. passenger cars, trucks, buses, RV’s, and motorcycles. To determine the effects of the presence of a truck or a heavy vehicle in the queue, additional data need to be collected and additional analysis will need to be conducted in order to develop more in-depth equations and recommendations regarding signal timing operations.

Pilot car speeds were reduced close to the activity area by as much as 20 mph. The researcher was unable to accurately factor in the length of the activity area since it varied and no additional information regarding speed reduction and re-acceleration to the maximum speed were available. Additional research could be conducted to more precisely determine a speed reduction factor and incorporate it into the equation proposed in this research. Also, the turnaround times for the pilot car could be factored in the equation with the help of some additional data.

Additional research could also be conducted to determine the exact values of pilot car turnaround time and platoon clearance time and deduct them from the value of the maximum green interval obtained from the equations stated earlier.

Although it is unlikely that all the issues with the system can be addressed in a single research step, it will remain a worthy goal.

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APPENDIX A

Portable Traffic Signal (PTS) Specifications

Portable Traffic Signal (PTS)

Two ADDCO Galaxy PTS-2000, PTS systems were used for the research. Figure 61 shows the two PTS units used for the research.

Figure 61. Two PTS units used for the study.

As shown in Figure 61, each trailer had a bank of batteries with solar recharging, two signal heads, and an integrated radio with solid state signal control and scaling redundant conflict monitoring system[1]. The PTS system was easy to transport, setup, operate, and take down at the end of the day. Technical details regarding the PTS unit relevant to the study are listed in the subsequent section. Figure 62 shows a single, fully raised PTS unit.

[1] GALAXY Procurement Specification: *ADDCO Solar Portable Traffic Signal Trailer with Galaxy Operating System PTS-2000.* Rev. October 3, 2014.

Figure 62. A fully raised PTS unit.

Overall Dimensions

Deployment height: pavement to bottom of upper signal head = 17 feet

Deployment height: pavement to bottom of lower signal head = 10 feet

Height: PTS fully raised = 20 feet 4 inches to the top of the signal head.

Transport height: pavement to bottom of upper signal head = 9 feet 2 inches

Transport height: pavement to bottom of lower signal head = 7 feet 11 inches

Width: at the widest point = 8 feet 3 inches

Length: master trailer with hitch = 14 feet 5 inches

Length: remote trailer with hitch = 12 feet 9 inches

Length: in tandem tow configuration = 25 feet 4 inches

Gross weight = 3,780 lbs. to 3,940 lbs.

Signal Heads Specifications

Figure 63 shows the signal heads on a single PTS unit.

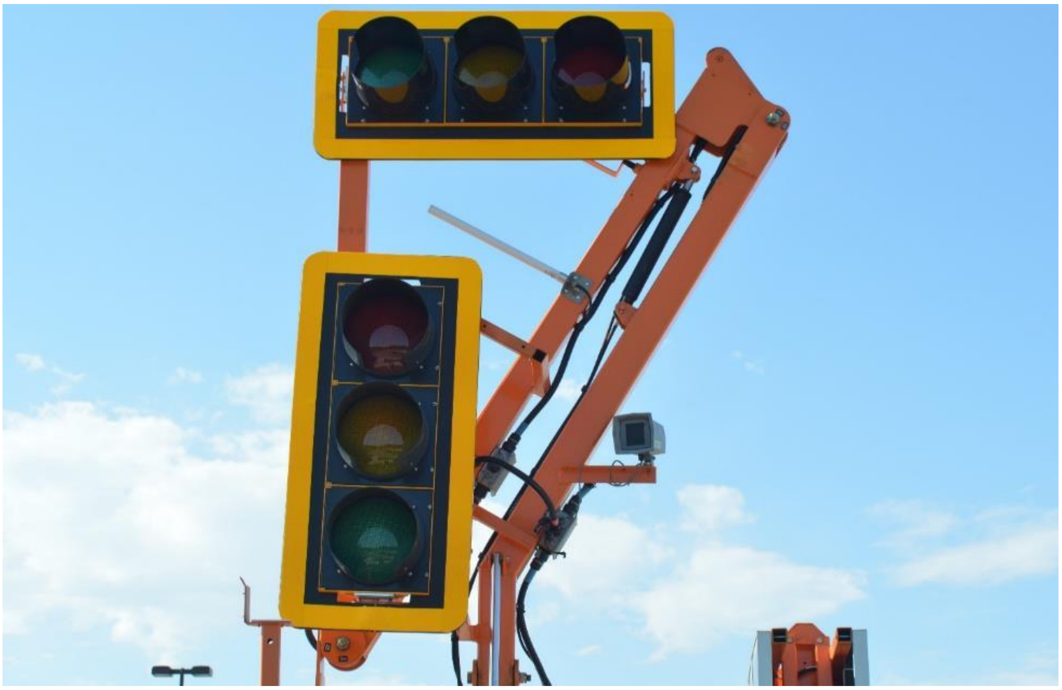

Figure 63. PTS signal heads.

1. Signal head LEDs were warranted for a 5-year life span.

2. Standard ITE approved polycarbonate 12 inch diameter signal heads.

3. There were two signal head assemblies per trailer standard. The outer signal head was a permanent mount. The second may be quickly mounted by the user either over the roadway or at the lower position on the mast (factory shipped position).

4. The signal heads had the ability to be rotated 180 degrees to face in the opposite direction with a simple lockable spring loaded release mechanism. In addition, many horizontal and vertical adjustment positions were available to provide optimum visibility to the drivers.

5. Both signal heads had the ability to rotate and lock in 10 degree increments to position the signal head for the optimum visibility to the drivers.

6. Optional: (a) Aluminum signal heads (b) Backing plates (c) Units capable of being transported and operated with backing plates.

7. A work zone safety light was located on the rear side of the upper signal head. Its function was to alert workers of the traffic signal light status. The work zone safety light illuminates when the traffic signal status is "red."

Batteries

Figure 64 shows the batteries provided in a single PTS unit.

Figure 64. Batteries provided. (Source: Procurement Specifications PTS-2000)

- Up to sixteen (16) 6 volt, 225 amp-hour deep cycle heavy duty batteries providing over 21 days continuous operation without solar array assist.
- Batteries are wired in a 12 VDC configuration.

Photo Voltaic Solar Array

Figure 65 shows the photo voltaic solar array on a single PTS unit.

- Up to six panels ranging from 80-95 watts power produced per panel.
- A tilt and rotate system increases solar collection efficiency by allowing the panels to be optimally set for exposure to the sun.
- An electro-mechanical system shall be included to raise and lower the solar panels into an optimum solar collection angle.

Figure 65. Tilt and rotate system for the solar panels.

Transmitter/Receiver Specifications

- Power Output: 10 mW -1 watt power output (up to 4 mile range)
- Frequency: ISM 902 - 928 MHz operating frequency
- Spread Spectrum: FHSS, frequency hopping spread spectrum
- Modulation: FSK frequency shift keying

Radio Remote Control

Figure 66 shows the handheld remote control used to operate the PTS unit.

Figure 66. PTS handheld remote control with external plug-in charger.

1. Electrical Specifications

   - External Power Supply Voltage: 10-18 VDC
   - Temperature: 30 degrees to 60 degrees C.

2. Operational Specifications

   - Activity time out: 5 minutes
   - Operating time on internal battery: minimum 10 hours
   - Distance from any unit: Up to 1/4 mile

Controls

Figure 67 shows the main control box on a single PTS unit.

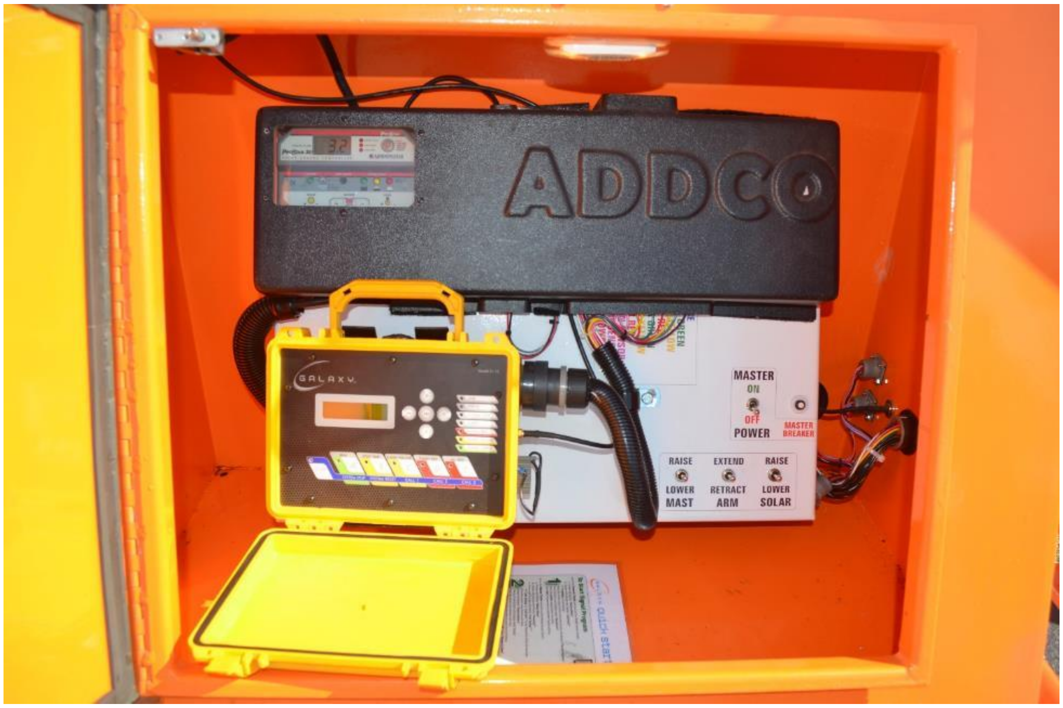

Figure 67. PTS control box.

As shown in Figure 67, all instrumentation was mounted in a large lockable, weatherproof NEMA 4 enclosure.

- Master power on-off switch,
- Raise/lower mast switch,
- Extend/retract signal arm switch,
- Battery voltmeter and cab light. The cab light was wired through the door switch to turn off when the control cab door was shut to conserve power, and
- Solar charge ammeter.

APPENDIX B

Survey of Practice

A survey of 19 different state DOTs was conducted during May and June 2014. The objective of the survey was to obtain an understanding of the practices followed in the various states regarding the use of PTS (referred to as temporary traffic signals in the survey), pilot car, and flagger operations. The survey was conducted via telephone or email depending on the preference of the state officials. The following section listed the questions used as a part of the survey followed by a summary of the survey responses for the various DOT's.

Q.1 Does the DOT use portable/ temporary traffic signals in any of its work zones?

(a) If yes, does the DOT have any existing guidelines for the use of PTS in work zones with or without flaggers or does it follow the MUTCD guidelines only?

(b) If yes, was there a website with this information, or could you please email me a copy of the guidance?

Q.2 Does the DOT currently use any pilot car operations in any of the work zones? If yes, then what kind of work activity was expected to make use of them? E.g. Overlay, bridge work, culvert replacement.

Q.3 What was the average length (or minimum and maximum length) of work zones that use pilot car operations and temporary traffic signals in the state?

Q.4 Does the DOT consider 'vehicle waiting time delays' when it comes to the use of these devices? Have there been any experiences when excessive delay had been found by the use of pilot car operations?

(a) Was there a threshold on the hourly volumes or queue lengths when using these devices?

Q.5 Was there a difference in guidance between the daytime and nighttime usage of pilot car or temporary traffic signal operations? What was the DOT's guidance for work on one-way work zone operations at night?

Arkansas DOT

The Arkansas DOT referred to the MUTCD guidelines and used the temporary traffic signals without flaggers in its work zones. The department used pilot car operation for bridge work and in long work zones of length greater than 1,000 feet and during daytime operations. The temporary traffic signals were deployed on short work sections when both ends of work zones were visible to each other and could be used during daytime and nighttime operations. Interestingly, the department suggested that temporary traffic signals should not be used for road sections with very high volumes.

Connecticut DOT

The Connecticut DOT referred to the MUTCD guidelines for the use of temporary traffic signals. The department never makes use of the pilot car operations for any of its work zones. The temporary traffic signals were used for work zones of length less than 300 feet and believes that it could be used in work zones of longer lengths. The department used hourly volumes as a measure to determine the applicability of these devices and believes that an hourly volume of 700-800 vehicles in both directions would result in excessive delays. The department generally adopted a temporary traffic signal for night time operations with flagger controlled work zones and STOP signs.

Florida DOT

The Florida DOT rarely used the temporary traffic signals in its work zones and referred to the MUTCD guidelines if needed. The department used pilot car operations (referred to as rolling road block operations in Florida) in some of its work zones. Pilot cars were used for not more than two to three hours in one day in any work zone. Temporary traffic signals, if used, would be adopted for longer durations. The department preferred using the pilot car operations at nighttime and in the non-peak hours due to lower traffic volumes.

Idaho DOT

The Idaho DOT referred to its own standard set of guidelines for the use of the temporary traffic signals in its work zones. The department makes use of pilot car operations mostly for chip seal operations and work zones involving culvert replacement. The maximum length of work zones for the use of pilot car operations or the temporary traffic signals was about five miles. The department had a threshold of 15 minutes for the wait time when using a pilot car operation or the temporary traffic signal. For example, the work would begin with a five mile long work zone and subsequent decrease in the length of the work zone, until work was completed, which reduced the wait time. The department adopted the use of temporary traffic signals on the one lane operations and preferred using it both day and nighttime. The department recommended the use of pilot car for daytime operations only.

Illinois DOT

The Illinois DOT referred to its own specifications for the use of temporary traffic signals and used the MUTCD as a supporting document. The department also does not adopt pilot car operations in any of its work zones. There was no maximum limit to the length of work zone that can make use of the temporary traffic signal, but in general the length varies from 250 feet to one-and-one-half miles. There was no threshold on the volumes that determine the use of the temporary traffic signal. The nine district offices made decisions pertaining to the use of the temporary traffic signal based on criteria such as: the number of lanes available, the effects of addition of a signal on the volumes, and anticipated green times. The closure lengths were a major factor and if longer closures lengths were planned, the department recommended splitting the work to avoid long closure lengths. On the other hand, the long work zones were retained if the work zone was expected to serve lower volumes. The department had no difference in guidance for daytime and nighttime operations. Also, they did not have a preference in terms of duration of work zone for the use of temporary traffic signals.

Indiana DOT

The temporary traffic signal was not approved by the state of Indiana. The department made use of pilot car operation with police participation on a few projects of high importance and occasionally for night time operations. The length of work zone for the pilot car operations varied from one-half mile to eight miles. The department considered a queue length of a one-and-one-half miles to be significant and queues longer than this length were unacceptable. The volume threshold for pilot car operations on Interstates with only one lane open for traffic was 1,400 cars per hour and closure of two-lanes simultaneously was discouraged for heavy volumes. The department adopts flagging for one lane closures on rural roads.

Iowa DOT

The Iowa DOT referred to its own developmental standards for the use of the temporary traffic signals. The department used a pilot car operation on two-lane work zones for temporary maintenance work activities such as resurfacing, patching, etc. but never with culvert replacement activities. Temporary traffic signals were deployed for short-term bridge work that were not very long in length. Temporary traffic signals and pilot car operations were used in work zones of length up to two and a half mile. The department had a threshold of 10 minutes for a driver wait time when using a pilot car operation. The department preferred using vehicular volumes as measure to determine the applicability of the traffic control device and not the vehicle waiting time delay. The department suggested shortening the length of work zones if excessive delays were anticipated. Pilot cars were used in the daytime and nighttime conditions though it was preferred to use the pilot cars only during the daytime operations. The department recommended appropriate lighting of the work zone for nighttime operations.

Kentucky Transportation Cabinet

The Kentucky DOT referred to its own standard drawings and the provisions of part four of the MUTCD for the application of temporary traffic signals. The department did not adopt the pilot cars in any of its work zones. Temporary traffic signals were used in work zones having a minimum length of 40 feet to a maximum of 180 feet. The department established a minimum of 500 feet of no passing zone before the work zone to ensure safety in the work zone. Temporary traffic signals were also used for nighttime operations. The department used a flagger on two-lane, two-way work zones only when the flaggers were visible to each other and located well in advance of the work zone. Illumination of flagger stations was recommended for nighttime operations.

Maryland DOT

The Maryland DOT used a temporary traffic signal very rarely in its work zones. Temporary traffic signal was used for two-lane, two-way bridge work usually 1,000 feet to 2,000 feet in length using the guidelines laid down by the Maryland MUTCD. Pilot car operations were never used in the state of Maryland and flaggers were usually deployed at work zones whenever necessary. The department advised the project managers to take appropriate measures if the queue lengths in work zones exceeded one mile in length. If necessary, flaggers were used for nighttime operations with appropriate lighting in the work zone.

Michigan DOT

The Michigan DOT referred to the MUTCD guidelines for the use of temporary traffic signals. The department used pilot cars in work zones for activities such as chip seal. According to the department, application of pilot cars and temporary traffic signals should not be done in work zones longer than two miles. Temporary traffic signals were used when both ends of the work zone were visible to each other. The department considered vehicle waiting time delays as a measure in determining the applicability of these devices. The department had a threshold of 15 minutes for the wait time when using a pilot car operation or a temporary traffic signal. The department used temporary traffic signals during night time operations and pilot cars during the day time operations.

Minnesota DOT

The Minnesota DOT used temporary traffic signals in its work zones with the MnDOT field manual and the MUTCD as references. The department also used pilot car operations in its work zones generally that were long in length. The use of pilot car operations was not entirely dependent on the length of the work zones, but on the existing ADT and the accesses at the site. Temporary traffic signals were used by the bridge crews for one-day operations and were independent of the length of the bridge.

Montana DOT

The Montana DOT referred to the MUTCD guidelines for the use of temporary traffic signals. The DOT also used pilot car operations in its work zones involving activities such as overlay, chip seal on two-lane rural highways and reconstruction projects. There was no recommended distance for the use of pilot cars or the temporary traffic signals, but a work zone length of two miles would generally deploy these two traffic control measures. The department considered vehicle waiting time delays when using either a pilot car or a temporary traffic signal and refrained from keeping the drivers waiting for more than ten minutes. There were cases of excessive delays caused during the pilot car operation, but they were not necessarily due to the pilot car operating in the work zone. The department did not prefer using a pilot car or a temporary traffic signal for nighttime operations and there was no special guidance for the work on one-way roads at night.

Nebraska DOT

The Nebraska DOT referred to the MUTCD guidelines when using a temporary traffic signal without the flaggers in its work zones. The department adopted a pilot car operation for general overlay work activity and a temporary traffic signal for culvert replacement work. Flagging was adopted in conjunction with pilot cars if the flaggers were able to see the ends of the work zone. Temporary traffic signals were never used in conjunction with the pilot car operation. The department had a threshold of 15 minutes for the wait time when using a pilot car operation. Temporary traffic signals were generally used in work zones of length less than 1,000 feet. The department gave critical importance to vehicle waiting time delay when adopting a pilot car operation or a temporary traffic signal. The work activity was generally divided into smaller sections for better phasing and reduction in delay times. The department used a temporary traffic signal for both daytime and nighttime operations and avoided the use of pilot car operations at night. The flagger stations were required to be properly illuminated if pilot car operations were to be adopted for nighttime work activity.

Nevada DOT

The Nevada DOT referred to the MUTCD for the use of a temporary traffic signal or PTS for repairs on bridges and also cases where permanent signals require repair. Pilot car operations were also used for overlay, bridge work and deck cleaning activities. The length of the work zones that made use of pilot car operations or temporary traffic signals varied from 0 to five miles. The department used a 20/30 rule which meant that a vehicle could be stopped for a maximum of 20 minutes per direction but could not be delayed for more than 30 minutes for the entire trip. The department used pilot car operations and temporary traffic signals for both daytime and nighttime work activities.

Ohio DOT

The Ohio DOT used the temporary traffic signals or PTS for two-lane one-way operations referring to its own set of standard drawings. The pilot car operations were never used in any work zones in Ohio. The department did not recommend any particular length for the use of a temporary traffic signal, but preferred using a traffic signal when ends of the work zone were visible to each other. The department used a temporary traffic signals for both the daytime and nighttime operations.

Oklahoma DOT

The Oklahoma DOT used temporary traffic signals mostly for bridge rehabilitation work and on short duration projects. The department used the MUTCD as a reference and developed guidelines and drawings for every project. At flagger operated work zones, the pilot car operations were used. The department preferred using a pilot car operation when the sight distance did not permit the use of other traffic control devices. There was no particular length for which the department recommended the use of pilot cars or temporary traffic signals and that the use of these devices relied on the sight distances and presence of vertical or horizontal curves. The department recommended the use of pilot car operations and temporary traffic signals for nighttime operations.

Tennessee DOT

The Tennessee DOT occasionally used the temporary traffic signals or PTS in its works zones. The department recommended the installation of a normal traffic signal if necessary and the use of a PTS would be entirely at the contractor’s discretion. Traffic signals were generally used for bridge maintenance and repair in the state with work zones varying in lengths from one mile to one-and-one-half miles and generally long-term projects. The department did not use pilot car operations in its work zones and may use them in case of emergency situations that needed to be addressed. The department considered queue length as an important factor when determining the use of traffic signals in its work zones and recommended inclusion of a buffer time in the cycle length to clear traffic for opposite lane. The department recommended installation of signs that suggest the expected wait times before the work zones. The goal would be to keep the wait times at a minimum but there was no specific amount of time that was recommended. Also, the traffic signals once installed were to be used for both daytime and nighttime operations.

Texas DOT

The Texas DOT used temporary traffic signals in its work zones referring to the guidelines from the TX-MUTCD and Texas Traffic Control Plans. The department used pilot car operations with flaggers for overlay, bridge work and culvert replacement. The pilot car operations usually were undertaken for safety concerns and did not necessarily have a fixed length of work zone where they would be used. On the other hand, temporary traffic signals would be used in work zones not longer than two miles. Radio connectivity was an important factor when using temporary traffic signals with the flaggers. The use of pilot cars in conjunction with temporary traffic signals did not require radio connectivity. The department considered vehicle waiting time delays and a five to ten minute wait period acceptable when using a temporary traffic signal. The department had never experienced excessive vehicle waiting time delays when using the pilot cars and any delays caused were believed to be because of driver error. For nighttime operations, pilot car operations and temporary traffic signals were generally not recommended by TXDOT. The temporary traffic signals in the entire state of Texas were actuated and worked without a pilot car. This was adopted so that the workforce could be used at a different location in the work zone. Temporary traffic signals had ten presets of different timings with one as a default program, one for the pilot car and the remaining eight being used as per the requirement when setting up a work zone. The green times for a temporary traffic signal were designed for speeds up to 25 mph. The department had used temporary traffic signals in both, rural and the urban areas with ADT's in the range of 2,500 to 3,000.

Wyoming DOT

The Wyoming DOT used temporary traffic signal in conjunction with pilot car operation in its work zones referring to the guidelines from the MUTCD. The department generally used the two traffic control measures in conjunction for one-lane two-way operations and when work was expected to last over several days. They used temporary traffic signals for work zones short in length or in situations where the travel time from one end to the other would be approximately 30 seconds. The department also used pilot car operations in conjunction with flagger operations for a few of its work zones. The department preferred using temporary traffic signals for nighttime operations.

APPENDIX C

Data for Delay Analysis

Table 26. Data for Delay Analysis 1

Hypothetical Delay		Existing Delay	
Arrival Time	**i^{th} Vehicle**	**Arrival Time**	**i^{th} Vehicle**
4:03:05 p.m.	0	4:04:31 p.m.	0
4:03:48 p.m.	1	4:05:14 p.m.	1
4:04:31 p.m.	2	4:05:57 p.m.	2
4:05:14 p.m.	3	4:06:40 p.m.	3
4:05:57 p.m.	4	4:07:23 p.m.	4
4:06:40 p.m.	5	4:08:06 p.m.	5
4:07:23 p.m.	6	4:08:49 p.m.	6
4:08:06 p.m.	7	4:09:32 p.m.	7
4:08:49 p.m.	8	4:10:15 p.m.	8
4:09:32 p.m.	9	4:10:58 p.m.	9
4:10:15 p.m.	10	4:11:41 p.m.	10
4:10:58 p.m.	11	4:12:24 p.m.	11
4:11:41 p.m.	12	4:13:07 p.m.	12
4:12:24 p.m.	13	4:13:50 p.m.	13
4:13:07 p.m.	14	4:14:33 p.m.	14
4:13:50 p.m.	15	4:15:16 p.m.	15
4:14:33 p.m.	16	4:16:16 p.m.	0
4:15:16 p.m.	17		
4:16:24 p.m.	0		

Table 27. Data for Delay Analysis 2

Hypothetical Delay		Existing Delay	
Arrival Time	**i^{th} Vehicle**	**Arrival Time**	**i^{th} Vehicle**
2:04:57 p.m.	0	2:07:29 p.m.	0
2:06:13 p.m.	1	2:08:45 p.m.	1
2:07:29 p.m.	2	2:10:01 p.m.	2
2:08:45 p.m.	3	2:11:17 p.m.	3
2:10:01 p.m.	4	2:12:33 p.m.	4
2:11:17 p.m.	5	2:13:49 p.m.	5
2:12:33 p.m.	6	2:15:05 p.m.	6
2:13:49 p.m.	7	2:16:21 p.m.	7
2:15:05 p.m.	8	2:17:37 p.m.	8
2:16:21 p.m.	9	2:18:13 p.m.	0
2:17:37 p.m.	10		
2:18:22 p.m.	0		

Table 28. Data for Delay Analysis 3

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
12:35:20 p.m.	0	12:37:32 p.m.	0
12:36:26 p.m.	1	12:38:38 p.m.	1
12:37:32 p.m.	2	12:39:44 p.m.	2
12:38:38 p.m.	3	12:40:50 p.m.	3
12:39:44 p.m.	4	12:41:56 p.m.	4
12:40:50 p.m.	5	12:43:02 p.m.	5
12:41:56 p.m.	6	12:44:08 p.m.	6
12:43:02 p.m.	7	12:45:14 p.m.	7
12:44:08 p.m.	8	12:46:20 p.m.	8
12:45:14 p.m.	9	12:47:25 p.m.	0
12:46:20 p.m.	10		
12:47:41 p.m.	0		

Table 29. Data for Delay Analysis 4

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
3:41:54 p.m.	0	3:45:24 p.m.	0
3:43:04 p.m.	1	3:46:34 p.m.	1
3:44:14 p.m.	2	3:47:44 p.m.	2
3:45:24 p.m.	3	3:48:54 p.m.	3
3:46:34 p.m.	4	3:50:04 p.m.	4
3:47:44 p.m.	5	3:51:14 p.m.	5
3:48:54 p.m.	6	3:52:24 p.m.	6
3:50:04 p.m.	7	3:53:34 p.m.	7
3:51:14 p.m.	8	3:54:44 p.m.	8
3:52:24 p.m.	9	3:55:54 p.m.	9
3:53:34 p.m.	10	3:57:04 p.m.	10
3:54:44 p.m.	11	3:58:14 p.m.	11
3:55:54 p.m.	12	3:59:24 p.m.	12
3:57:04 p.m.	13	4:00:34 p.m.	13
3:58:14 p.m.	14	4:01:44 p.m.	14
3:59:24 p.m.	15	4:02:54 p.m.	15
4:00:34 p.m.	16	4:04:04 p.m.	16
4:01:44 p.m.	17	4:05:14 p.m.	17
4:02:54 p.m.	18	4:06:24 p.m.	18
4:04:04 p.m.	19	4:07:34 p.m.	19
4:05:14 p.m.	20	4:08:34 p.m.	0
4:06:24 p.m.	21		
4:07:34 p.m.	22		
4:08:43 p.m.	0		

Table 30. Data for Delay Analysis 5

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
4:08:41 p.m.	0	4:13:20 p.m.	0
4:10:38 p.m.	1	4:15:41 p.m.	1
4:12:35 p.m.	2	4:18:02 p.m.	2
4:14:32 p.m.	3	4:20:23 p.m.	3
4:16:29 p.m.	4	4:21:11 p.m.	0
4:18:26 p.m.	5		
4:20:23 p.m.	6		
4:21:59 p.m.	0		

Table 31. Data for Delay Analysis 6

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
11:58:52 a.m.	0	11:59:49 a.m.	0
11:59:49 a.m.	1	12:00:46 p.m.	1
12:00:46 p.m.	2	12:01:43 p.m.	2
12:01:43 p.m.	3	12:02:40 p.m.	3
12:02:40 p.m.	4	12:03:37 p.m.	4
12:03:37 p.m.	5	12:04:34 p.m.	5
12:04:34 p.m.	6	12:05:31 p.m.	6
12:05:31 p.m.	7	12:06:28 p.m.	7
12:06:28 p.m.	8	12:07:25 p.m.	8
12:07:25 p.m.	9	12:08:22 p.m.	9
12:08:22 p.m.	10	12:09:19 p.m.	10
12:09:19 p.m.	11	12:10:16 p.m.	11
12:10:16 p.m.	12	12:11:13 p.m.	12
12:11:13 p.m.	13	12:12:00 p.m.	0
12:12:04 p.m.	0		

Table 32. Data for Delay Analysis 7

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
1:35:29 p.m.	0	1:36:55 p.m.	0
1:36:55 p.m.	1	1:38:21 p.m.	1
1:38:21 p.m.	2	1:39:47 p.m.	2
1:39:47 p.m.	3	1:41:13 p.m.	3
1:41:13 p.m.	4	1:42:39 p.m.	4
1:42:39 p.m.	5	1:44:05 p.m.	5
1:44:05 p.m.	6	1:45:31 p.m.	6
1:45:31 p.m.	7	1:46:08 p.m.	0
1:46:14 p.m.	0		

Table 33. Data for Delay Analysis 8

Hypothetical Delay		Existing Delay	
Arrival time	i^{th} Vehicle	Arrival time	i^{th} Vehicle
2:31:56 p.m.	0	2:35:23 p.m.	0
2:33:05 p.m.	1	2:36:32 p.m.	1
2:34:14 p.m.	2	2:37:41 p.m.	2
2:35:23 p.m.	3	2:38:50 p.m.	3
2:36:32 p.m.	4	2:39:59 p.m.	4
2:37:41 p.m.	5	2:41:08 p.m.	5
2:38:50 p.m.	6	2:42:17 p.m.	6
2:39:59 p.m.	7	2:43:26 p.m.	7
2:41:08 p.m.	8	2:44:35 p.m.	8
2:42:17 p.m.	9	2:45:13 p.m.	0
2:43:26 p.m.	10		
2:44:35 p.m.	11		
2:45:27 p.m.	0		

Table 34. Data for Delay Analysis 9

Hypothetical Delay		Existing Delay	
Arrival time	i^{th} Vehicle	Arrival time	i^{th} Vehicle
2:57:35 p.m.	0	3:07:19 p.m.	0
3:00:01 p.m.	1	3:09:45 p.m.	1
3:02:27 p.m.	2	3:10:15 p.m.	0
3:04:53 p.m.	3		
3:07:19 p.m.	4		
3:09:45 p.m.	5		
3:12:15 p.m.	0		

Table 35. Data for Delay Analysis 10

Hypothetical Delay		Existing Delay	
Arrival time	i^{th} Vehicle	Arrival time	i^{th} Vehicle
11:32:13 a.m.	0	11:38:58 a.m.	0
11:33:34 a.m.	1	11:40:19 a.m.	1
11:34:55 a.m.	2	11:41:40 a.m.	2
11:36:16 a.m.	3	11:43:01 a.m.	3
11:37:37 a.m.	4	11:44:22 a.m.	4
11:38:58 a.m.	5	11:44:52 a.m.	0
11:40:19 a.m.	6		
11:41:40 a.m.	7		
11:43:01 a.m.	8		
11:44:22 a.m.	9		
11:45:30 a.m.	0		

Table 36. Data for Delay Analysis 11

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
11:52:42 a.m.	0	11:56:42 a.m.	0
11:53:30 a.m.	1	11:57:30 a.m.	1
11:54:18 a.m.	2	11:58:18 a.m.	2
11:55:06 a.m.	3	11:59:06 a.m.	3
11:55:54 a.m.	4	11:59:54 a.m.	4
11:56:42 a.m.	5	12:00:42 p.m.	5
11:57:30 a.m.	6	12:01:30 p.m.	6
11:58:18 a.m.	7	12:02:18 p.m.	7
11:59:06 a.m.	8	12:03:06 p.m.	8
11:59:54 a.m.	9	12:03:54 p.m.	9
12:00:42 p.m.	10	12:04:42 p.m.	10
12:01:30 p.m.	11	12:05:30 p.m.	11
12:02:18 p.m.	12	12:06:35 p.m.	0
12:03:06 p.m.	13		
12:03:54 p.m.	14		
12:04:42 p.m.	15		
12:05:30 p.m.	16		
12:07:04 p.m.	0		

Table 37. Data for Delay Analysis 12

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
10:23:31 a.m.	0	10:28:25 a.m.	0
10:24:20 a.m.	1	10:29:14 a.m.	1
10:25:09 a.m.	2	10:30:03 a.m.	2
10:25:58 a.m.	3	10:30:52 a.m.	3
10:26:47 a.m.	4	10:31:41 a.m.	4
10:27:36 a.m.	5	10:32:30 a.m.	5
10:28:25 a.m.	6	10:33:19 a.m.	6
10:29:14 a.m.	7	10:34:08 a.m.	7
10:30:03 a.m.	8	10:34:57 a.m.	8
10:30:52 a.m.	9	10:35:46 a.m.	9
10:31:41 a.m.	10	10:36:51 a.m.	0
10:32:30 a.m.	11		
10:33:19 a.m.	12		
10:34:08 a.m.	13		
10:34:57 a.m.	14		
10:35:46 a.m.	15		
10:37:34 a.m.	0		

Table 38. Data for Delay Analysis 13

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
12:54:10 p.m.	0	12:57:46 p.m.	0
12:55:04 p.m.	1	12:58:40 p.m.	1
12:55:58 p.m.	2	12:59:34 p.m.	2
12:56:52 p.m.	3	1:00:28 p.m.	3
12:57:46 p.m.	4	1:01:22 p.m.	4
12:58:40 p.m.	5	1:02:16 p.m.	5
12:59:34 p.m.	6	1:03:10 p.m.	6
1:00:28 p.m.	7	1:04:04 p.m.	7
1:01:22 p.m.	8	1:04:58 p.m.	8
1:02:16 p.m.	9	1:05:52 p.m.	9
1:03:10 p.m.	10	1:06:43 p.m.	0
1:04:04 p.m.	11		
1:04:58 p.m.	12		
1:05:52 p.m.	13		
1:07:06 p.m.	0		

Table 39. Data for Delay Analysis 14

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
3:35:04 p.m.	0	3:43:05 p.m.	0
3:35:41 p.m.	1	3:43:42 p.m.	1
3:36:18 p.m.	2	3:44:19 p.m.	2
3:36:55 p.m.	3	3:44:56 p.m.	3
3:37:32 p.m.	4	3:45:33 p.m.	4
3:38:09 p.m.	5	3:46:10 p.m.	5
3:38:46 p.m.	6	3:46:47 p.m.	6
3:39:23 p.m.	7	3:47:24 p.m.	7
3:40:00 p.m.	8	3:48:01 p.m.	8
3:40:37 p.m.	9	3:48:38 p.m.	9
3:41:14 p.m.	10	3:49:15 p.m.	10
3:41:51 p.m.	11	3:50:15 p.m.	0
3:42:28 p.m.	12		
3:43:05 p.m.	13		
3:43:42 p.m.	14		
3:44:19 p.m.	15		
3:44:56 p.m.	16		
3:45:33 p.m.	17		
3:46:10 p.m.	18		
3:46:47 p.m.	19		
3:47:24 p.m.	20		
3:48:01 p.m.	21		
3:48:38 p.m.	22		

3:49:15 p.m.	23
3:51:33 p.m.	0

Table 40. Data for Delay Analysis 15

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
11:39:30 a.m.	0	11:40:38 a.m.	0
11:40:04 a.m.	1	11:41:12 a.m.	1
11:40:38 a.m.	2	11:41:46 a.m.	2
11:41:12 a.m.	3	11:42:20 a.m.	3
11:41:46 a.m.	4	11:42:54 a.m.	4
11:42:20 a.m.	5	11:43:28 a.m.	5
11:42:54 a.m.	6	11:44:02 a.m.	6
11:43:28 a.m.	7	11:44:36 a.m.	7
11:44:02 a.m.	8	11:45:10 a.m.	8
11:44:36 a.m.	9	11:45:44 a.m.	9
11:45:10 a.m.	10	11:46:18 a.m.	10
11:45:44 a.m.	11	11:46:52 a.m.	11
11:46:18 a.m.	12	11:47:26 a.m.	12
11:46:52 a.m.	13	11:48:00 a.m.	13
11:47:26 a.m.	14	11:48:34 a.m.	14
11:48:00 a.m.	15	11:49:08 a.m.	15
11:48:34 a.m.	16	11:49:42 a.m.	16
11:49:08 a.m.	17	11:50:16 a.m.	17
11:49:42 a.m.	18	11:50:50 a.m.	18
11:50:16 a.m.	19	11:51:24 a.m.	19
11:50:50 a.m.	20	11:52:29 a.m.	0
11:51:24 a.m.	21		
11:52:36 a.m.	0		

Table 41. Data for Delay Analysis 16

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
1:41:22 p.m.	0	1:42:20 p.m.	0
1:42:20 p.m.	1	1:43:18 p.m.	1
1:43:18 p.m.	2	1:44:16 p.m.	2
1:44:16 p.m.	3	1:45:14 p.m.	3
1:45:14 p.m.	4	1:46:12 p.m.	4
1:46:12 p.m.	5	1:47:10 p.m.	5
1:47:10 p.m.	6	1:48:08 p.m.	6
1:48:08 p.m.	7	1:49:06 p.m.	7
1:49:06 p.m.	8	1:50:04 p.m.	8
1:50:04 p.m.	9	1:51:02 p.m.	9
1:51:02 p.m.	10	1:52:00 p.m.	10
1:52:00 p.m.	11	1:52:53 p.m.	0
1:52:58 p.m.	0		

Table 42. Data for Delay Analysis 17

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
2:04:17 p.m.	0	2:05:32 p.m.	0
2:05:32 p.m.	1	2:06:47 p.m.	1
2:06:47 p.m.	2	2:08:02 p.m.	2
2:08:02 p.m.	3	2:09:17 p.m.	3
2:09:17 p.m.	4	2:10:32 p.m.	4
2:10:32 p.m.	5	2:11:47 p.m.	5
2:11:47 p.m.	6	2:13:02 p.m.	6
2:13:02 p.m.	7	2:14:17 p.m.	7
2:14:17 p.m.	8	2:14:51 p.m.	0
2:14:57 p.m.	0		

Table 43. Data for Delay Analysis 18

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
11:26:17 a.m.	0	11:27:13 a.m.	0
11:27:13 a.m.	1	11:28:09 a.m.	1
11:28:09 a.m.	2	11:29:05 a.m.	2
11:29:05 a.m.	3	11:30:01 a.m.	3
11:30:01 a.m.	4	11:30:57 a.m.	4
11:30:57 a.m.	5	11:31:53 a.m.	5
11:31:53 a.m.	6	11:32:49 a.m.	6
11:32:49 a.m.	7	11:33:45 a.m.	7
11:33:45 a.m.	8	11:34:41 a.m.	8
11:34:41 a.m.	9	11:35:37 a.m.	9
11:35:37 a.m.	10	11:36:33 a.m.	10
11:36:33 a.m.	11	11:37:29 a.m.	11
11:37:29 a.m.	12	11:38:25 a.m.	12
11:38:25 a.m.	13	11:39:25 a.m.	0
11:39:30 a.m.	0		

Table 44. Data for Delay Analysis 19

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
4:03:13 p.m.	0	4:04:02 p.m.	0
4:04:02 p.m.	1	4:04:51 p.m.	1
4:04:51 p.m.	2	4:05:40 p.m.	2
4:05:40 p.m.	3	4:06:29 p.m.	3
4:06:29 p.m.	4	4:07:18 p.m.	4
4:07:18 p.m.	5	4:08:07 p.m.	5
4:08:07 p.m.	6	4:08:56 p.m.	6
4:08:56 p.m.	7	4:09:45 p.m.	7
4:09:45 p.m.	8	4:10:34 p.m.	8
4:10:34 p.m.	9	4:11:23 p.m.	9
4:11:23 p.m.	10	4:12:12 p.m.	10
4:12:12 p.m.	11	4:13:01 p.m.	11
4:13:01 p.m.	12	4:13:50 p.m.	12
4:13:50 p.m.	13	4:14:39 p.m.	13
4:14:39 p.m.	14	4:15:29 p.m.	0
4:15:33 p.m.	0		

Table 45. Data for Delay Analysis 20

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
4:15:32 p.m.	0	4:17:02 p.m.	0
4:17:02 p.m.	1	4:18:32 p.m.	1
4:18:32 p.m.	2	4:20:02 p.m.	2
4:20:02 p.m.	3	4:21:32 p.m.	3
4:21:32 p.m.	4	4:23:02 p.m.	4
4:23:02 p.m.	5	4:24:32 p.m.	5
4:24:32 p.m.	6	4:26:02 p.m.	6
4:26:02 p.m.	7	4:27:32 p.m.	7
4:27:32 p.m.	8	4:28:15 p.m.	0
4:28:21 p.m.	0		

Table 46. Data for Delay Analysis 21

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
10:27:08 a.m.	0	10:32:08 a.m.	0
10:28:23 a.m.	1	10:33:23 a.m.	1
10:29:38 a.m.	2	10:34:38 a.m.	2
10:30:53 a.m.	3	10:35:53 a.m.	3
10:32:08 a.m.	4	10:37:08 a.m.	4
10:33:23 a.m.	5	10:38:23 a.m.	5
10:34:38 a.m.	6	10:39:38 a.m.	6
10:35:53 a.m.	7	10:40:16 a.m.	0
10:37:08 a.m.	8		
10:38:23 a.m.	9		
10:39:38 a.m.	10		
10:40:41 a.m.	0		

Table 47. Data for Delay Analysis 22

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
12:59:02 p.m.	0	1:02:32 p.m.	0
12:59:44 p.m.	1	1:03:14 p.m.	1
1:00:26 p.m.	2	1:03:56 p.m.	2
1:01:08 p.m.	3	1:04:38 p.m.	3
1:01:50 p.m.	4	1:05:20 p.m.	4
1:02:32 p.m.	5	1:06:02 p.m.	5
1:03:14 p.m.	6	1:06:44 p.m.	6
1:03:56 p.m.	7	1:07:26 p.m.	7
1:04:38 p.m.	8	1:08:08 p.m.	8
1:05:20 p.m.	9	1:08:50 p.m.	9
1:06:02 p.m.	10	1:09:32 p.m.	10
1:06:44 p.m.	11	1:10:14 p.m.	11
1:07:26 p.m.	12	1:10:56 p.m.	12
1:08:08 p.m.	13	1:11:38 p.m.	13
1:08:50 p.m.	14	1:12:38 p.m.	0
1:09:32 p.m.	15		
1:10:14 p.m.	16		
1:10:56 p.m.	17		
1:11:38 p.m.	18		
1:13:01 p.m.	0		

Table 48. Data for Delay Analysis 23

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
12:17:28 p.m.	0	12:18:18 p.m.	0
12:18:18 p.m.	1	12:19:08 p.m.	1
12:19:08 p.m.	2	12:19:58 p.m.	2
12:19:58 p.m.	3	12:20:48 p.m.	3
12:20:48 p.m.	4	12:21:38 p.m.	4
12:21:38 p.m.	5	12:22:28 p.m.	5
12:22:28 p.m.	6	12:23:18 p.m.	6
12:23:18 p.m.	7	12:24:08 p.m.	7
12:24:08 p.m.	8	12:24:58 p.m.	8
12:24:58 p.m.	9	12:25:48 p.m.	9
12:25:48 p.m.	10	12:26:38 p.m.	10
12:26:38 p.m.	11	12:27:28 p.m.	11
12:27:28 p.m.	12	12:28:18 p.m.	12
12:28:18 p.m.	13	12:29:08 p.m.	13
12:29:08 p.m.	14	12:29:58 p.m.	14
12:29:58 p.m.	15	12:31:03 p.m.	0
12:31:08 p.m.	0		

Table 49. Data for Delay Analysis 24

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
2:24:59 p.m.	0	2:29:14 p.m.	0
2:26:24 p.m.	1	2:30:39 p.m.	1
2:27:49 p.m.	2	2:32:04 p.m.	2
2:29:14 p.m.	3	2:33:29 p.m.	3
2:30:39 p.m.	4	2:34:54 p.m.	4
2:32:04 p.m.	5	2:36:19 p.m.	5
2:33:29 p.m.	6	2:37:44 p.m.	6
2:34:54 p.m.	7	2:38:14 p.m.	0
2:36:19 p.m.	8		
2:37:44 p.m.	9		
2:38:29 p.m.	0		

Table 50. Data for Delay Analysis 25

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
3:25:14 p.m.	0	3:27:50 p.m.	0
3:27:50 p.m.	1	3:30:26 p.m.	1
3:30:26 p.m.	2	3:33:02 p.m.	2
3:33:02 p.m.	3	3:35:38 p.m.	3
3:35:38 p.m.	4	3:38:14 p.m.	4
3:38:14 p.m.	5	3:38:44 p.m.	0
3:38:52 p.m.	0		

Table 51. Data for Delay Analysis 26

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
3:38:48 p.m.	0	3:39:58 p.m.	0
3:39:58 p.m.	1	3:41:08 p.m.	1
3:41:08 p.m.	2	3:42:18 p.m.	2
3:42:18 p.m.	3	3:43:28 p.m.	3
3:43:28 p.m.	4	3:44:38 p.m.	4
3:44:38 p.m.	5	3:45:48 p.m.	5
3:45:48 p.m.	6	3:46:58 p.m.	6
3:46:58 p.m.	7	3:48:08 p.m.	7
3:48:08 p.m.	8	3:49:18 p.m.	8
3:49:18 p.m.	9	3:50:28 p.m.	9
3:50:28 p.m.	10	3:51:05 p.m.	0
3:51:09 p.m.	0		

Table 52. Data for Delay Analysis 27

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
11:40:22 a.m.	0	11:42:16 a.m.	0
11:42:16 a.m.	1	11:44:10 a.m.	1
11:44:10 a.m.	2	11:46:04 a.m.	2
11:46:04 a.m.	3	11:47:58 a.m.	3
11:47:58 a.m.	4	11:49:52 a.m.	4
11:49:52 a.m.	5	11:51:46 a.m.	5
11:51:46 a.m.	6	11:53:40 a.m.	6
11:53:40 a.m.	7	11:54:10 a.m.	0
11:54:15 a.m.	0		

Table 53. Data for Delay Analysis 28

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
1:37:53 p.m.	0	1:38:25 p.m.	0
1:38:25 p.m.	1	1:38:57 p.m.	1
1:38:57 p.m.	2	1:39:29 p.m.	2
1:39:29 p.m.	3	1:40:01 p.m.	3
1:40:01 p.m.	4	1:40:33 p.m.	4
1:40:33 p.m.	5	1:41:05 p.m.	5
1:41:05 p.m.	6	1:41:37 p.m.	6
1:41:37 p.m.	7	1:42:09 p.m.	7
1:42:09 p.m.	8	1:42:41 p.m.	8
1:42:41 p.m.	9	1:43:13 p.m.	9
1:43:13 p.m.	10	1:43:45 p.m.	10
1:43:45 p.m.	11	1:44:17 p.m.	11
1:44:17 p.m.	12	1:44:49 p.m.	12
1:44:49 p.m.	13	1:45:21 p.m.	13
1:45:21 p.m.	14	1:45:53 p.m.	14
1:45:53 p.m.	15	1:46:25 p.m.	15
1:46:25 p.m.	16	1:46:57 p.m.	16
1:46:57 p.m.	17	1:47:29 p.m.	17
1:47:29 p.m.	18	1:48:01 p.m.	18
1:48:01 p.m.	19	1:48:33 p.m.	19
1:48:33 p.m.	20	1:49:05 p.m.	20
1:49:05 p.m.	21	1:49:37 p.m.	21
1:49:37 p.m.	22	1:50:09 p.m.	22
1:50:09 p.m.	23	1:50:41 p.m.	23
1:50:41 p.m.	24	1:51:13 p.m.	24
1:51:13 p.m.	25	1:53:10 p.m.	0
1:53:15 p.m.	0		

Table 54. Data for Delay Analysis 29

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
11:42:39 a.m.	0	11:42:59 a.m.	0
11:42:59 a.m.	1	11:43:19 a.m.	1
11:43:19 a.m.	2	11:43:39 a.m.	2
11:43:39 a.m.	3	11:43:59 a.m.	3
11:43:59 a.m.	4	11:44:19 a.m.	4
11:44:19 a.m.	5	11:44:39 a.m.	5
11:44:39 a.m.	6	11:44:59 a.m.	6
11:44:59 a.m.	7	11:45:19 a.m.	7
11:45:19 a.m.	8	11:45:39 a.m.	8
11:45:39 a.m.	9	11:45:59 a.m.	9
11:45:59 a.m.	10	11:46:19 a.m.	10
11:46:19 a.m.	11	11:46:39 a.m.	11
11:46:39 a.m.	12	11:46:59 a.m.	12
11:46:59 a.m.	13	11:47:19 a.m.	13
11:47:19 a.m.	14	11:47:39 a.m.	14
11:47:39 a.m.	15	11:47:59 a.m.	15
11:47:59 a.m.	16	11:48:19 a.m.	16
11:48:19 a.m.	17	11:48:39 a.m.	17
11:48:39 a.m.	18	11:48:59 a.m.	18
11:48:59 a.m.	19	11:49:19 a.m.	19
11:49:19 a.m.	20	11:49:39 a.m.	20
11:49:39 a.m.	21	11:49:59 a.m.	21
11:49:59 a.m.	22	11:50:19 a.m.	22
11:50:19 a.m.	23	11:52:12 a.m.	0
11:52:21 a.m.	0		

Table 55. Data for Delay Analysis 30

Hypothetical Delay		Existing Delay	
Arrival time	**i^{th} Vehicle**	**Arrival time**	**i^{th} Vehicle**
12:16:07 p.m.	0	12:16:25 p.m.	0
12:16:25 p.m.	1	12:16:43 p.m.	1
12:16:43 p.m.	2	12:17:01 p.m.	2
12:17:01 p.m.	3	12:17:19 p.m.	3
12:17:19 p.m.	4	12:17:37 p.m.	4
12:17:37 p.m.	5	12:17:55 p.m.	5
12:17:55 p.m.	6	12:18:13 p.m.	6
12:18:13 p.m.	7	12:18:31 p.m.	7
12:18:31 p.m.	8	12:18:49 p.m.	8
12:18:49 p.m.	9	12:19:07 p.m.	9
12:19:07 p.m.	10	12:19:25 p.m.	10
12:19:25 p.m.	11	12:19:43 p.m.	11
12:19:43 p.m.	12	12:20:01 p.m.	12
12:20:01 p.m.	13	12:20:19 p.m.	13
12:20:19 p.m.	14	12:20:37 p.m.	14
12:20:37 p.m.	15	12:20:55 p.m.	15
12:20:55 p.m.	16	12:21:13 p.m.	16
12:21:13 p.m.	17	12:21:31 p.m.	17
12:21:31 p.m.	18	12:21:49 p.m.	18
12:21:49 p.m.	19	12:22:07 p.m.	19
12:22:07 p.m.	20	12:22:25 p.m.	20
12:22:25 p.m.	21	12:22:43 p.m.	21
12:22:43 p.m.	22	12:23:01 p.m.	22
12:23:01 p.m.	23	12:23:19 p.m.	23
12:23:19 p.m.	24	12:23:37 p.m.	24
12:23:37 p.m.	25	12:23:55 p.m.	25
12:23:55 p.m.	26	12:24:13 p.m.	26
12:24:13 p.m.	27	12:24:31 p.m.	27
12:24:31 p.m.	28	12:24:49 p.m.	28
12:24:49 p.m.	29	12:25:07 p.m.	29
12:25:07 p.m.	30	12:28:12 p.m.	0
12:28:18 p.m.	0		

APPENDIX D

Charts for Delay Analysis

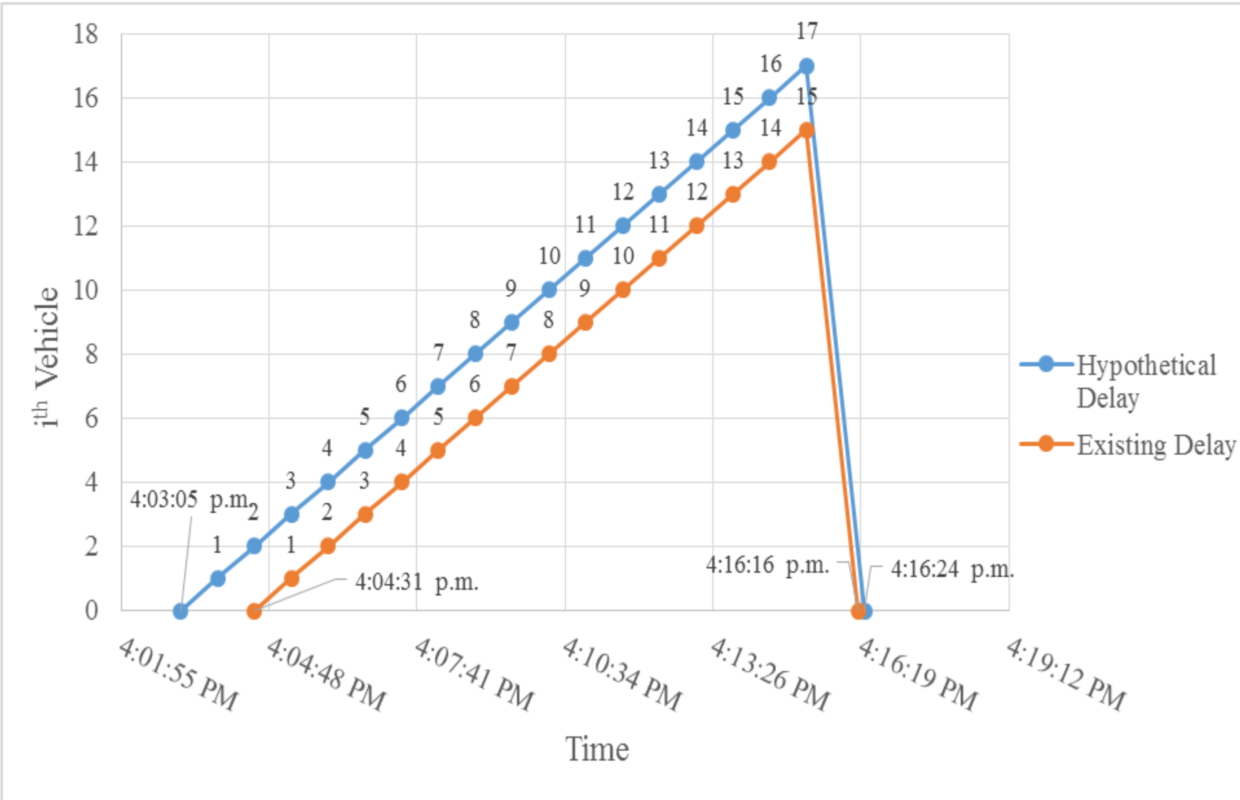

Figure 68. Delay analysis 1.

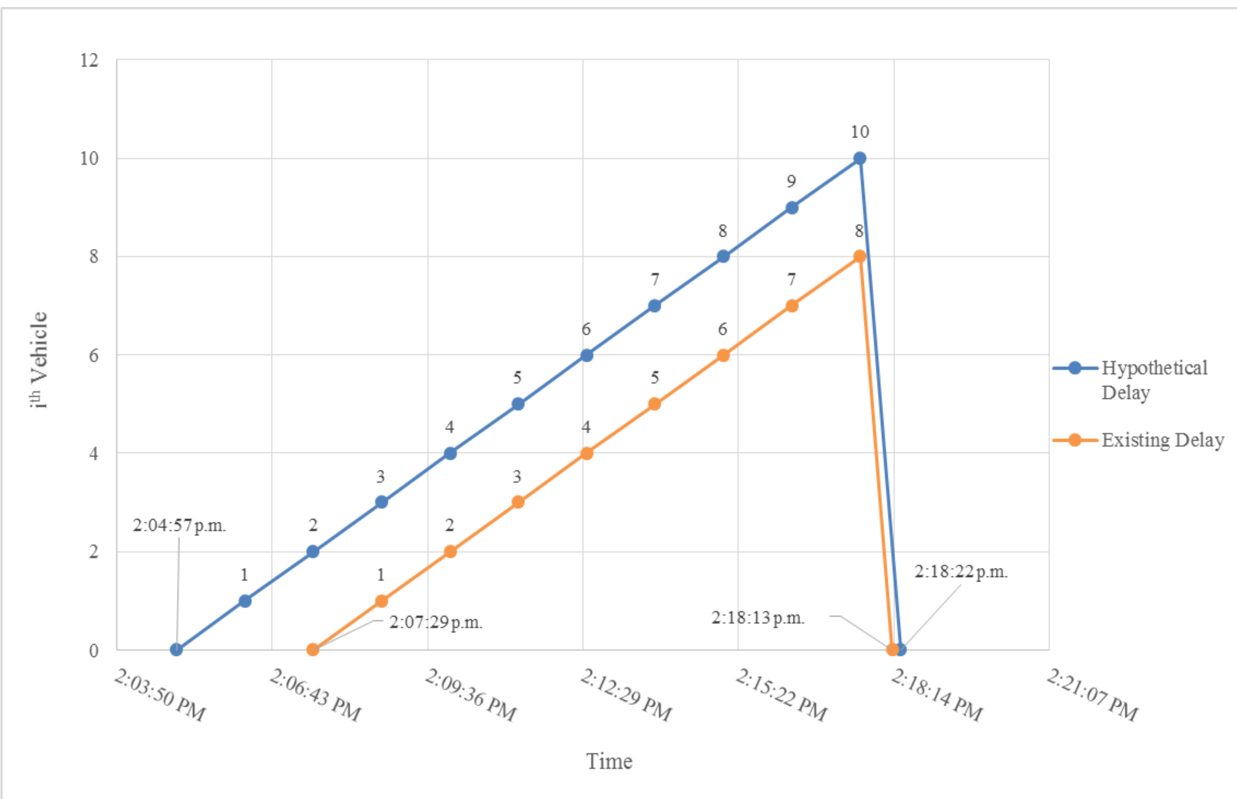

Figure 69. Delay analysis 2.

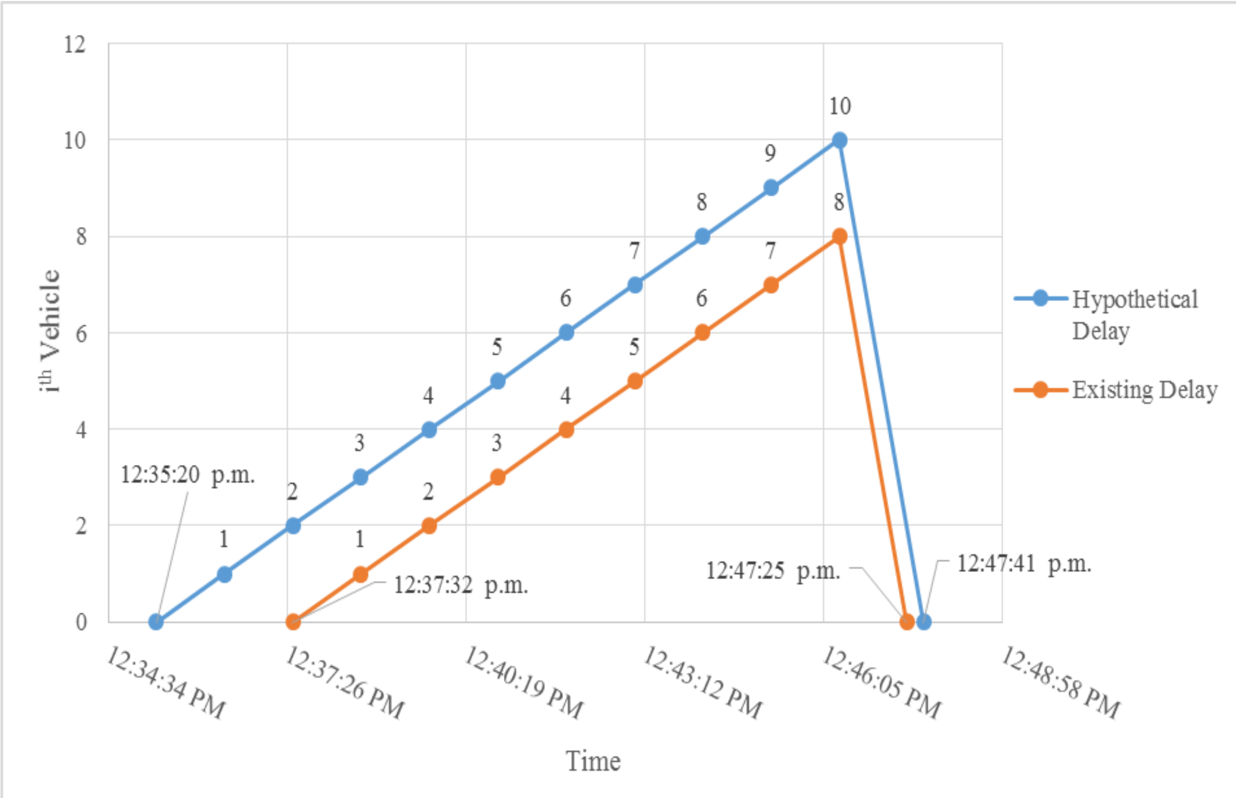

Figure 70. Delay analysis 3.

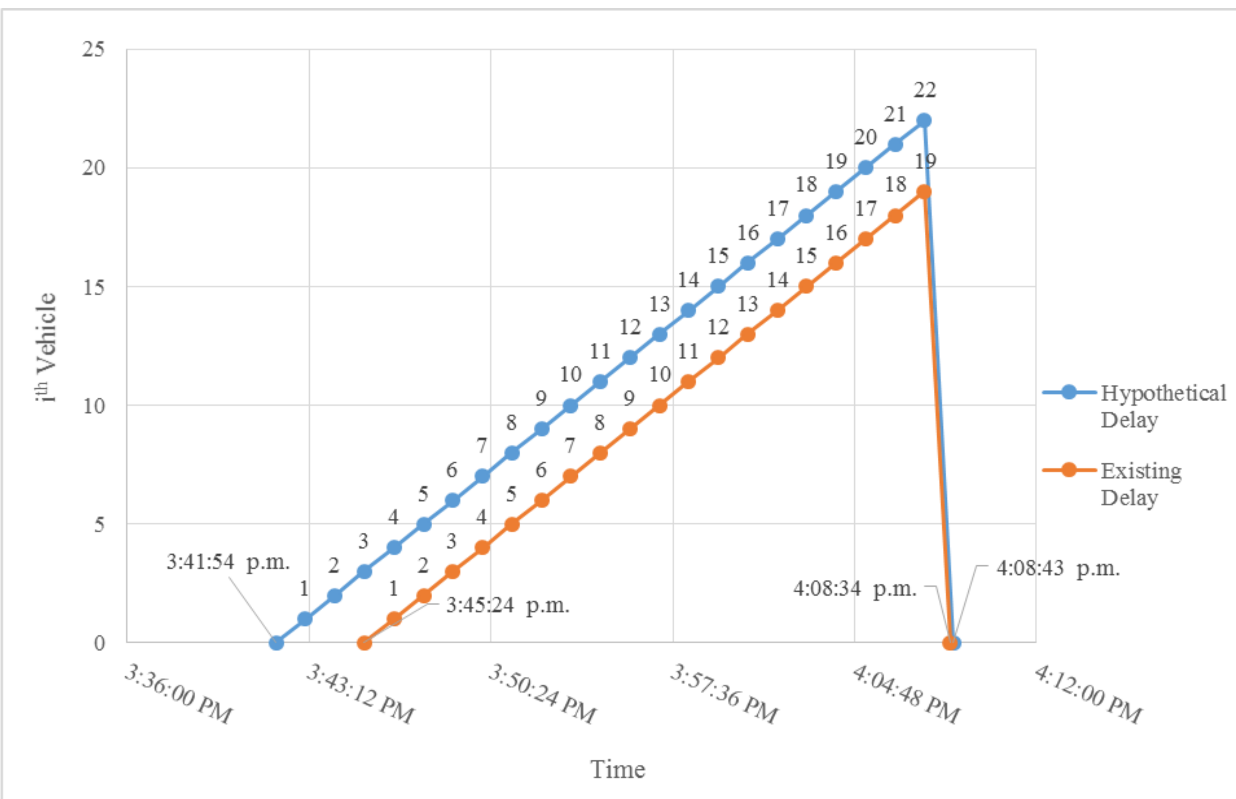

Figure 71. Delay analysis 4.

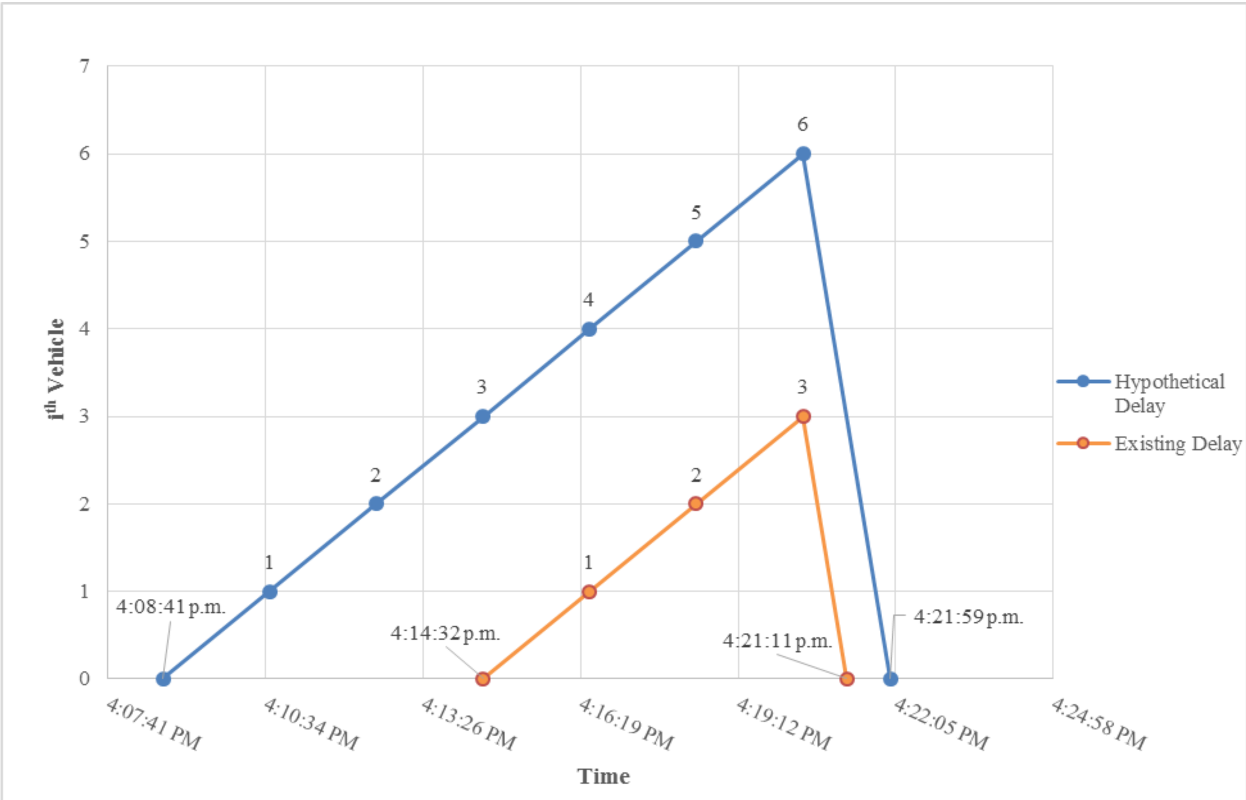

Figure 72. Delay analysis 5.

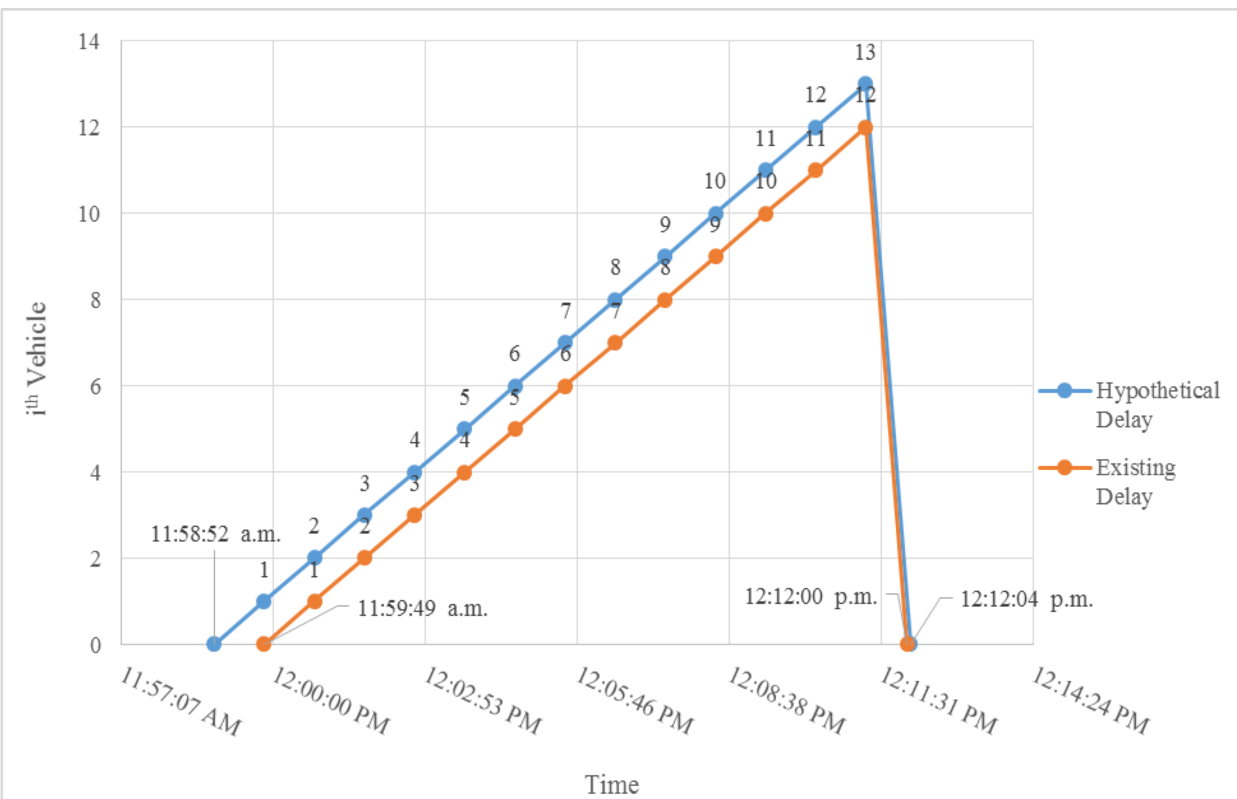

Figure 73. Delay analysis 6.

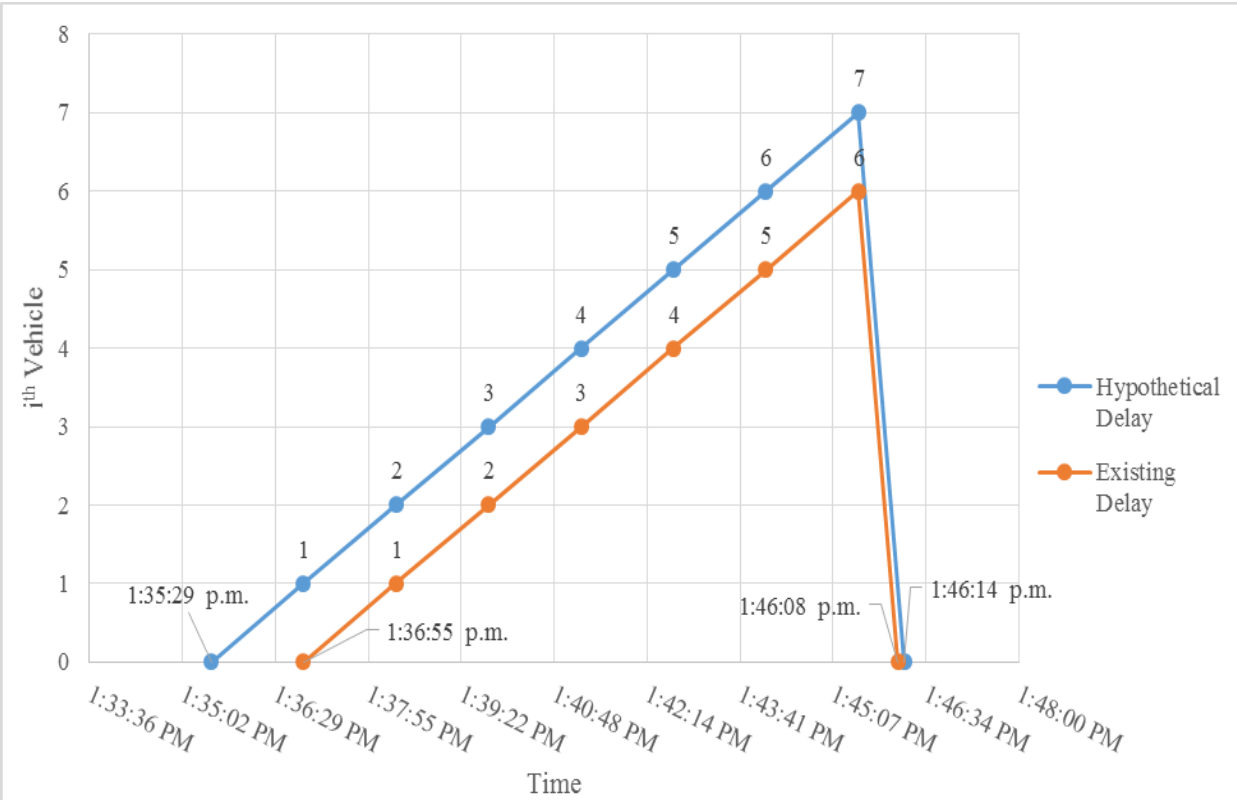

Figure 74. Delay analysis 7.

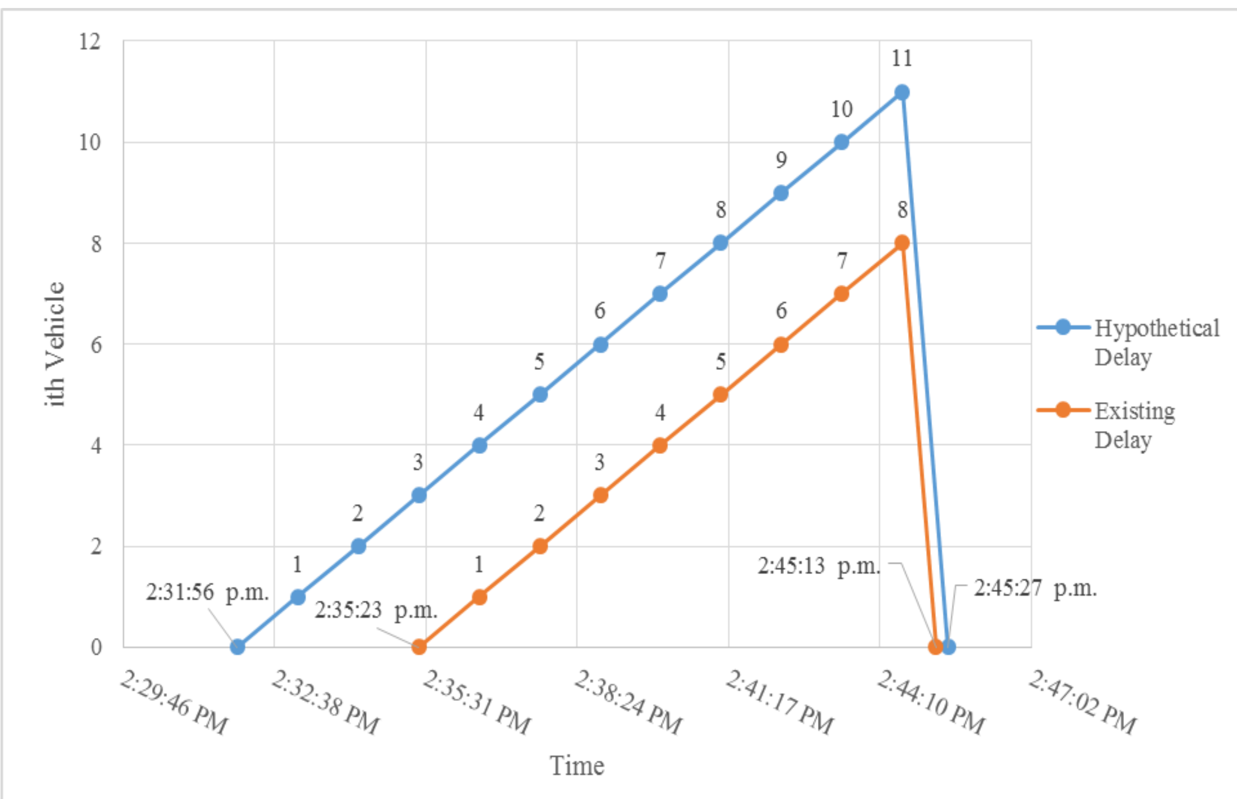

Figure 75. Delay analysis 8.

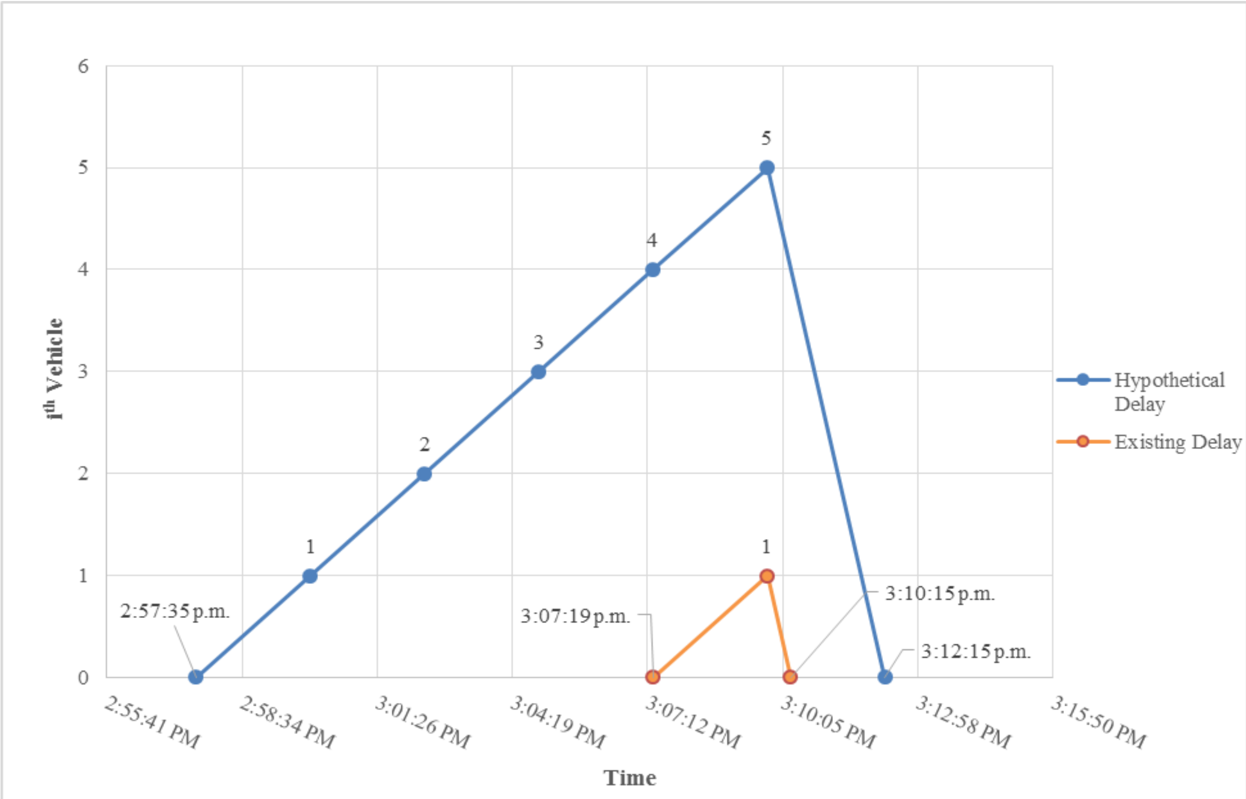

Figure 76. Delay analysis 9.

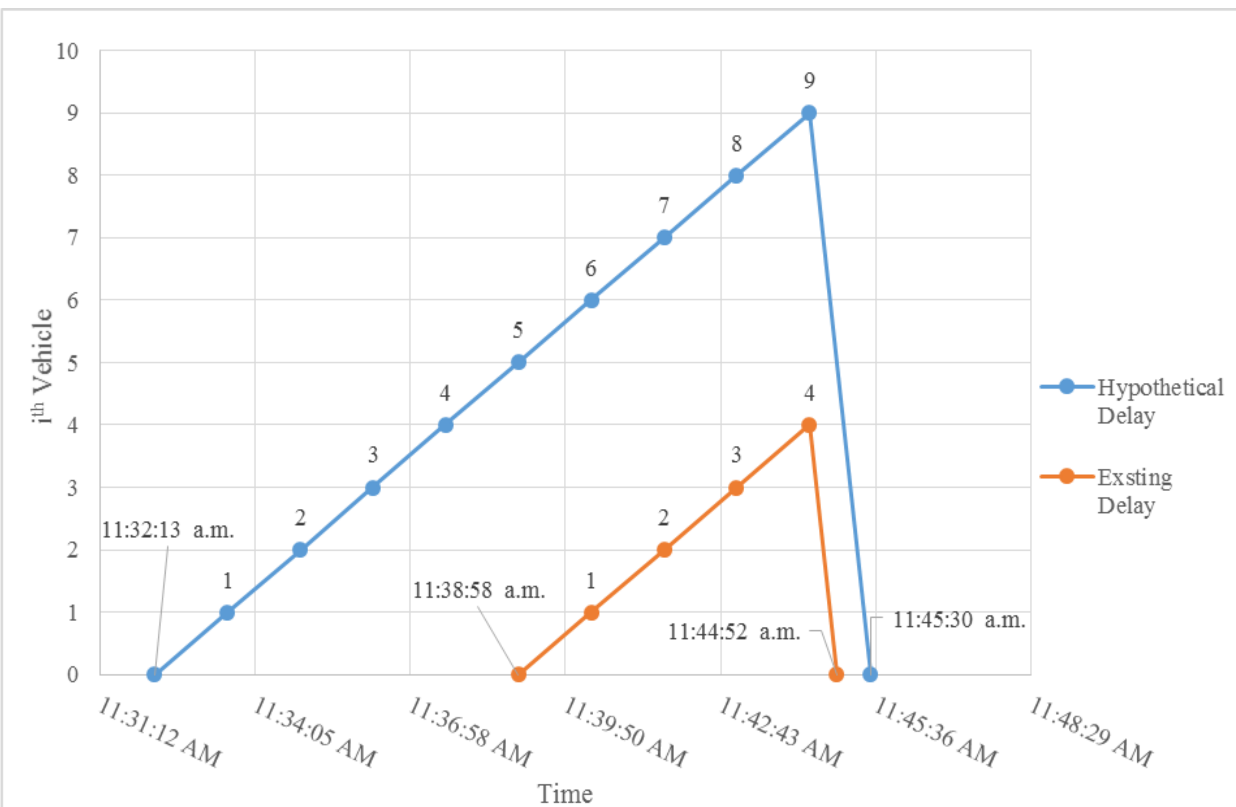

Figure 77. Delay analysis 10.

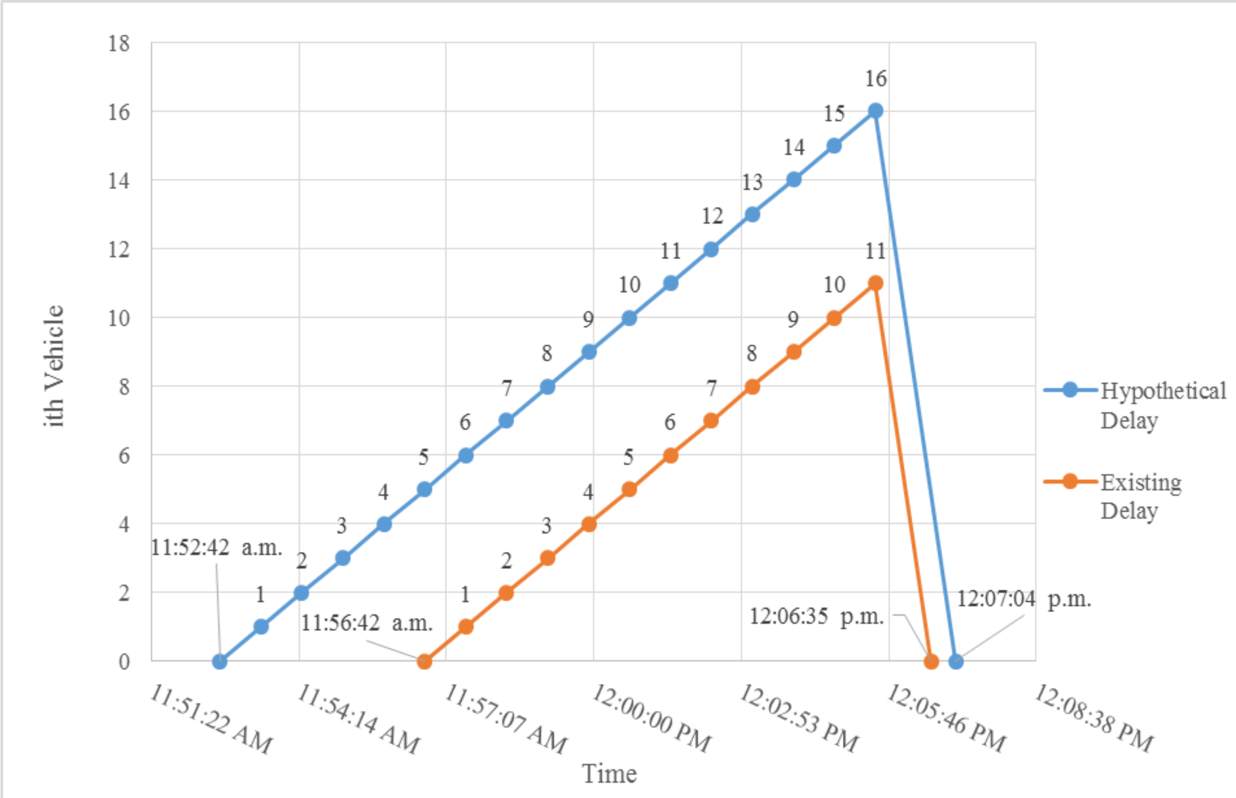

Figure 78. Delay analysis 11.

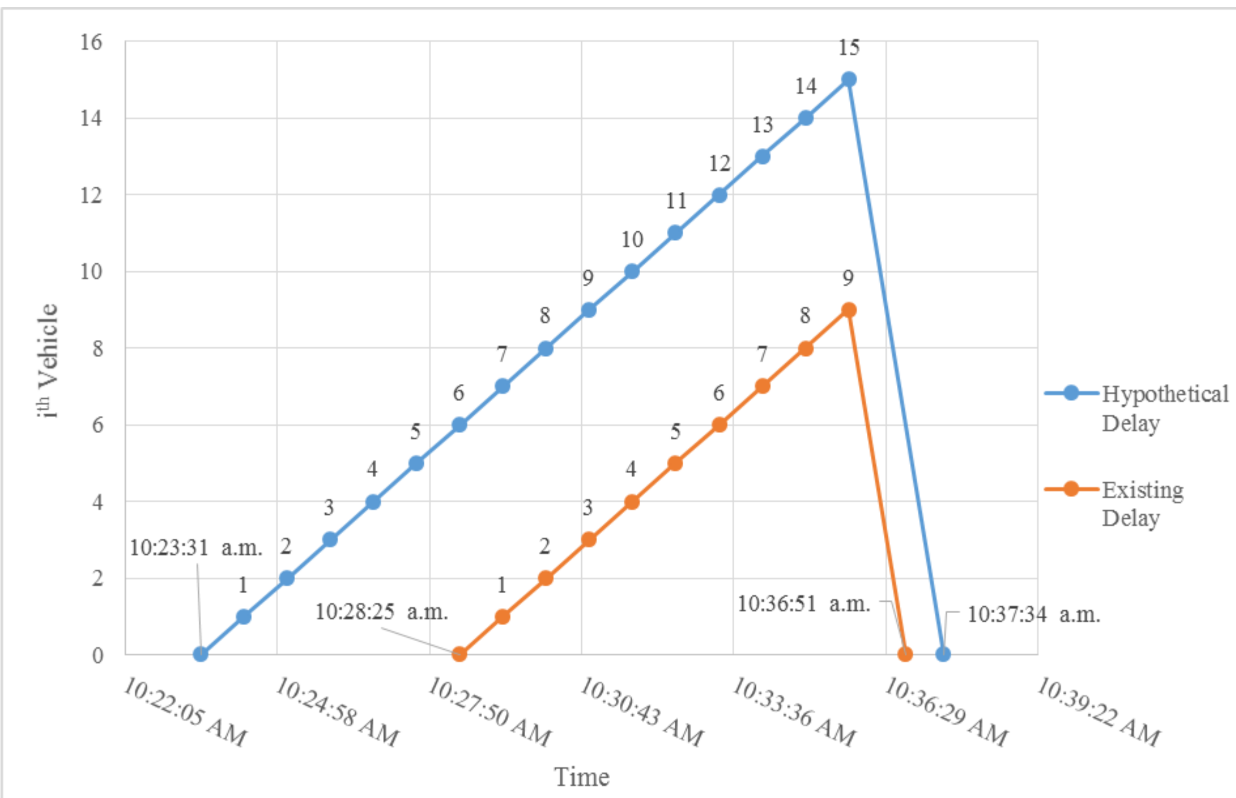

Figure 79. Delay analysis 12.

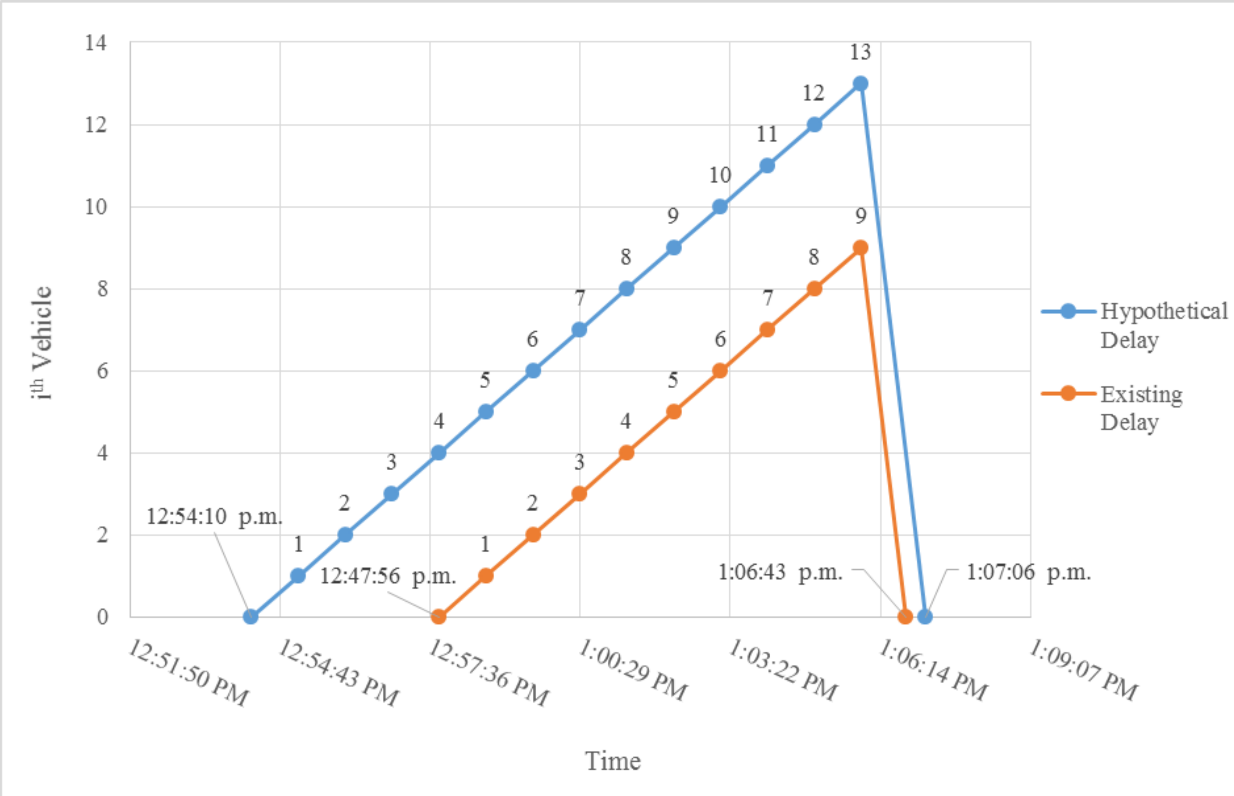

Figure 80. Delay analysis 13.

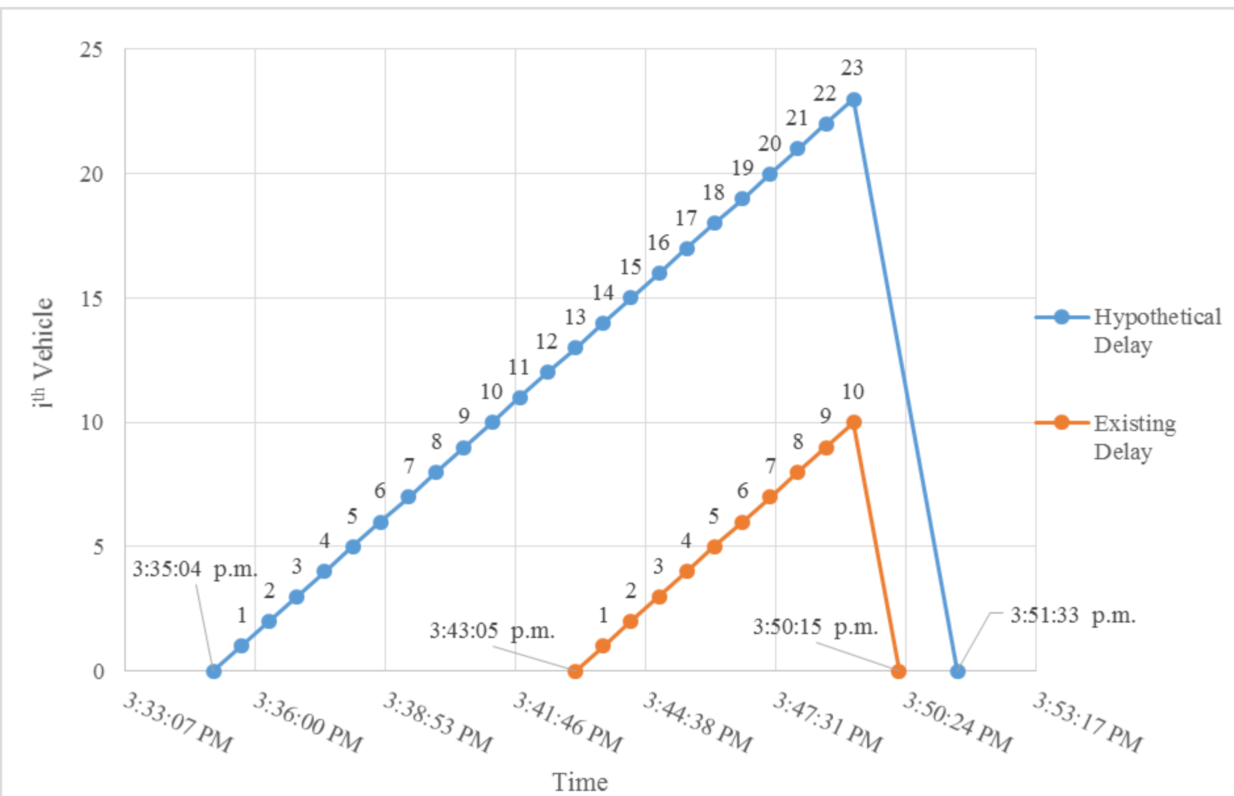

Figure 81. Delay analysis 14.

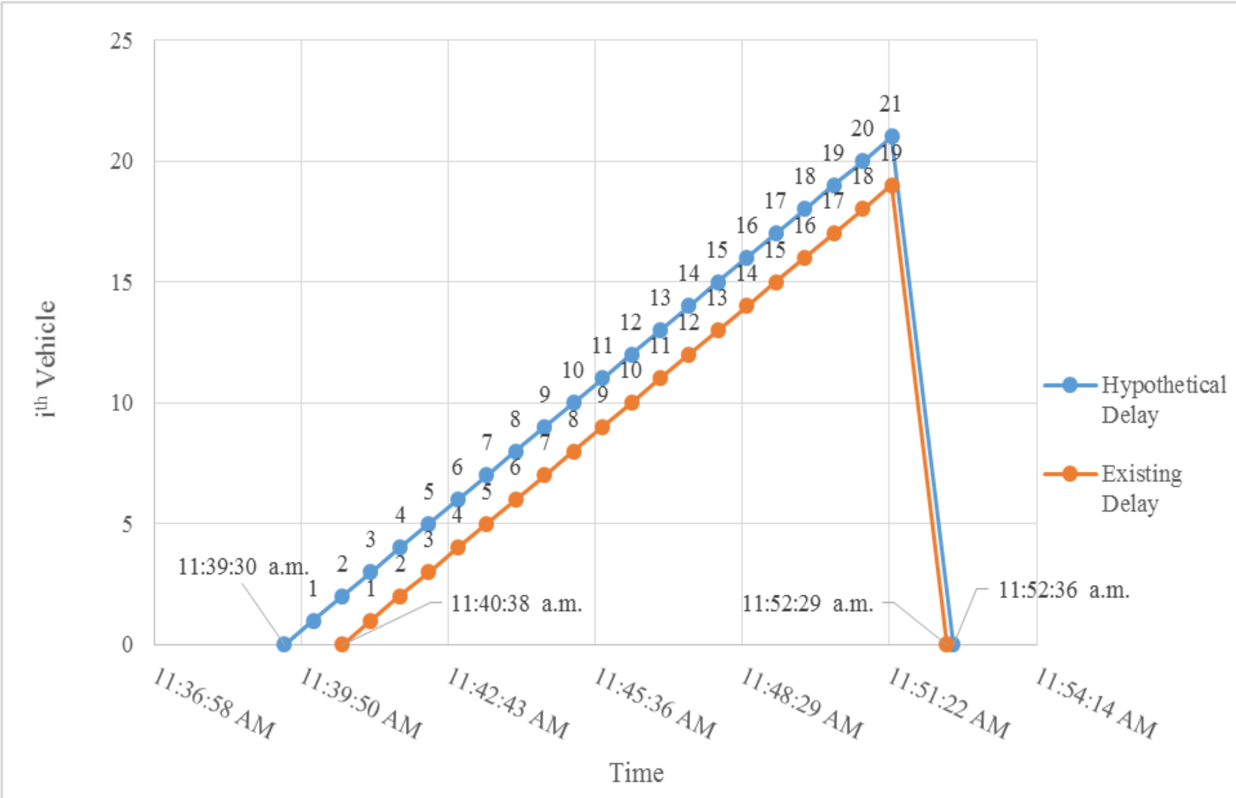

Figure 82. Delay analysis 15.

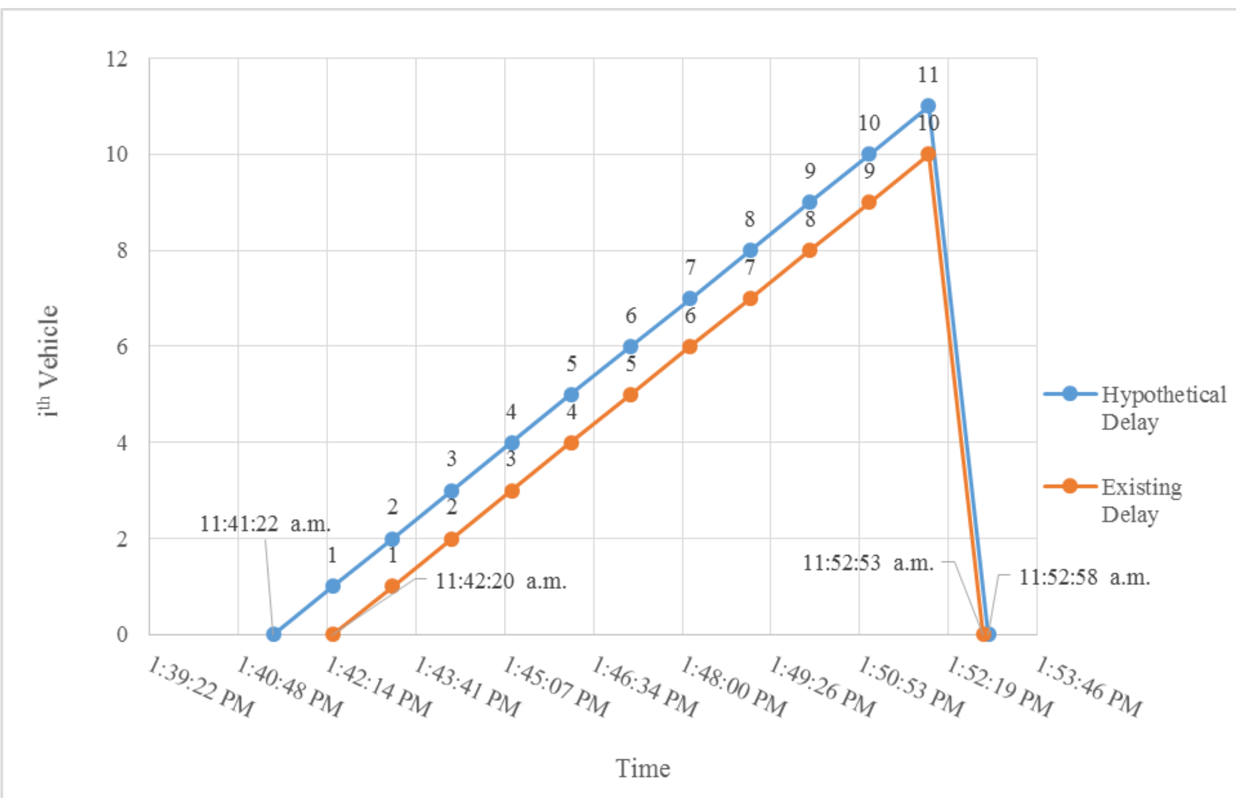

Figure 83. Delay analysis 16.

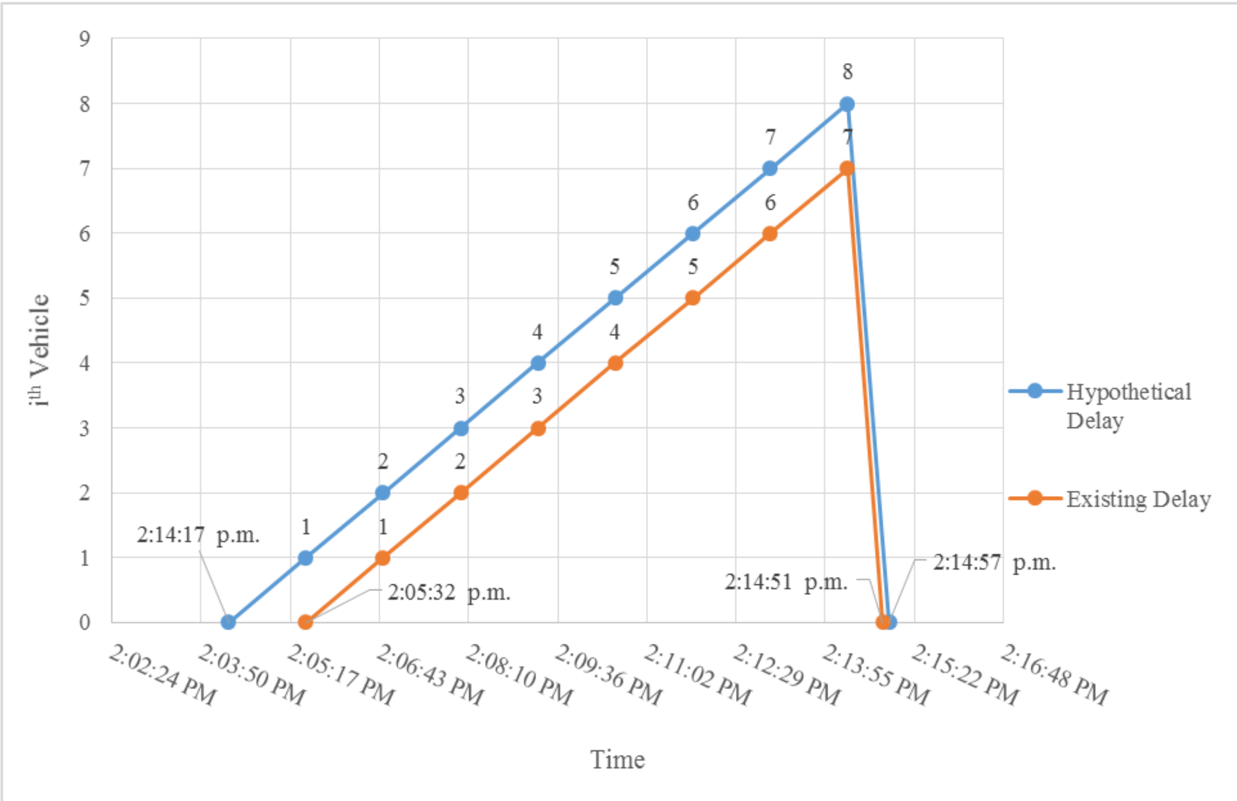

Figure 84. Delay analysis 17.

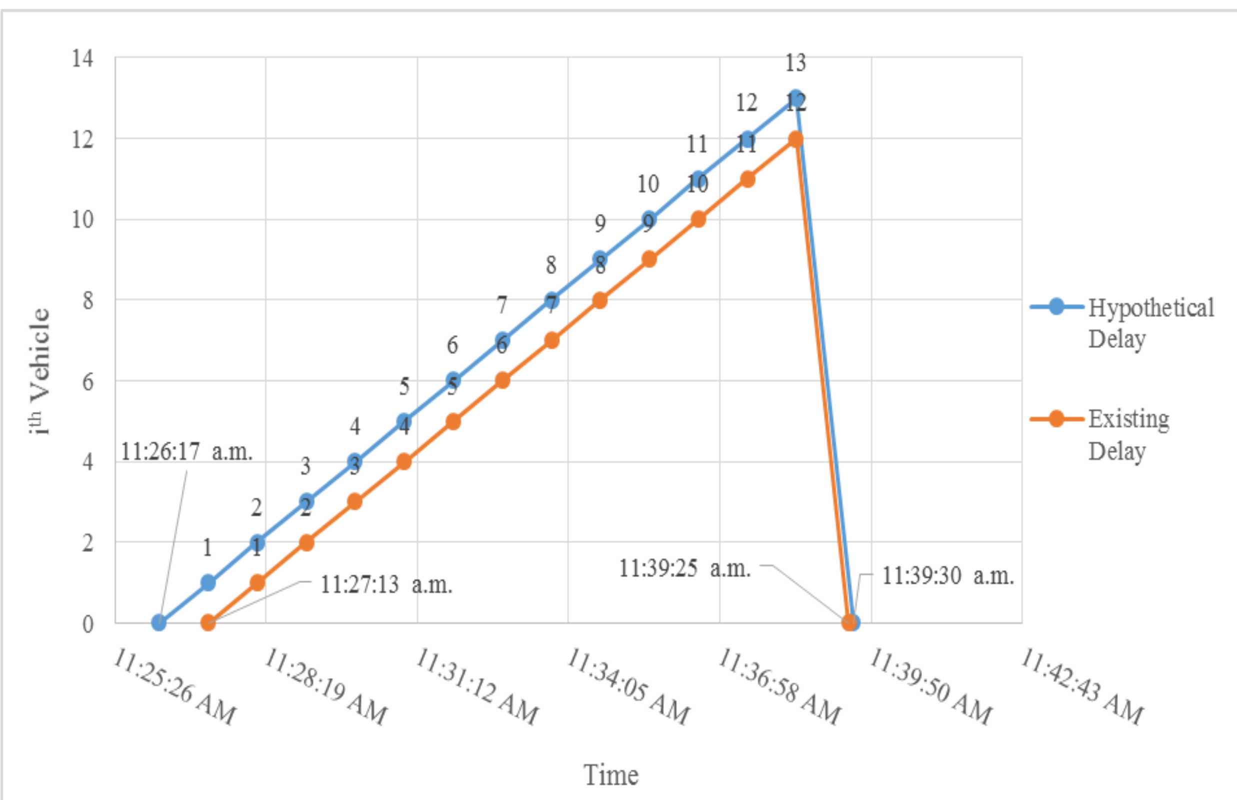

Figure 85. Delay analysis 18.

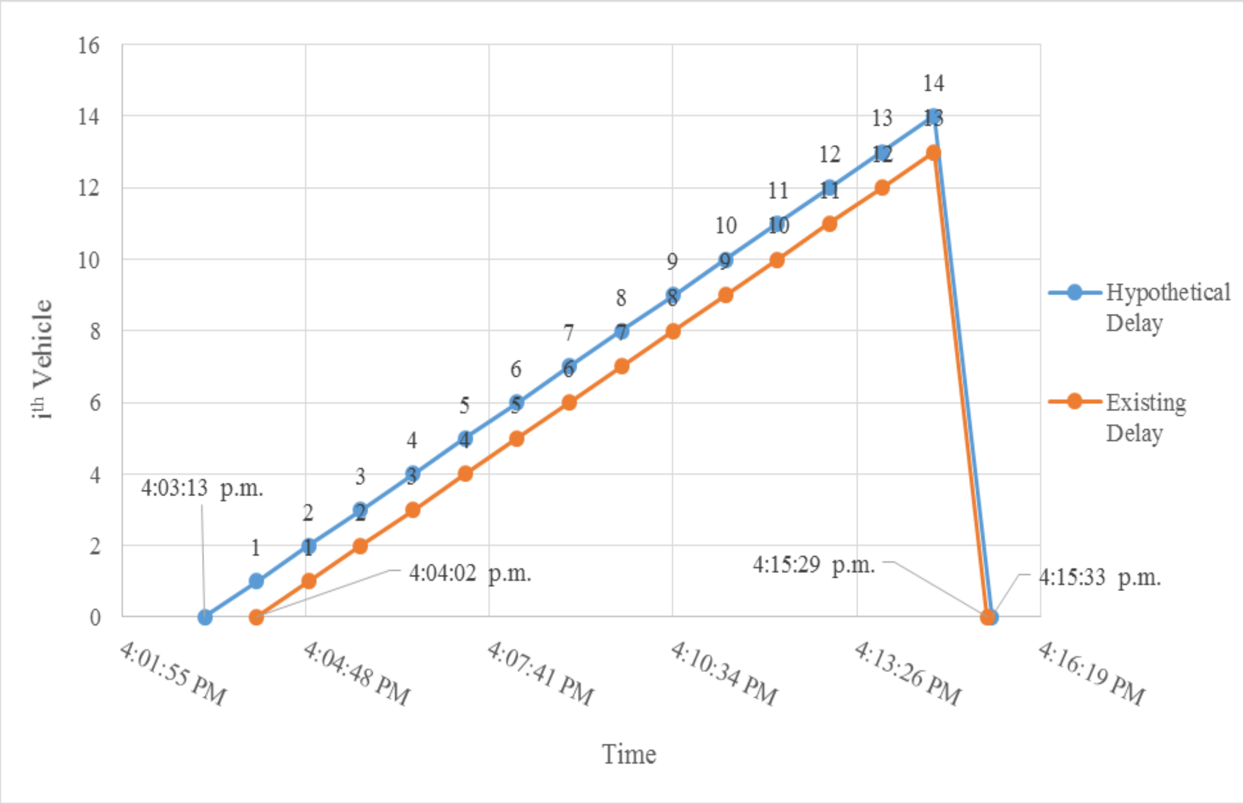

Figure 86. Delay analysis 19.

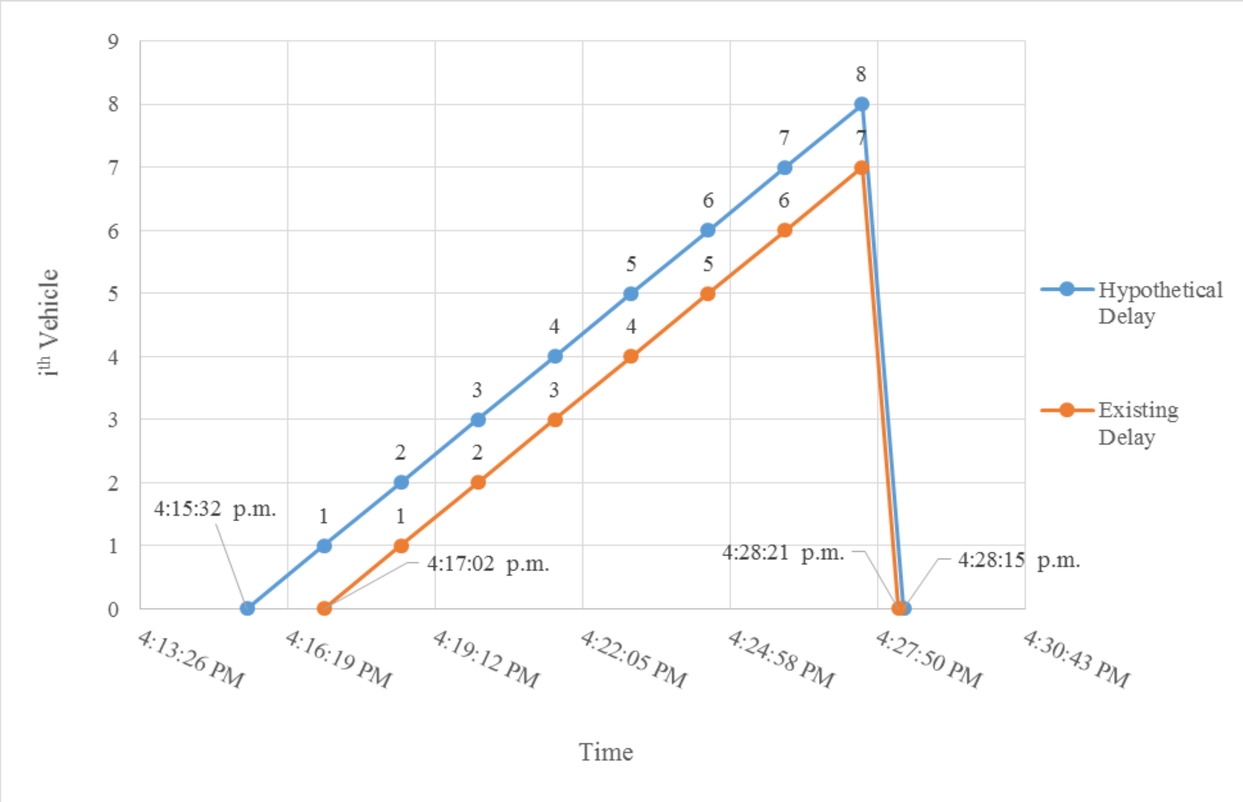

Figure 87. Delay analysis 20.

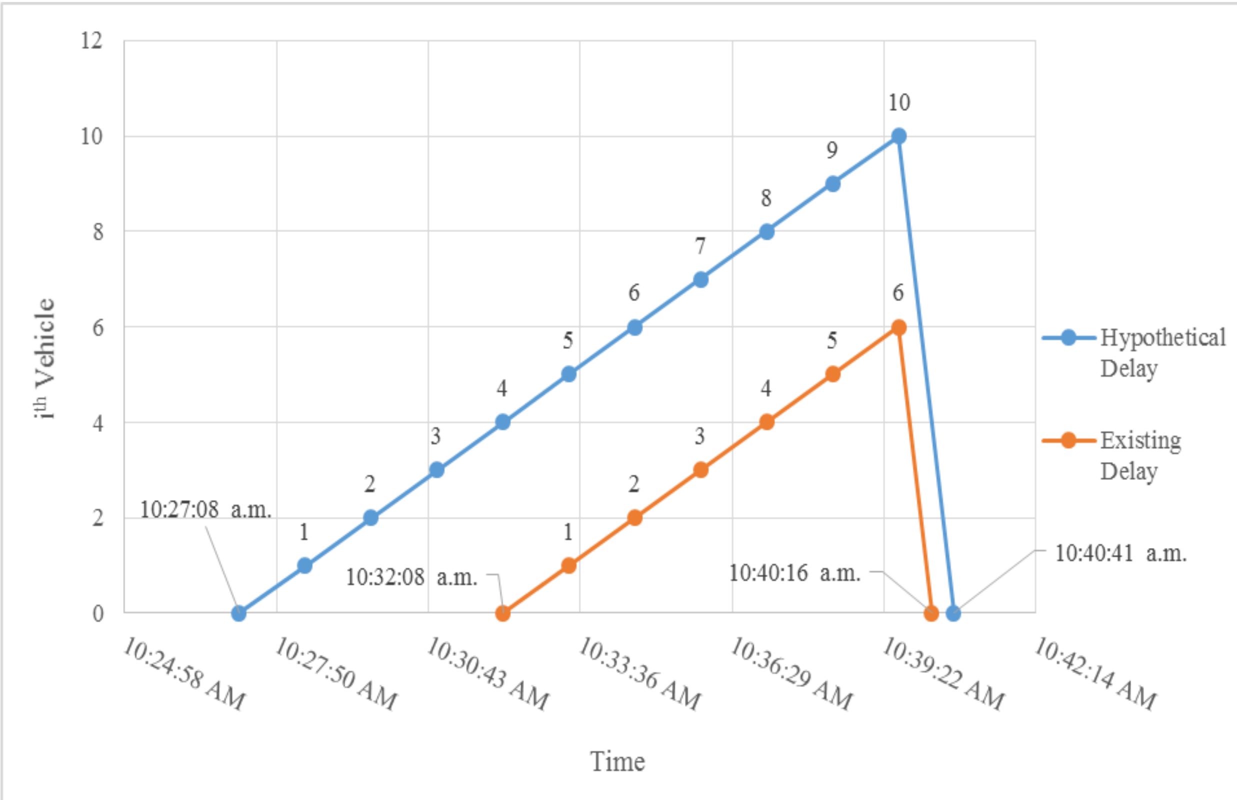

Figure 88. Delay analysis 21.

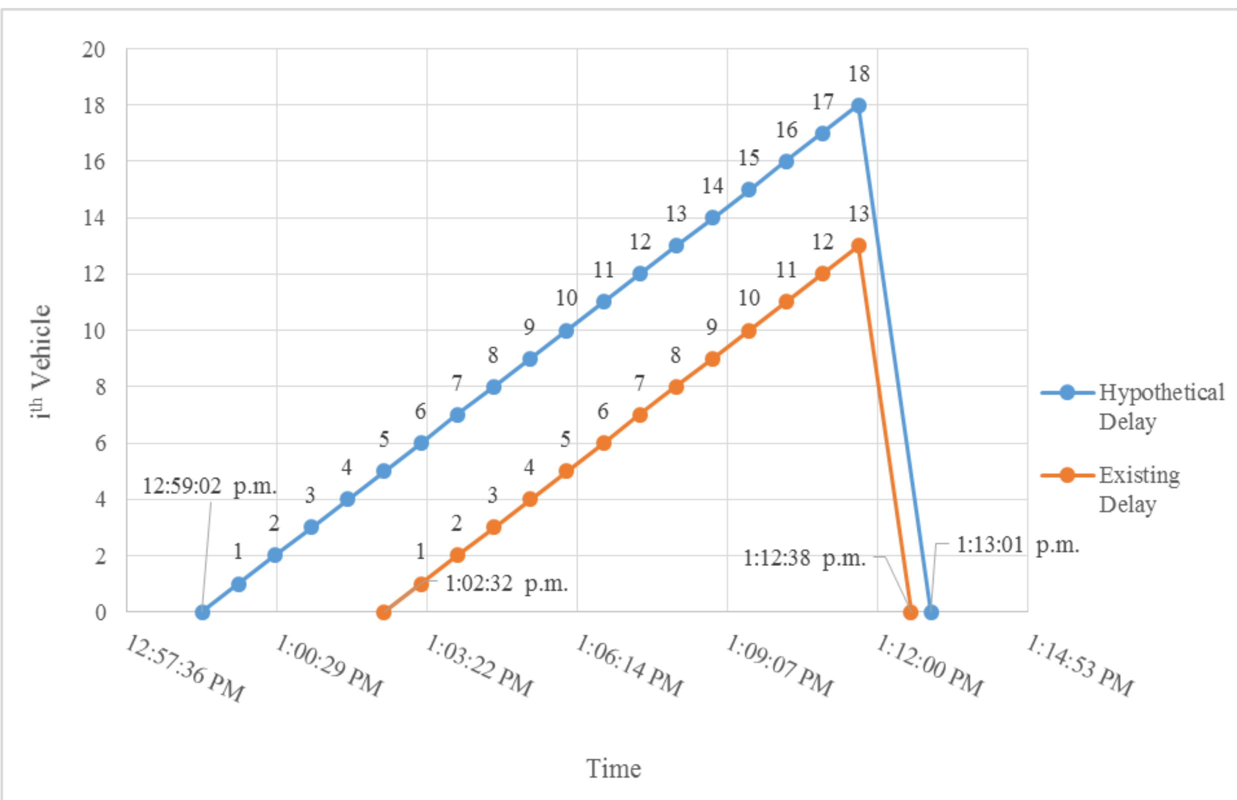

Figure 89. Delay analysis 22.

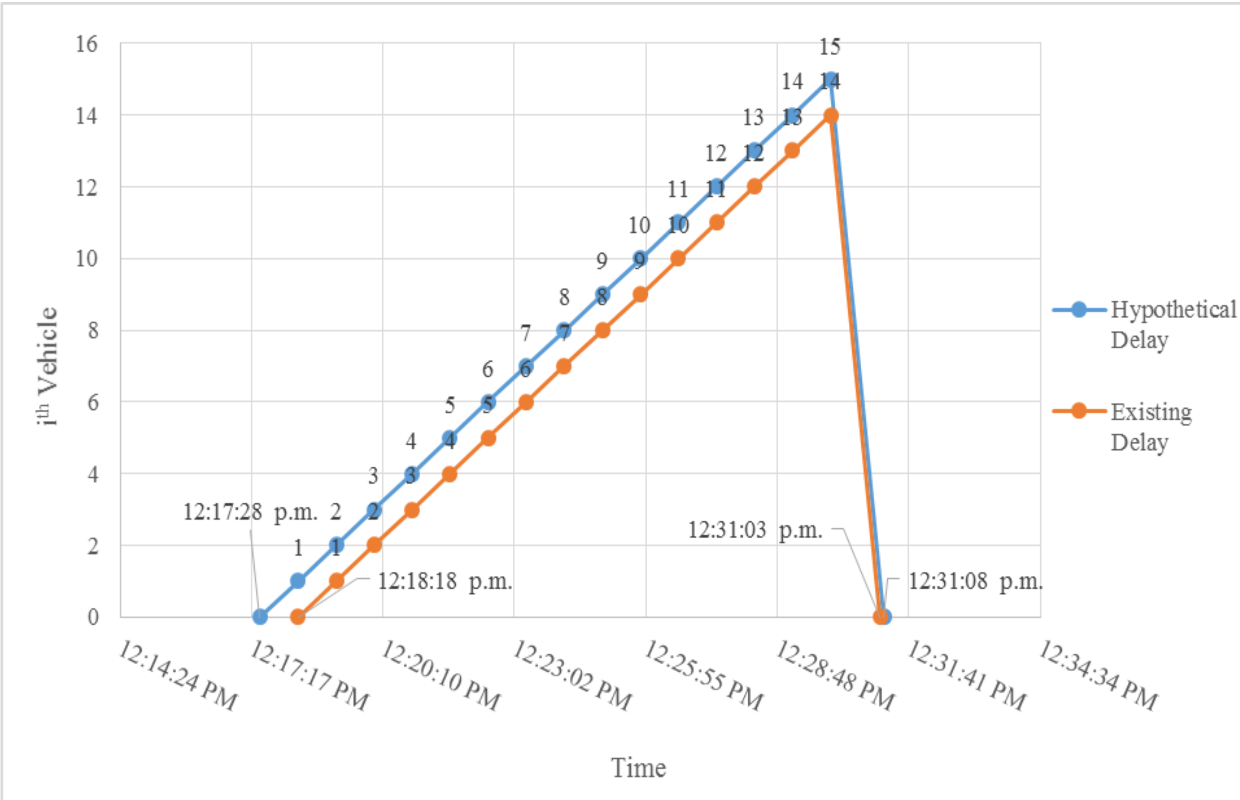

Figure 90. Delay analysis 23.

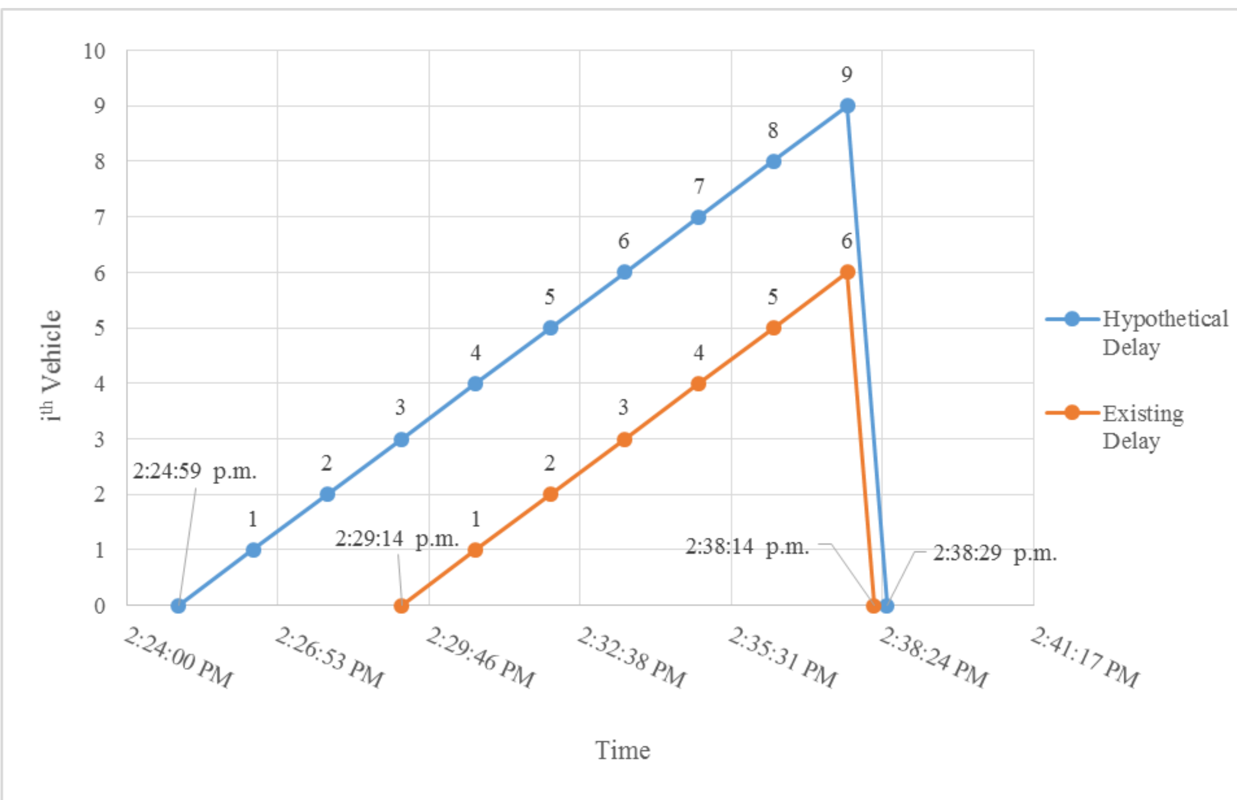

Figure 91. Delay analysis 24.

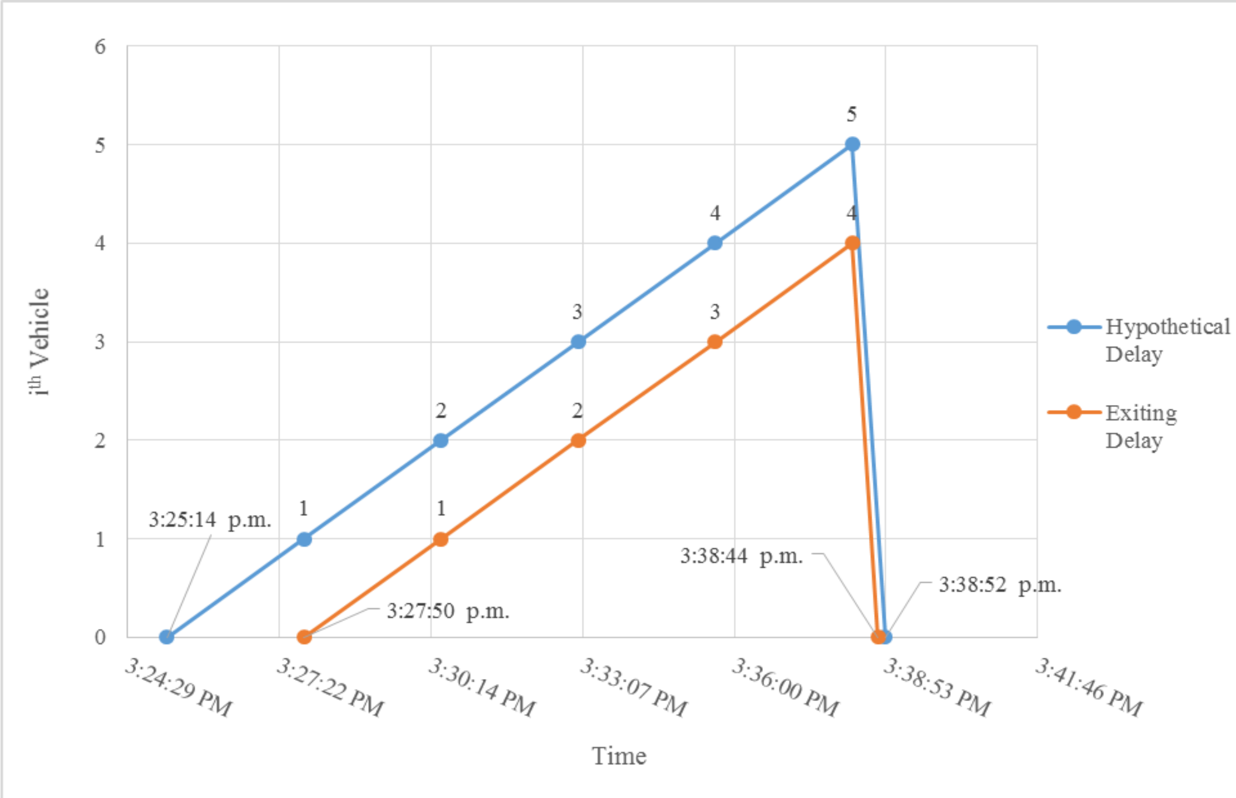

Figure 92. Delay analysis 25.

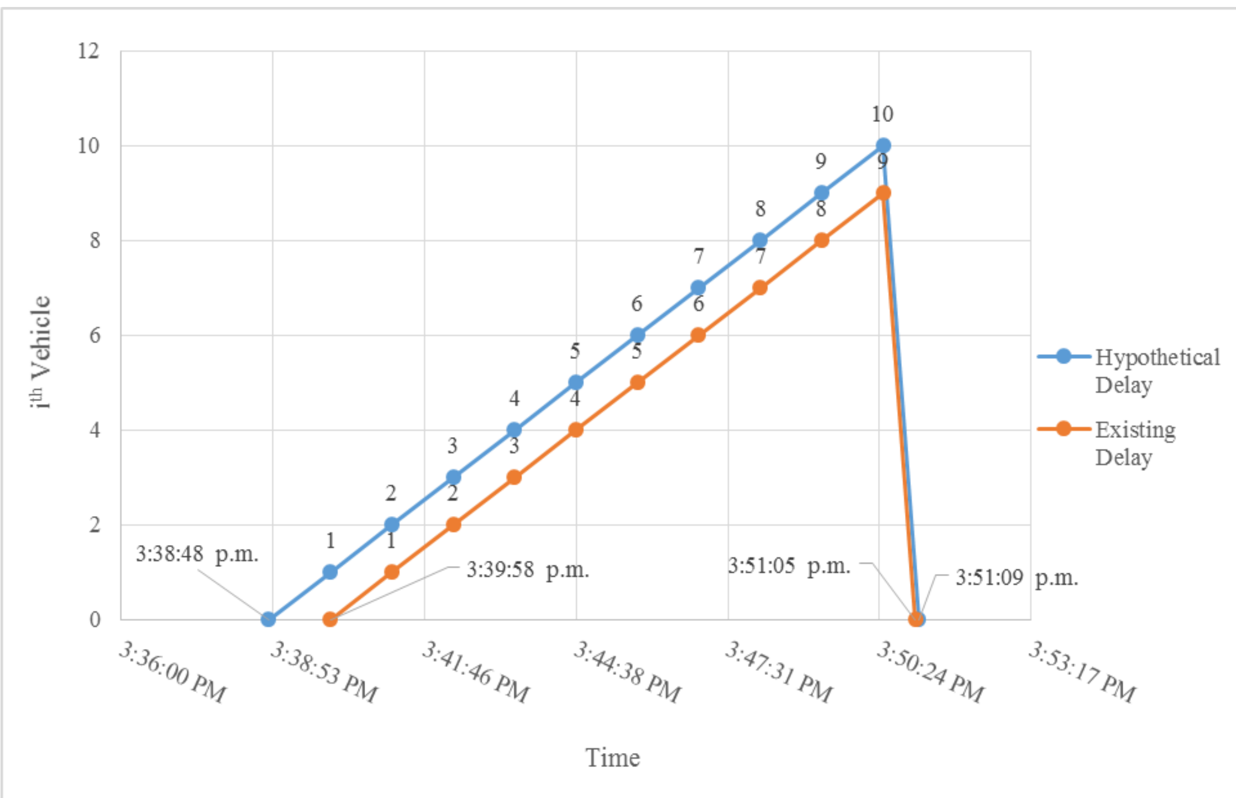

Figure 93. Delay analysis 26.

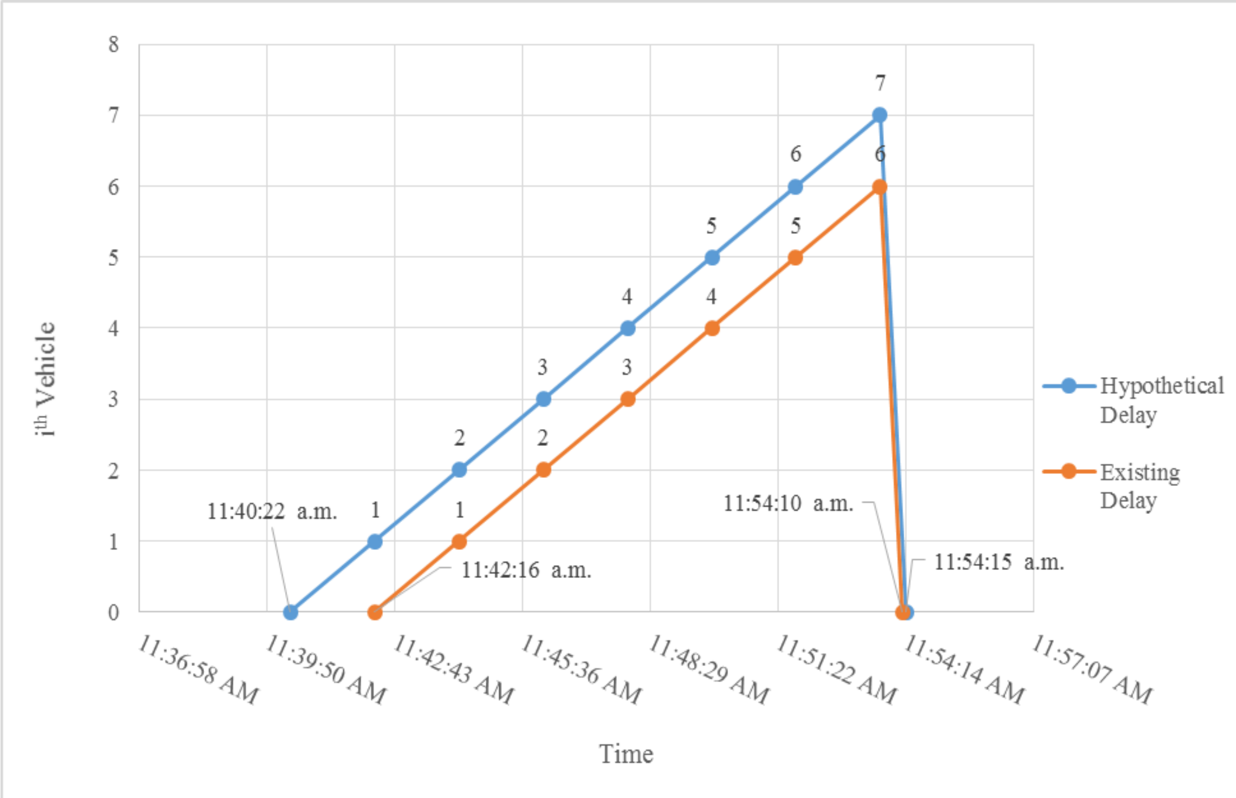

Figure 94. Delay analysis 27.

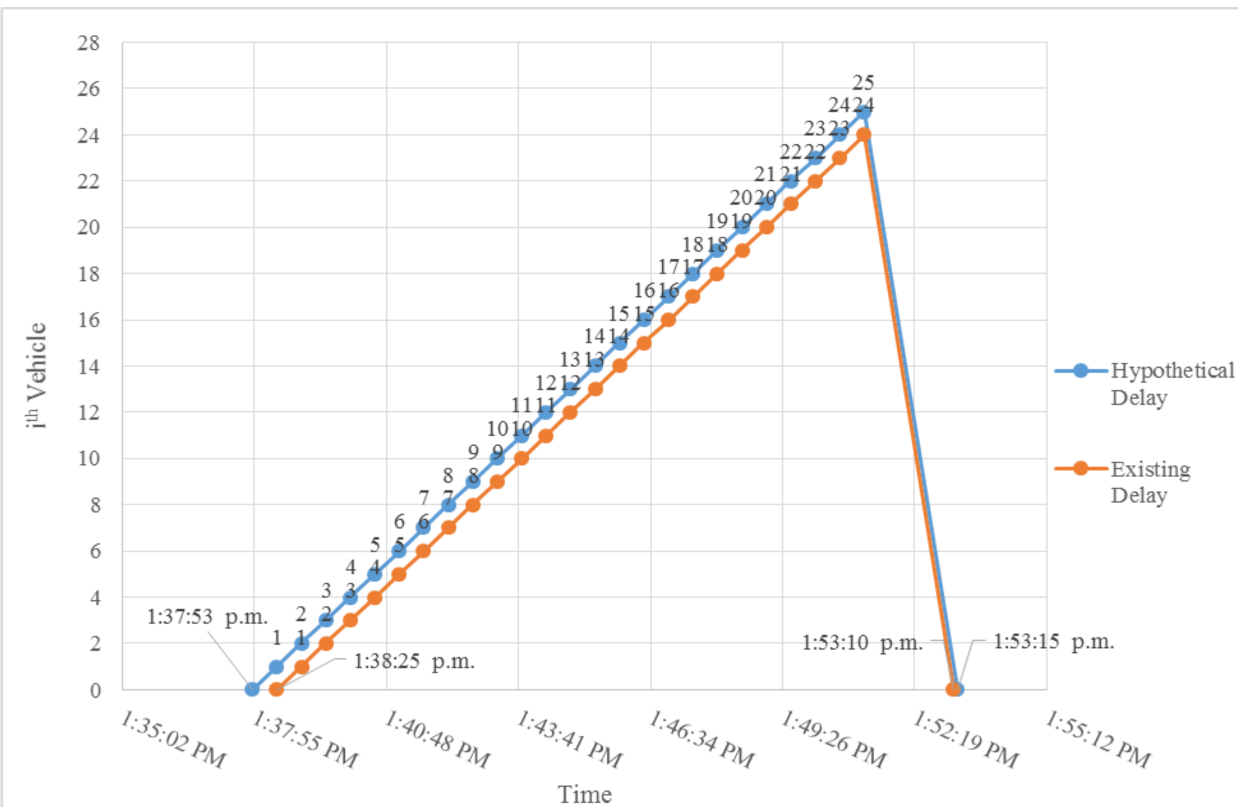

Figure 95. Delay analysis 28.

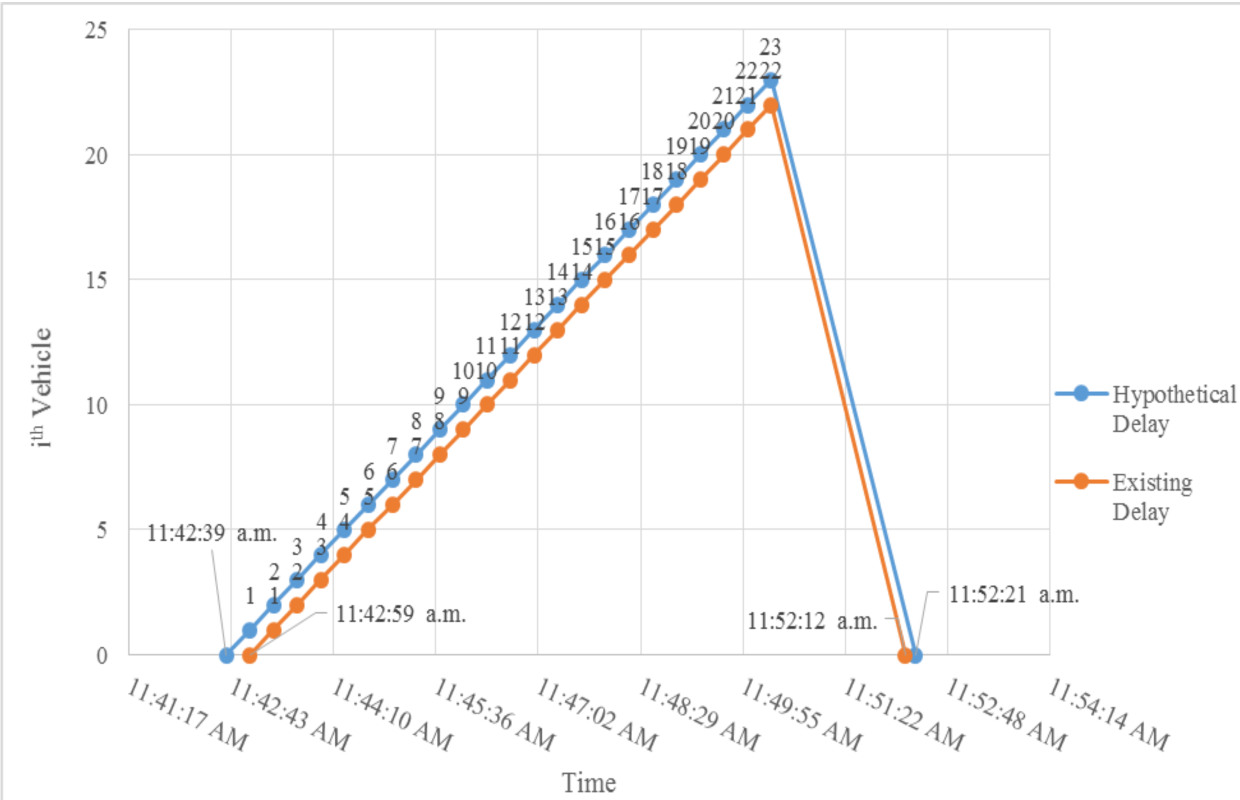

Figure 96. Delay analysis 29.

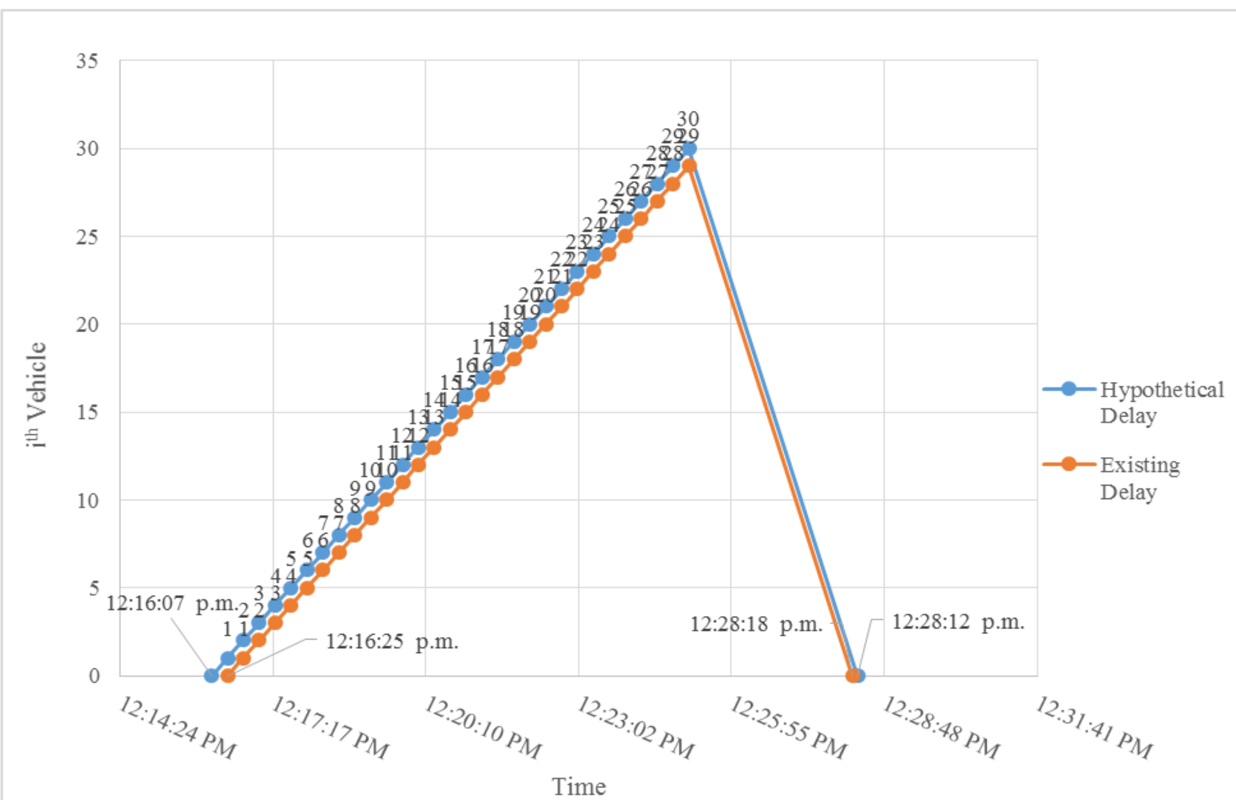

Figure 97. Delay analysis 30.

APPENDIX E

Temporary Traffic Control Plans

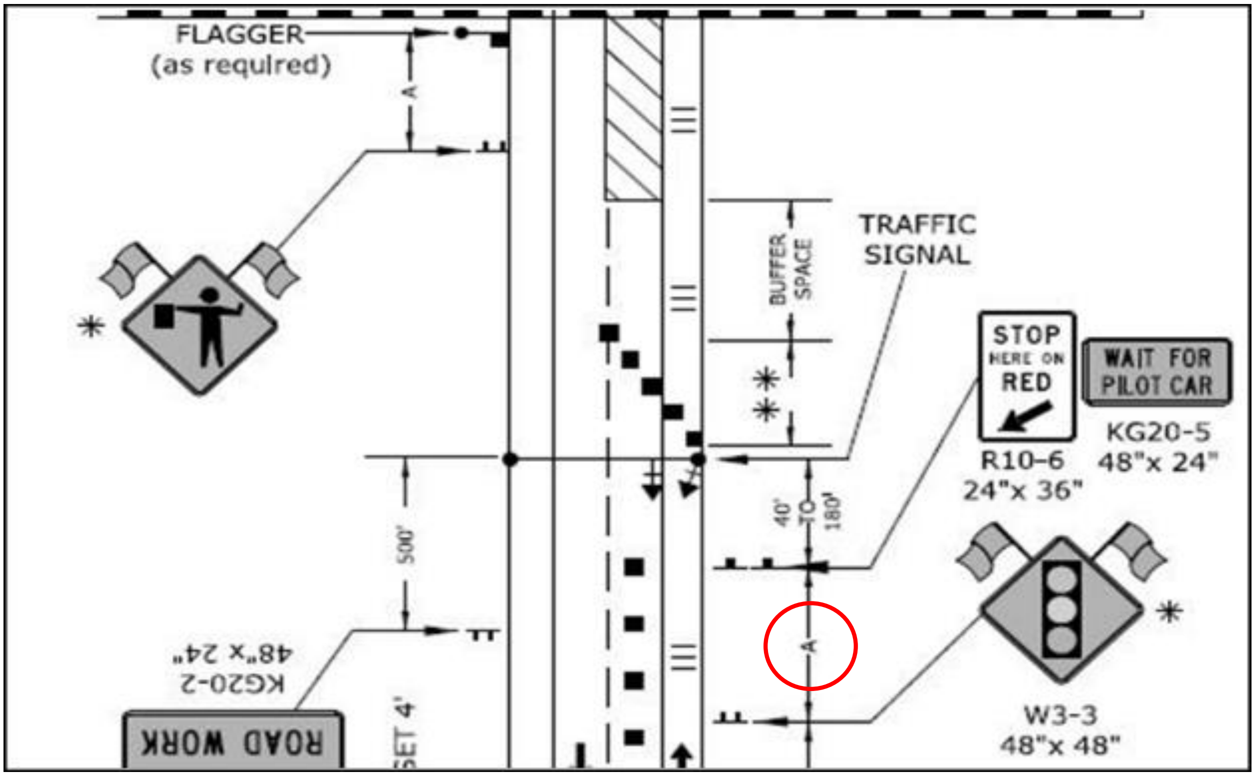

Figure 98. Snapshot of the temporary traffic control plan used for locating the traffic signs (Source: KDOT).

MINIMUM ADVANCE WARNING SIGN SPACING (IN FEET):

	A	B	C
URBAN (40 MPH OR LOWER)	100	100	100
URBAN (45 MPH OR HIGHER)	350	350	350
RURAL (55 MPH OR LOWER)	500	500	500
RURAL (60 MPH OR HIGHER)	750	750	750
EXPRESSWAY/FREEWAY	1000	1500	2640

THE MINIMUM SPACING BETWEEN SIGNS SHALL BE NO LESS THAN 100', UNLESS DIRECTED BY THE ENGINEER.

THE SPACING BETWEEN ANY SIGNS MAY BE INCREASED BEYOND THE MINIMUM VALUES IN THE TABLE ABOVE AS APPROVED BY THE ENGINEER IN ORDER TO MAXIMIZE VISIBILITY.

Figure 99. Snapshot of TE-710 used for determining the distance 'A' (Source: KDOT).

APPENDIX F

Additional Charts for Maximum Feasible Green Interval (G_{max}) and Maximum Feasible Length of Work Zone (L_w)

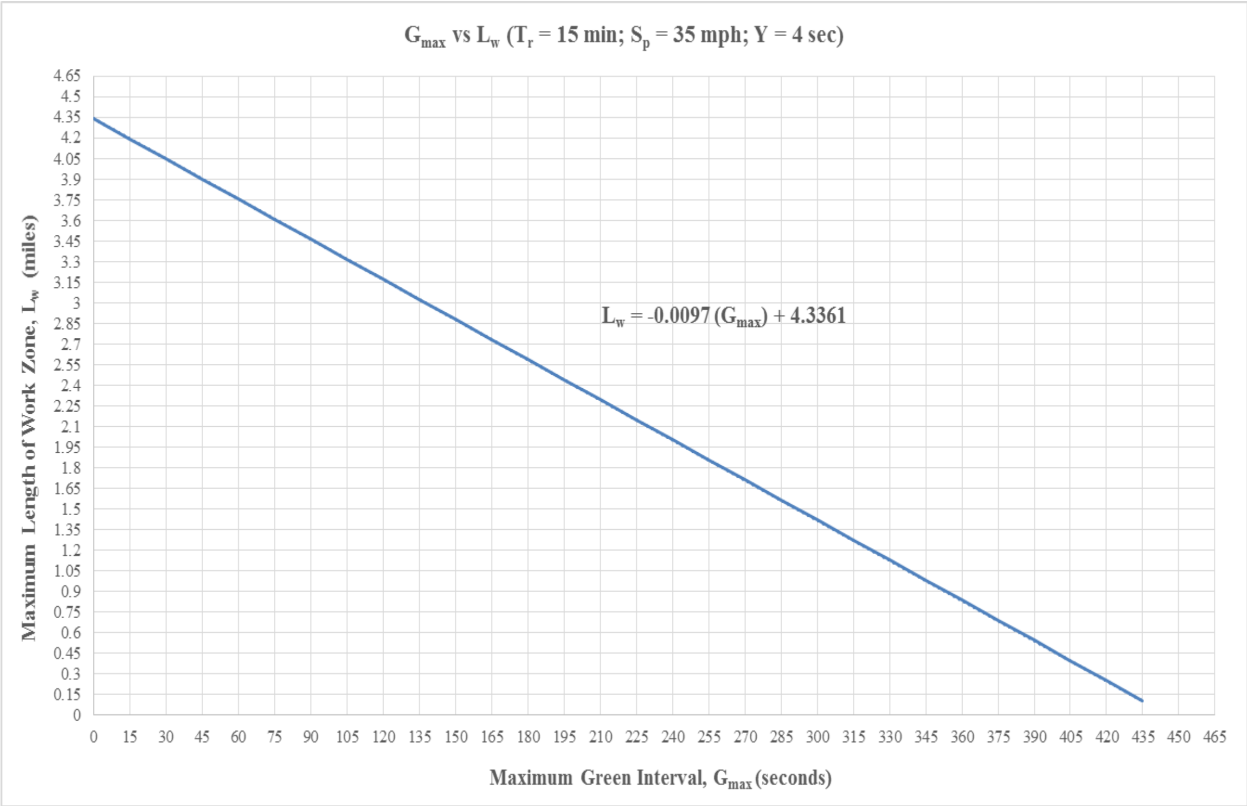

Figure 100. Plot for G_{max} against L_w at T_r = 15 mins; S_p = 35 mph; Y = 4 sec.

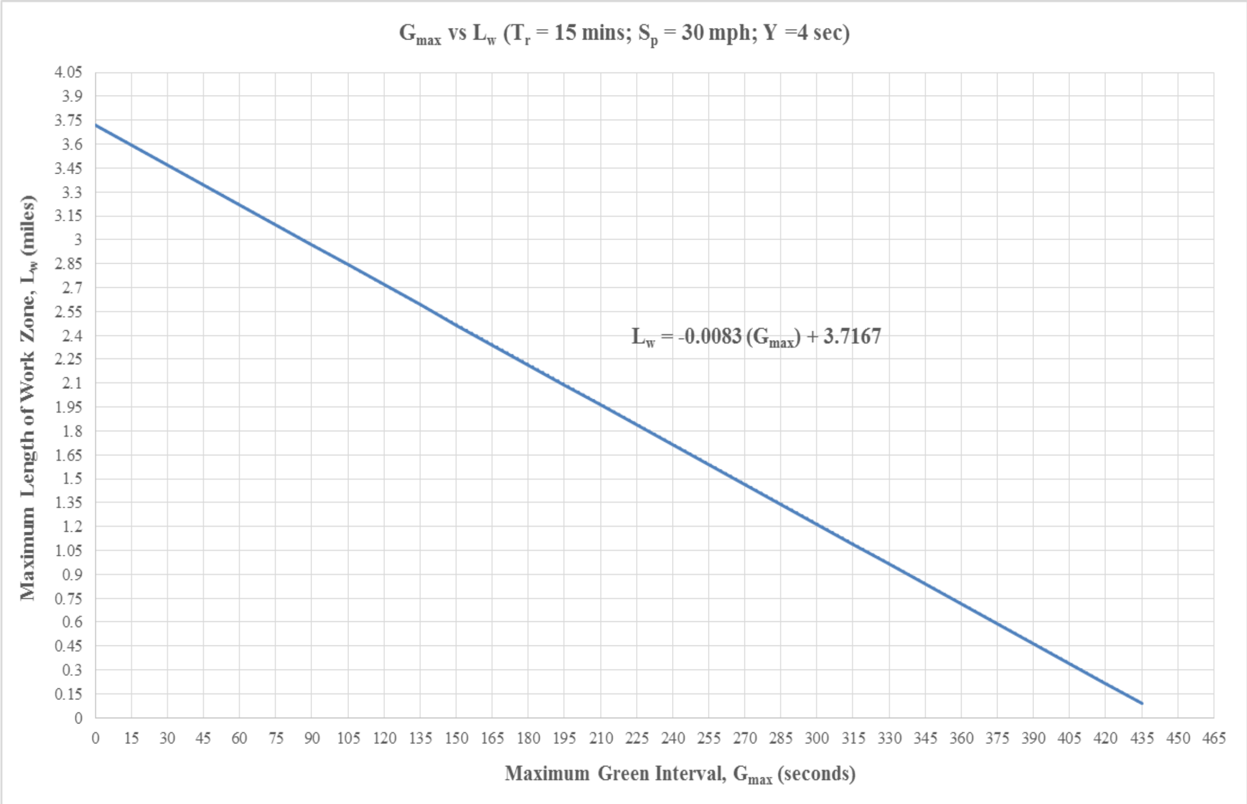

Figure 101. Plot for G_{max} against L_w at T_r = 15 mins; S_p = 30 mph; Y = 4 sec.

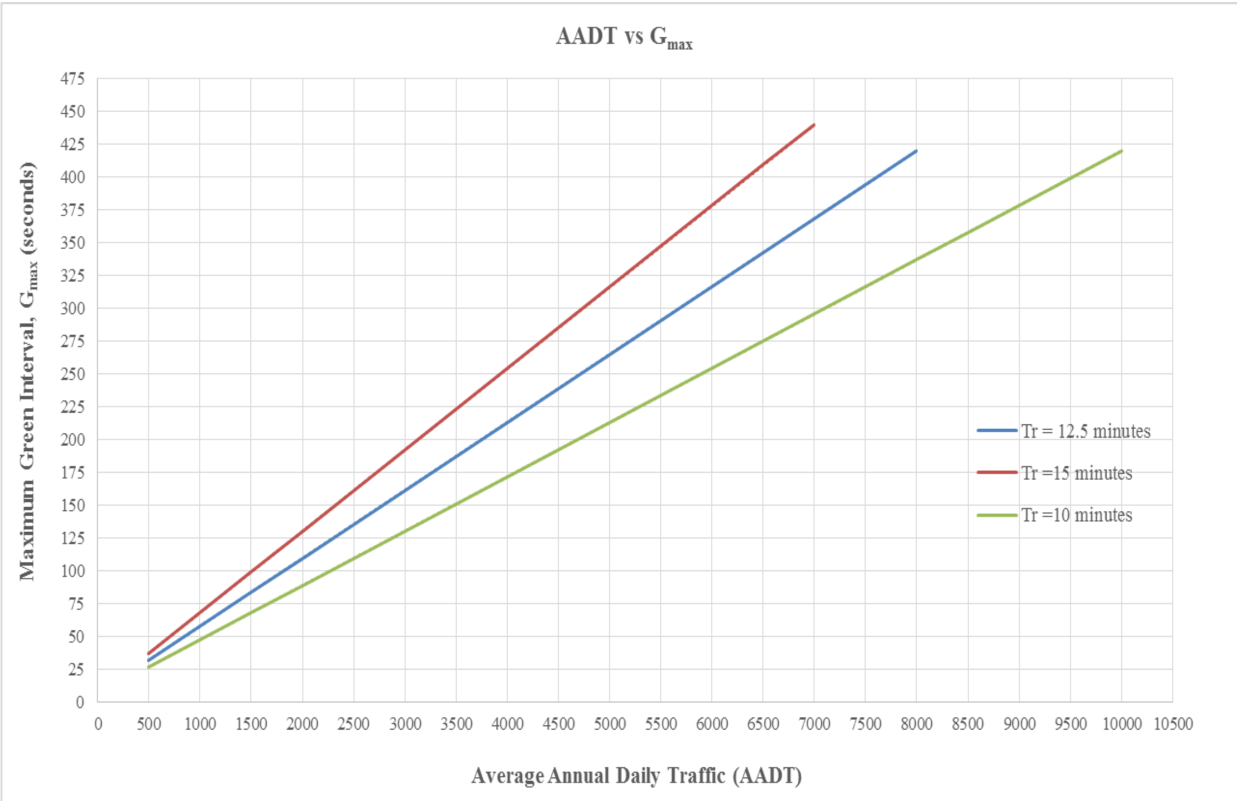

Figure 102. Comparison of the *AADT* against G_{max} for different T_r.

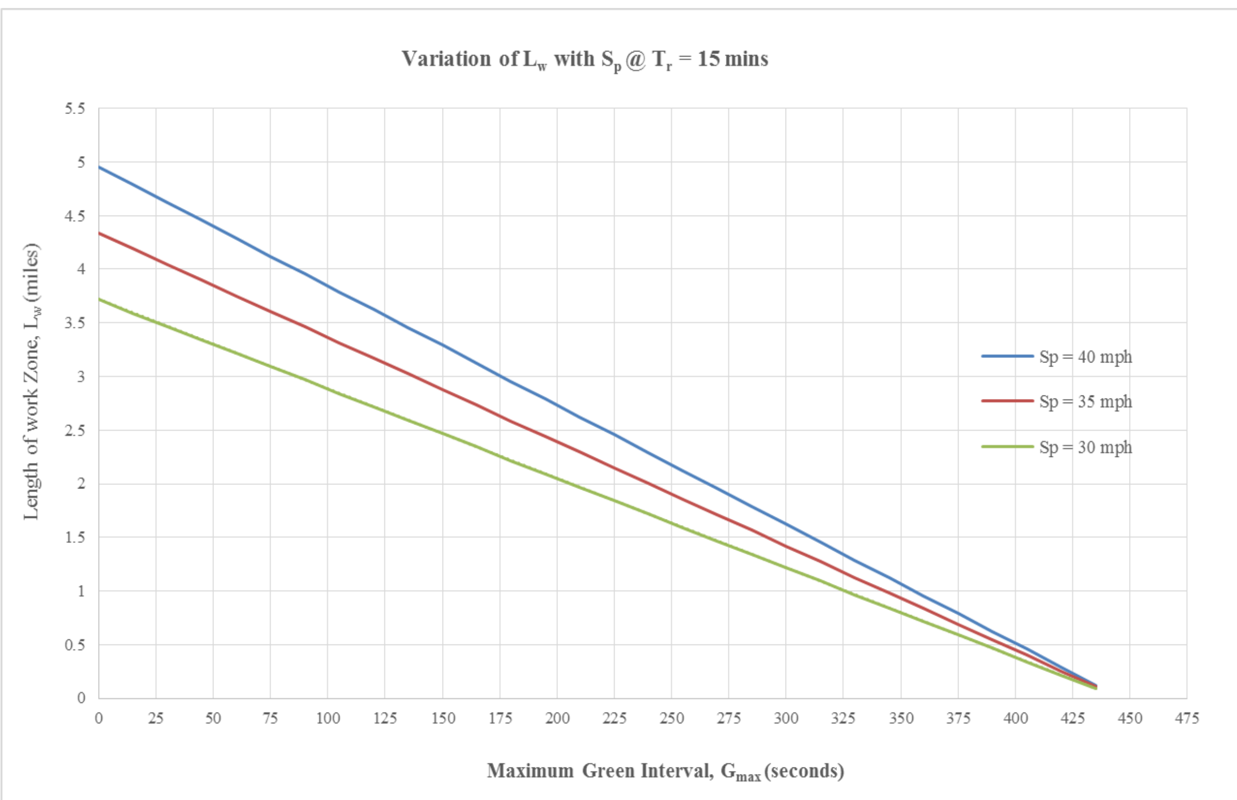

Figure 103. Comparison of G_{max} against L_w for different S_p.

APPENDIX G

Additional Pictures

Figure 104. Oversize vehicle following a pilot car.