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Evaluation of Temporary Traffic Signals in Conjunction with Pilot Car Operations at Two-Way Long Temporary Work Zones

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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 to compare three different conditions for controlling one-lane traffic in conjunction with pilot car operations: flagging only, a PTS system with the presence of a flagger, and a PTS system without the presence of a flagger. The primary measures of effectiveness were determined as Red Light Running (RLR) violation 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 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 the percentage of violations for the flagger only, PTS with a flagger, and PTS without a flagger were 1.1, 1.3, and 3.1 percent, respectively. A test of proportions conducted on the three samples at a 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 without a flagger, as compared to when flagging only operations were used. 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. It was also found 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. It was found that there was a statistically significant difference in the number of RLR vehicles that left the stopped queue and the number of vehicles that disregarded the PTS control for both the conditions.

An exploratory delay analysis indicated that the presence of a flagger reduced the total delay by approximately 5 percent of the delay that could have occurred during the normal operations when flaggers waved the vehicles through the red light. Finally, 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 annual average daily traffic (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 other measures were suggested, such as engineering studies to more accurately estimate queue lengths, installation of static signs indicating the expected wait time, and regular inspections of the PTS units by site supervisors or crew members to mitigate excessive delays and monitor for RLR vehicles.

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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 to compare three different conditions for controlling one-lane traffic in conjunction with pilot car operations: flagging only, a PTS system with the presence of a flagger, and a PTS system without the presence of a flagger. The primary measures of effectiveness were determined as Red Light Running (RLR) violation 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 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 the percentage of violations for the flagger only, PTS with a flagger, and PTS without a flagger were 1.1, 1.3, and 3.1 percent, respectively. A test of proportions conducted on the three samples at a 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 without a flagger, as compared to when flagging only operations were used. 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. It was also found 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. It was found that there was a statistically significant difference in the number of RLR vehicles that left the stopped queue and the number of vehicles that disregarded the PTS control for both the conditions.

An exploratory delay analysis indicated that the presence of a flagger reduced the total delay by approximately 5 percent of the delay that could have occurred during the normal operations when flaggers waved the vehicles through the red light. Finally, 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 annual average daily traffic (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 other measures were suggested, such as engineering studies to more accurately estimate queue lengths, installation of static signs indicating the expected wait time, and regular inspections of the PTS units by site supervisors or crew members to mitigate excessive delays and monitor for RLR vehicles.

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Chapter 1: Introduction

1.1 General Background

Lane closures at 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. Traditionally, flaggers at each end of the work zone are used to control the alternating traffic. A Portable Traffic Signal (PTS) system is a traffic control device designed to facilitate the movement of one-way traffic at temporary lane-closure type work zones. A PTS system consists of two portable trailers with traffic signals attached to a pole and mast arm. Communications between trailers are typically fiber optics, radio, or a synchronized timer. In work zones with pilot car operations, PTS systems can operate as an actuated traffic signal controlled by the pilot car operator which allows for higher directional flows to accommodate an increased travel time through the work zone. To minimize 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 are visible to stopped traffic.

The 2009 edition of the *Manual on Uniform Traffic Control Devices* (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 (FHWA, 2012). Similarly, the Kansas Department of Transportation (KDOT) Section 805, Work Zone Traffic Control and Safety, of the *Special Provision to the Standard Specifications* recommends that pilot car operations could be used to assist and lead traffic during one-way vehicular operations, at a distance greater than that which could be seen between flaggers (KDOT, 2007). 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.

1.2 Research Gap

An initial review of the existing literature on PTS systems showed limited research on their use in general.

Carlson et al. (2015) evaluated pilot cars and portable traffic control signals with and without flaggers. They found that only 3 percent of the drivers did not comply with the signals and pilot vehicles for the studied conditions. The research team concluded that there was no significant or practical difference in the number of violations when a signal was used with and without a flagger and recommended to use the portable traffic signals without a flagger to control traffic at lane closures on two-lane, two-way roadways.

Finley, Songchitruksa, and Jenkins (2015) evaluated alternate methods for controlling traffic on one-lane, two-way highways in Ohio. It was found that the violation rate for the portable traffic signals was 47.1 violations per 100 stop cycles, which was significantly different than the violations for the flagger method. The researchers also found that 99 percent of the violations had occurred at the end of the green interval when the non-compliant vehicles were able to see the end of the departed queue at a short distance and followed it to enter the work zone. The researchers recommended using the portable traffic signals for work zones with durations of at least half a day and identified high volume roads with flat side slopes as suitable locations for using these systems.

Several studies have indicated the cost benefits of using PTS systems instead of flaggers for controlling traffic at lane-closure type work zones. A study conducted by Ullman and Levine (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. A follow up study by Daniels, Venglar, and Picha (2000) developed thresholds and limitations of temporary traffic signals at work zones based on three study sites in Texas. It was found that the cost of purchase could be recovered after 2 years of operation if the equipment was used 8 to 10 days per month and savings in subsequent years were estimated at $20,000 to $30,000 per year (for 1999-2000).

Although the literature reported herein provided some information regarding the use of PTS system and its applications, only a limited number were able to provide guidelines regarding the use of these devices with pilot car operations at long lane-closure type work zones, indicating that an important research gap exists.

1.3 Research Need

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 found to be approximately 3.86 flagger fatalities per year (Pratt, Fosbroke, & Marsh, 2001). The Bureau of Labor Statistics (BLS) found for fatal occupational injuries at road construction sites from 2003 to 2010, 442 workers were killed at road construction sites after being struck by a vehicle or mobile work zone related equipment (BLS, 2013). 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 errant driver.

As stated previously, 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 minimal guidance provided to design engineers and contractors regarding the use of PTS systems in conjunction with pilot car operations and/or flagger operations. Although the 2009 MUTCD did not prohibit the use of a PTS system in conjunction with a pilot car, Paragraph 4 of Section 6C.13 of the 2009 MUTCD required the use of a flagger when using a pilot car to control traffic at one-lane, two-way work zones and was stated as, “A flagger shall be stationed on the approach to the activity area to control vehicular traffic until the pilot vehicle is available” (FHWA, 2012).

Furthermore, on August 31, 2010, the Federal Highway Administration (FHWA) provided their interpretation for the use of a flagger with a pilot car in the letter “Use of Pilot Car with Temporary Traffic Control Signals” and provided the following reasons for Paragraph 4, Section 6C.13 (FHWA, 2010):

- Since work zones adopting pilot car operations are long, presence of a flagger assures the road users of the presence of a work zone and that they will be eventually given the opportunity to travel through the lane-closure area.

- A several minute wait at the signal on red indication might result in the road users becoming impatient and proceeding into the work zone assuming that the signal unit had malfunctioned.
- A flagger would alert the work crew and the pilot car operator regarding a noncompliant vehicle that enters the work zone.

As 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. Furthermore, there is minimal guidance within the 2009 MUTCD regarding the work zone traffic volume thresholds where a PTS system would fail and safety could be compromised. Other useful information was also unavailable to support proposed guidance in the 2009 MUTCD to the safe operation of a PTS system in a work zone, such as appropriate signal timings and length of work zone.

1.4 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. Three conditions were selected 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 present; and
- A PTS system without a flagger present.

Data were to be collected at two-lane, two-way work zones anticipating pilot car operations and flagger operations. All the collected data were to be analyzed using the primary measures of effectiveness, which 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 research was anticipated to be completed by conducting an operational evaluation, a statistical evaluation, and developing a model to provide guidelines for the use of PTS systems at long work zones in conjunction with pilot car operations. The operational evaluation was conducted by investigating and reporting on 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 calculating 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 and safety could be compromised. 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” (TE710) Standard used for this research were provided by KDOT and can be found in Appendix F.

1.5 Report Organization

This report is divided into eight 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 provides a description of the general data collection methodology. Chapter 4 provides a detailed description of the test locations where data collection was conducted. Chapter 5 describes the data analyses as well as calculations for each of the analyses. Chapter 6 provides findings from the general field observations and from the results of the data analyses. Chapter 7 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 8 discusses the scope for future research.

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. Only the literature that was directly related to the research was included and is summarized in this chapter.

2.1 Portable (or Temporary) Traffic Signals

Carlson et al. (2015) evaluated pilot cars and portable traffic control signals with and without flaggers. Data were collected at eight test sites, two-lane two-way rural roads in the Brownwood District, Texas, in May and October 2013. The eight test locations represented varying annual average daily traffic (AADT) ranging from 470 to 2,800 vehicles per day (as of 2011) and with speed limits ranging from 55 to 75 mph. Also, the length of lane closures varied at every test location and ranged from 0.41 to 1.42 miles. The research team calculated the violation rates for the signals with and without a flagger conditions and found that only three percent of the drivers did not comply with the signals and pilot vehicles for both the studied conditions. They also found that there was no statistically significant or practical difference in the number of violations when a signal was used with and without a flagger, based on the results of a test of proportions conducted at a 0.05 level of significance. Therefore, it was recommended to use the portable traffic signals without a flagger to control traffic at lane closures on two-lane, two-way roadways. Finally, the research team also developed guidelines to assist pilot car drivers in the selection of appropriate green time based on a start-up lost time of 4 seconds and assumed each vehicle axle required 1 second of green time.

Finley et al. (2015) evaluated alternate methods for controlling traffic on one-lane, two-way highways in Ohio. Data were collected at 15 lane-closure type work zones in District 11, Carrollton County, OH, for four conditions: flagger with a STOP/SLOW paddle, red/yellow automated flagger assistance device (AFAD) with a flagger at each end of the work zone, red/yellow AFAD with one flagger operating both the devices, and portable traffic signals at both ends of the work zone. The AADT ranged from 520 to 9,230 vehicles per day and the length of lane-closures ranged from 700 to 3,430 feet. It was found that the violation rate for the portable traffic signals was 47.1 violations per 100 stop cycles. Based on the results of a test of proportions conducted at a 0.05 level of significance, it was found that the number of violations for the portable traffic signal method were significantly different than the violations for the flagger method. The researchers also found that 99 percent of the violations had occurred at the end of the green interval when the non-compliant vehicles were able to see the end of the departed queue at a short distance and followed it to enter the work zone. They also found that the average green interval when the portable traffic signals were used was 39 seconds, and found that in 36 percent of the cycles the vehicle queue did not clear completely. The researchers conducted a cost-benefit analysis and found that on a limited usage of the portable traffic signal systems, the cost of purchase could be recovered in about 9 years. It was concluded that if the green intervals were determined based on the approaching traffic volumes and work zone lengths, the use of portable traffic signal systems would not result in a significant increase in the driver delay as compared to the flagger method. Finally, the researchers recommended using the portable traffic signals for work zones with durations of at least half a day, and identified high volume roads with flat side slopes as suitable locations for using these systems.

Ullman and Levine (1987) 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. The three sites chosen represented traffic volumes varying from 600 to 10,000 ADT (as of 1985) and work zone lengths ranging from 0.11 to 0.49 miles. Data were collected for traffic volumes, driver noncompliance of the signal, and vehicle stopped delay. Data for delay and compliance were collected for approximately 4 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 were 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 installing a temporary STOP HERE ON RED sign next to the stop line, enhancing the need for stopping. Table 2.1 shows that the fixed-time portable signals provided significant cost savings over the use of flaggers.

Table 2.1: Summary of Portable Signal Costs and Benefits

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

Source: Finley et al. (2015)

Note: Data for Site 2 was not used in the analysis because the delay estimates could not be estimated for flagger control.

[a] Based on 1986 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 2.1, the costs of additional vehicle delay were based on the estimates of value of travel time by Chui and McFarland (1986) which were available at the time of their research. Based on an approximate cost of $8,000 (as of 1987) per signal, the researchers estimated that the cost of purchase of the signals would be recovered after approximately 1,600 hours of service. Therefore, it was found that substantial savings in flagger labor costs could be achieved by using a portable fixed-time traffic signal system with savings ranging from $9 to $14 per hour. These savings in labor costs were calculated based on the wages and benefits of approximately $6 per hour for a Maintenance Technician I working for the Texas State Department of Highways and Public Transportation in 1987.

Daniels et al. (2000) studied the use of PTS technology to replace flaggers as a means for improving the efficiency of two-lane rural maintenance operations in Texas. 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. Field tests were performed for a total of 20 days over a 3-month period from June 1998 to August 1998 at three test locations (two hilly and one curving road) in the San Antonio District of the Texas Department of Transportation (TxDOT). 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. During this study, many maintenance sections were functioning with inadequate staff, therefore the researchers assumed that only one flagger position could be eliminated and calculated the potential savings anticipated by the use of this technology. It was found that the cost of purchase could be recovered after 2 years of operation if the equipment was used 8 to 10 days per month and savings in subsequent years were estimated at $20,000 to $30,000 per year (for 1999-2000). From their field test cases, the researchers found that PTS systems were technically feasible in improving the crew efficiency and flexibility on two-lane rural work zones for maintenance operations. TxDOT guidelines in 1996 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 lengths up to 2,600 feet where the ends of the work zone were not visible to each other. They also suggested that the maximum time before driver confusion and a possible violation was 4 minutes. Therefore, the threshold for maximum wait time was recommended at 4 minutes and corresponding values were developed for the yellow clearance time, the red clearance time, and the maximum green time. Finally, the researchers also recommended values for minimum green time and the extension interval to be 7 to 10 seconds and 3 seconds, respectively.

Stout (2013) presented the different applications of PTS systems in short-term work zones and indicated that using these systems could replace flaggers, making them available for other work activities. The main advantages for using the signal systems were found to be the speed, portability, and ease of installation.

A report by the Roadway Safety Consortium (n.d.) listed the different strategies for improving the safety of workers in work zones by suggesting measures for improving flagger visibility and minimizing the risks of flaggers being hit by errant vehicles. The report recommended the use of PTS systems at one-way work zones which were expected to last for several days and at one-lane work zones to remove flaggers from being directly exposed to approaching traffic It was indicated that appropriate signal timings were vital when implementing temporary traffic signals, as extensive wait times could lead to confusion, driver impatience, and decreased compliance. It was recommended to use pilot car operations for alternating one-way work zones where the travel paths were not clear and where travel speeds adjacent to the activity area were to be kept low.

In 2013, the Oregon Department of Transportation (ODOT) Safety Audit identified the strengths and weaknesses within ODOT's Traffic Control Plan (TCP) standards, practices, and their implementation (ODOT, 2013). After reviewing 29 highway work zones, the report identified the temporary/portable traffic signals and pilot car operations as successful methods to alternate traffic at one-lane, two-way work zones. The report also indicated that pilot car operations were effective in maintaining safe operating speeds and minimal traffic delays at work zones with lower traffic volumes (<2,000 ADT) and limited side roads. Similarly, it was also found that pilot car operations were not as successful in minimizing traffic delays for work zones with higher traffic volumes (>3,500 ADT), several driveways, and an end-to-end distance of 1 to 2 miles.

A traffic advisory leaflet detailed practices in England, UK, for the use of PTS systems at road and street works (Department for Transport, 2011). 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 setting up the PTS units, since poor setups could increase the risk of crashes, additional costs in fuel and time, increased pollution, and driver frustration.

Lee, Park, Kim and Lee (2012) studied the effectiveness of a vehicle-actuated signal control system on work zone operations for two-lane highways in Korea. 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 the 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 short 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 meter (1,200 ft) long work zone. In work zones with lengths of 200 meters (600 ft), 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 with lengths of 400 meters (1,200 ft), 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 with lengths of 200 meters (600 ft) and 400 meters (1,200 ft). The results of conflict analysis showed that ADAR had no crossing conflicts and fewer conflicts than other signal control methods, especially for 200 meter (600 ft) long work zones where ADAR had no conflicts. Since the average control delay exceeded 100 seconds for work zones with lengths of 400 meters (1,200 ft), 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 lengths greater than 400 meters (1,200 ft) to reduce delays and increase traffic safety.

2.2 Pilot Car and Flagger Operations

Rys, Jacob, Clark, Gutierrez, and Kovala (2012), in Phase I of their study, examined the most effective method of informing drivers about delay time when approaching a pilot car operation at a two-lane rural highway work zone. 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 a portable message sign with countdown timer. Table 2.2 provides the summary of the feasibility of these different notification systems based on various evaluation criteria (Rys & Jacob, 2009).

As shown in Table 2.2, 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 portable message signs with a countdown timer were 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 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 4 to 5 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 US-77 in Riley County, Kansas. The test was run for 3 hours and 112 public survey questionnaires were distributed. 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 (Hobson, 2012). 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 1 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.

Table 2.2: Summary of Comparison of Information Dissemination Systems Used

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

Source: Rys et al. (2012)
[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)

The 2008 *KDOT Flagger Handbook* presented operations and guidance for personnel who would be used as flaggers in work zones (KDOT, 2008). 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.

2.3 Temporary Traffic Control Devices

Carlson, Fontaine, and Hawkins (2000) evaluated the various traffic control devices, treatments, and practices for rural high-speed maintenance work zones. Nine work zones, in which four were two-lane highways with flagger operations, 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 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.

Fontaine, Carlson, and Hawkins (2000) evaluated the use of seven devices at six short-term two-lane work sites in the Childress District, TX: portable rumble strips, drone radar, fluorescent yellow worker vests, retroreflective vehicle visibility improvements, fluorescent orange signs, and speed display trailers. Speed data were collected by the LIDAR guns for the free flow speeds throughout the work zones, and traffic counters with piezoelectric sensors were 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 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.

All the literature reported herein was useful in development of the research methodology presented in Chapter 3, provided some guidelines during the data reduction and analyses, and finally, also supported some of the recommendations discussed in Chapter 7.

Chapter 3: Research Methodology

This chapter is divided into four parts and details the research methodology and tasks in the order that they were conducted as part of this study. After conducting a detailed review of previous literature, the following tasks were conducted and described in this chapter: the survey of practice, the closed-course field testing, the site selection and data collection methodology, the work zone traffic control operations, and an overview of the data reduction and data analyses.

3.1 Survey of Practice

To understand the commonality of portable traffic signals in work zones in combination with pilot car operations, and if any specifications were used by a state highway agency, a survey of state highway agencies was conducted between May and June 2014. Out of all of the possible state highway agencies, the research team received information back from 19, based on telephone or email communications with work zone engineers within each state highway agency. A summary of the survey is shown in Table 3.1.

As shown in Table 3.1, it was found that 18 of the 19 states that responded to the survey used PTS system in work zones. It was also found that 12 state highway agencies used the MUTCD as the primary reference, while six state Departments of Transportation (DOTs) developed additional guidelines as reference for the use of PTS systems, pilot car operations, and flagger operations. Finally, it was also found that two state highway agencies used a PTS system in conjunction with pilot car operations and three state highway agencies used a PTS system in conjunction with flagger operations. Based on the survey, the research team found that although PTS systems are common in the state highway agencies surveyed, additional guidance is still needed to fully understand their use and acceptance as a work zone traffic control device. Appendix B provides a detailed description of the responses for all the 19 state DOTs that were surveyed.

Table 3.1: Summary of Responses for the Survey of Practice

State DOT	Pilot Car Operation	Portable Traffic Signal	PTS with Pilot Car	PTS with Flagger Operation	Maximum Length of Work Zone for PTS (miles)	MUTCD	Own Standards
Arkansas	Yes	Yes	No	No	0.2	Yes	-
Connecticut	No	Yes	No	Yes	NS	Yes	-
Florida	Yes	Yes	No	No	NS	Yes	-
Idaho	Yes	Yes	No	No	5	-	Yes
Illinois	No	Yes	No	No	1.5	-	Yes
Indiana	Yes	No	NA	NA	NA	-	-
Iowa	Yes	Yes	No	No	2.5	-	Yes
Kentucky	No	Yes	No	No	0.03	Yes	Yes
Maryland	No	Yes	NA	NS	0.4	-	Yes
Michigan	Yes	Yes	No	No	2	Yes	-
Minnesota	Yes	Yes	No	Yes	NS	Yes	Yes
Montana	Yes	Yes	No	Yes	2	Yes	-
Nebraska	Yes	Yes	No	No	0.2	Yes	-
Nevada	Yes	Yes	No	NS	5	Yes	-
Ohio	No	Yes	NA	No	NS	-	Yes
Oklahoma	Yes	Yes	No	No	NS	Yes	-
Tennessee	No	Yes	No	NS	1.5	Yes	-
Texas	Yes	Yes	Yes	No	NS	-	Yes
Wyoming	Yes	Yes	Yes	No	NS	Yes	-

Note: “NA” Not applicable because the PTS or pilot car operations were not used, “NS” No maximum length of work zone was specified during the survey, “-” Did not use the corresponding guidelines.

3.2 Closed-Course Field Test

A closed-course testing was performed on August 4, 2014, in the East Lot of the Park and Ride facilities at the University of Kansas. Figure 3.1 shows a photo from the closed-course testing.

Figure 3.1: Closed-Course Field Testing of the Signal Units at the University of Kansas

As shown in Figure 3.1, the functioning of the several components and the features of the ADDCO PTS-2000 unit with the Galaxy operating system were demonstrated by representatives from John Thomas, Inc. (Mr. Doug Niemerg and Mr. Roger Alexander). At the time, instructions were provided for operating the main control box on the PTS unit to lower and raise the mast arm and solar panels, operate the handheld Galaxy Flagger Remote (GFR), and alter the signal timings. Mr. Garry Olson (KDOT) was also present at the time of this closed-course testing.

3.3 Site Selection and Data Collection

The next step in the research was to select suitable test locations where data were to be collected. For selecting the test locations, specific characteristics of the work zone included the following:

- The work zone must be considered a long work zone. This meant that pilot car operations were required to escort a queue of vehicles through the work zone.
- The work zone must be a two-lane state highway and have a project where one-lane, two-way traffic operations were required.
- Work operations were conducted during daylight hours.

Based on these guidelines, four locations were identified by working with KDOT and selected for the data collection. The following were the four test locations that were selected for this research:

1. US-56 near Burlingame, KS
2. K-31 near Melvern, KS
3. US-24 near Beloit, KS
4. US-50 near Newton, KS

Data were collected at these four test locations 3 days per week for a period of 4 weeks in August 2014. A detailed description of all the test locations and data collection is provided in Chapter 5.

3.3.1 Equipment Used

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

3.3.1.1 Safety

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

3.3.1.2 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.

3.3.1.3 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 1 to 2 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 3.2 shows the video camera used for the research.

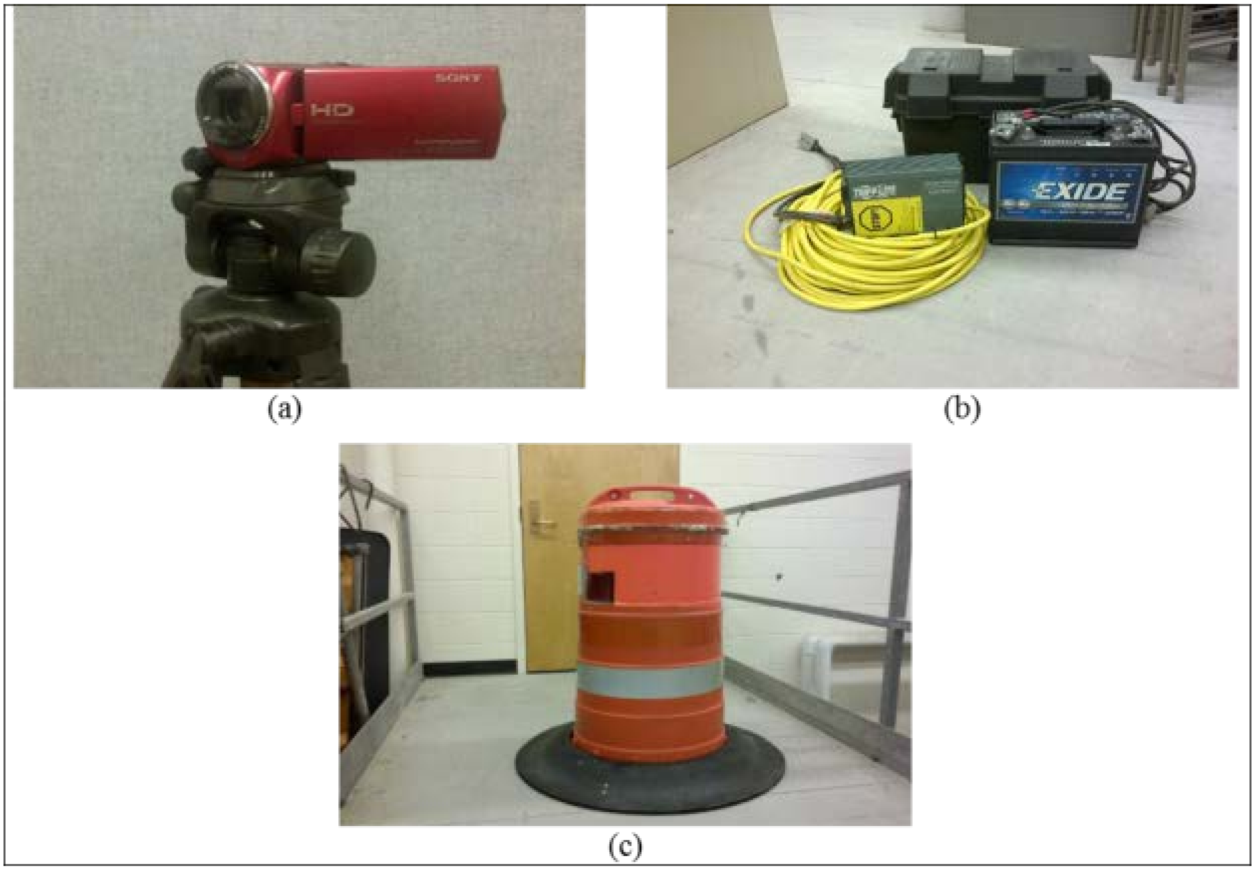

Figure 3.2: Sony HDR CX-220 Camera Used for Video Data Collection

As shown in Figure 3.2(a), 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 3.2(b) shows the battery and the inverters used for the research.

As shown in Figure 3.2(b), 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-foot-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 3.2(c) shows the custom built drum used to place the video cameras for the research.

As shown in Figure 3.2(c), three standard traffic drums were borrowed from Twin Traffic Marketing Corp. for placing the video cameras during the data collection. 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.

3.3.1.4 Traffic Signs

The four traffic signs used for the purpose of the research were: SIGNAL AHEAD [W3-3], STOP HERE ON RED [R10-6], FLAGGER AHEAD [W20-7A], and WAIT FOR PILOT CAR [KG20-5]. Figure 3.3 shows the SIGNAL AHEAD sign used for the research.

Figure 3.3 Traffic Signs Used

As shown in Figure 3.3, the SIGNAL AHEAD signs were borrowed from C-Hawkk's construction office in Eudora, KS. The location of the signage was determined based on the temporary traffic control plans 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 3.3 shows the STOP HERE ON RED sign, FLAGGER AHEAD sign, and WAIT FOR PILOT CAR sign used for the research.

As shown in Figure 3.3, the STOP HERE ON RED signs were borrowed from C-Hawkk'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.

3.3.2 Experimental Design and Data Collection Methodology

A general data collection and equipment setup methodology was established prior to the field data collection. Figure 3.4 shows the equipment setup plan that was designed to indicate the location of the PTS unit, video cameras, and the traffic signs during the field data collection.

As shown in Figure 3.4, 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. Data were required to be collected at all the work zone ends established by the contractor during the selected dates. The collected data were considered to be valid only if the section of the roadway on which the signal and/or flagger were located was the major approach and the rest of the road geometry at that work zone end did not alter the work zone traffic operations (discussed in Section 3.3.3). The following section describes the general procedure that was followed at every test location in regards to equipment setup and video data collection.

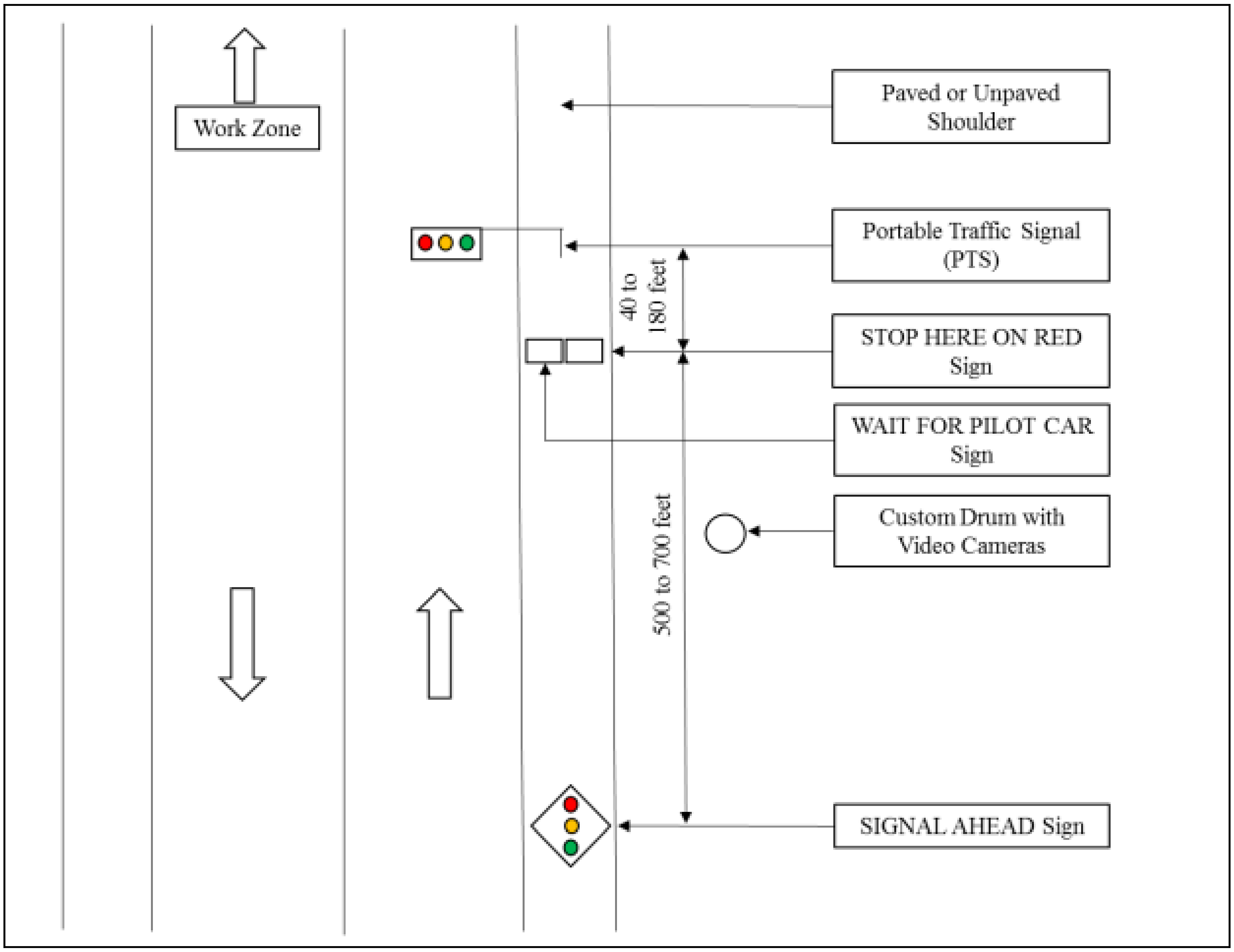

Figure 3.4: Designed Equipment Setup Plan

3.3.2.1 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, one camera on tripod at the end of the work zone, an external battery with an inverter, and the traffic signs as per the plan shown in Figure 3.4. The additional signs were setup a short time after the other work zone signage was setup by the contractor. The team periodically checked the PTS units, video cameras, and the signs to ensure that the setup was unaltered and data were collected. To ensure that the driver behavior was not affected, the research team ensured that no contractor/official vehicle was parked next to the signal and/or the data collection setup.

Data collection started as soon as the data equipment was setup 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 during the data reduction process. A minimum of 8 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. The rest of the equipment was then prepared for the following day.

3.3.3 Work Zone Traffic Control Operations

The contractor established the work zone for one-lane, two-way traffic at all test locations. At all the test locations, pilot car operations were used to escort the queue of stopped vehicles and guide them through the work zone at safe speeds. Figure 3.5 shows a standard contractor pilot that was used during this research with the PILOT CAR FOLLOW ME sign [G20-4].

Figure 3.5: Standard Pilot Car with the Pilot Car Sign Installed

When a portable traffic signal system was used with or without a flagger present, the pilot car drivers were solely responsible for operating the signal and activating the green phase prior to escorting the stopped queue. Figure 3.6 shows a photo of the GFR remote control device used for operating the signal unit in this research study. When activating the red and green phases on the signal unit, the pilot car drivers first selected the appropriate call button (for example, “Call 1”) on the GFR Remote control and then selected the “Red Rest/Pilot” button to activate the maximum green interval. In any circumstances if the pilot car drivers did not press the “Red Rest/Pilot” button, the signal activated only the minimum green interval even if the stopped queue was not completely cleared. The pilot car drivers were required to proceed into the work zone only when the signal green phase was active. They would repeat the steps for the activation of the green interval in events when the signal did not display a green indication.

Figure 3.6: Galaxy Flagger Remote Control Device

When the pilot car drivers approached the stopped queue of vehicles, they completed their U-turn by making a 90-degree turn using an available driveway or side road at the flagger/signal station to escort the vehicles into the work zone. For this study, the research team members essentially designed the signals as semi-actuated traffic signals with minimum and maximum green times and a green extension time. Green extensions were provided using radar sensors, and continued until no traffic was detected or until the maximum green time was reached. When a flagger was used with a signal and the pilot car operations, the flagger would provide the pilot car driver with information regarding the proper functioning of the signal and act as an additional presence to identify and minimize red light running vehicles and/or signal anomalies.

On the first day of data collection at all test locations, 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 (for two cycles) in the pilot car to familiarize the pilot car driver with the GFR device for the PTS units and verified the correct functioning of all 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 the first few cycles to ensure the proper functioning of the system and identify anomalies. The relocation of the PTS unit and all the other data collection equipment was required when the work zone end stations were moved.

3.4 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 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 5. The data analyses were divided into three parts as listed below.

First, an evaluation and comparison of the different operational 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 at a 0.05 level of significance was used to analyze the two data sets. The null and alternate hypotheses for the test were:

H_o: $p_1 \geq p_2$

H_A: $p_1 < p_2$

Where:

p_1 & p_2 = proportions of red light running vehicles in the conditions that were analyzed.

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 4 provides a detailed description of the field data collection conducted at the four test locations mentioned previously.

Chapter 4: Field Data Collection

Field data were collected at four locations 3 days per week for 4 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.).

Figure 4.1 shows a map of the four test locations where data were collected for the purpose of this research study.

Figure 4.1: Map Showing the Four Test Locations for Field Data Collection

As shown in Figure 4.1, data were collected at the following four different test locations in Kansas:

- Test Location 1: US-56 near Burlingame
- Test Location 2: K-31 near Melvern
- Test Location 3: US-24 near Beloit
- Test Location 4: US-50 near Newton

Figure 4.2 shows a photo of the three conditions for which data were collected during this research study.

Figure 4.2: Three Study Conditions: (a) Flagger Only; (b) PTS with a Flagger; (c) PTS without a Flagger

As shown in Figure 4.2, at each of the four 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 present in conjunction with a pilot car operation.

Table 4.1 provides a summary of the entire data collection conducted from August 5, 2014, to August 28, 2014.

Table 4.1: 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; All numbers are rounded off.

As shown in Table 4.1, 161 hours of valid video data (after excluding setup and tear down video data) were available for analysis of the three study conditions from each of the test locations. A detailed description of the test locations, the site characteristics, and the data collection summary is provided in the subsequent sections.

4.1 Test Location 1: US-56 Burlingame, KS

Data were collected at a work zone on US-56 near Burlingame and Scranton, in Osage County, KS, from August 5, 2014, to August 7, 2014, for the PTS with a flagger and PTS without a flagger conditions. Additionally, data were collected for the flagger only condition on July 30 and July 31, 2014, at the same location. Table 4.2 presents a summary of the site characteristics for the test location.

Table 4.2: Summary of Site Characteristics for Test Location 1

Location	**US-56, Osage County, KS, near Burlingame and Scranton**	
Roadway Characteristics	Type	Two-lane, two-way rural highway
	Surface	Asphalt
	Lane Width	12'-0"
	Speed Limits	30 to 60 mph
	AADT	1,010/60 to 3,320/140 vpd
Work Zone Characteristics	Contractor	Dustrol, Inc.
	Type of Work Activity	Hot-in-place recycle (HIR) pavement preservation
	End-to-End Distance	2 to 2.5 miles
	Visibility	Activity area not visible to stopped traffic
PTS Characteristics	Minimum Green Interval	30 seconds
	Maximum Green Interval	60 seconds
	Gap to Red	5 seconds

Note: "AADT" – Average Annual Daily Traffic, "vpd" – vehicles per day.

Figure 4.3 shows a map of the Test Location 1 and all the work zone ends where data were collected.

As shown in Figure 4.3, data were collected at 14 work zone ends for the three study conditions. For work zone Ends 1 to 4, the work zone moved southbound on July 30 and 31, 2014. From August 5, 2014, onwards, data were collected over the following work zone sections: 5 to 6, 7 to 8, 9 to 10, 11 to 12, and 13 to 14. Table 4.3 presents a summary of the data collection at each of the work zone ends at the test location for the different study conditions.

As shown in Table 4.3, a total of approximately 50 hours of field video data were collected at the test location for the three study conditions. It was also found that the green phase on the signal was not activated 14 times during the entire data collection period at this location. A detailed discussion of the possible reasons for inactivated signal green phases is presented in Chapter 7.

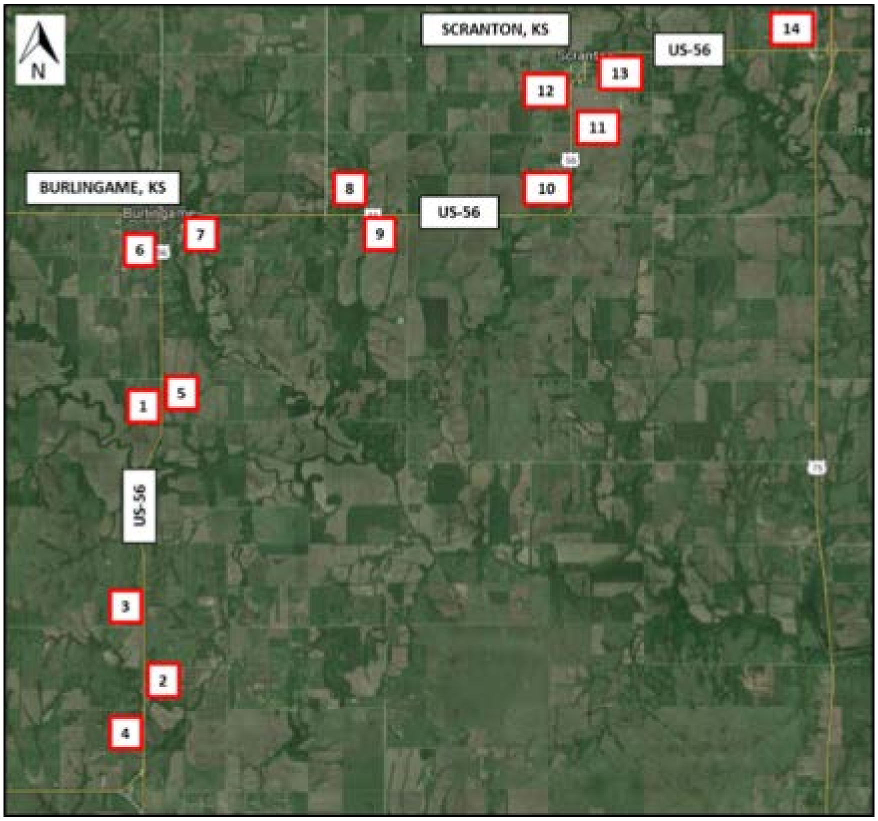

Figure 4.3: Map Showing Work Zone Ends at Test Location 1 on US-56

Table 4.3: Summary of Data Collection for Test Location 1

Date	Work Zone End	Condition	Start of Session	End of Session	Total Data Collected	Inactive Green Phases
7/30/2014	1	A	12:47 p.m.	3:10 p.m.	2 hours 23 mins	NA
	2	A	3:40 p.m.	4:54 p.m.	1 hour 14 mins	NA
7/31/2014	3	A	8:10 a.m.	12:50 p.m.	4 hours 40 mins	NA
	4	A	1:03 p.m.	4:03 p.m.	3 hours 00 mins	NA
8/5/2014	5	B	8:51 a.m.	11:54 a.m.	3 hours 03 mins	2
	6	NA	NA	NA	NA	NA
	7	B	12:42 p.m.	5:11 p.m.	4 hours 29 mins	3
	8	B	12:48 p.m.	4:56 p.m.	4 hours 08 mins	4
8/6/2014	9	C	8:12 a.m.	2:32 p.m.	6 hours 20 mins	1
	10	C	8:52 a.m.	2:16 p.m.	5 hours 24 mins	3
8/7/2014	11	C	9:10 a.m.	12:55 p.m.	3 hours 45 mins	0
	12	C	9:04 a.m.	12:14 p.m.	3 hours 10 mins	1
	13	C	2:00 p.m.	6:00 p.m.	4 hours 00 mins	0
	14	C	1:00 p.m.	5:35 p.m.	4 hours 35 mins	0
Total					**50 hours 11 mins**	**14**

Note: “NA” – Not applicable because signal not used and no data were collected; “mins” – minutes.

4.2 Test Location 2: K-31 near Melvern, KS

Data were collected at a work zone on K-31 near Melvern, KS, from August 12, 2014, to August 14, 2014, for the three conditions mentioned previously. Table 4.4 presents a summary of the site characteristics for the test location.

Table 4.4: Summary of Site Characteristics for Test Location 2

Location	**K-31, Osage County, KS, near Melvern**	
Roadway Characteristics	Type	Two-lane, two-way rural highway
	Surface	Asphalt
	Lane Width	12'-0"
	Speed Limits	30 to 55 mph
	AADT	490/65 to 585/65 vpd
Work Zone Characteristics	Contractor	Dustrol, Inc.
	Type of Work Activity	Hot-in-place recycle (HIR) pavement preservation
	End-to-End Distance	2 to 2.5 miles
	Visibility of Activity Area	Activity area not visible to stopped traffic
PTS Characteristics	Minimum Green Interval	30 seconds
	Maximum Green Interval	60 seconds
	Gap to Red	5 seconds

Note: "AADT" – Average Annual Daily Traffic, "vpd" – vehicles per day.

Figure 4.4 shows a map of the Test Location 2 and all the work zone ends where data were collected.

As shown in Figure 4.4, data were collected at 6 work zone ends for the three study conditions. The following were the work zone sections where data were collected: 1 to 2, 3 to 4, and 5 to 6. Table 4.5 presents a summary of the data collection at each of the work zone ends at the test location for the different study conditions.

As shown in Table 4.5, a total of approximately 41 hours of field video data were collected at the test location for the three study conditions. It was also found that the green phase on the signal was not activated 10 times during the entire data collection period at this location. A detailed discussion of the possible reasons for inactivated signal green phases is presented in Chapter 7.

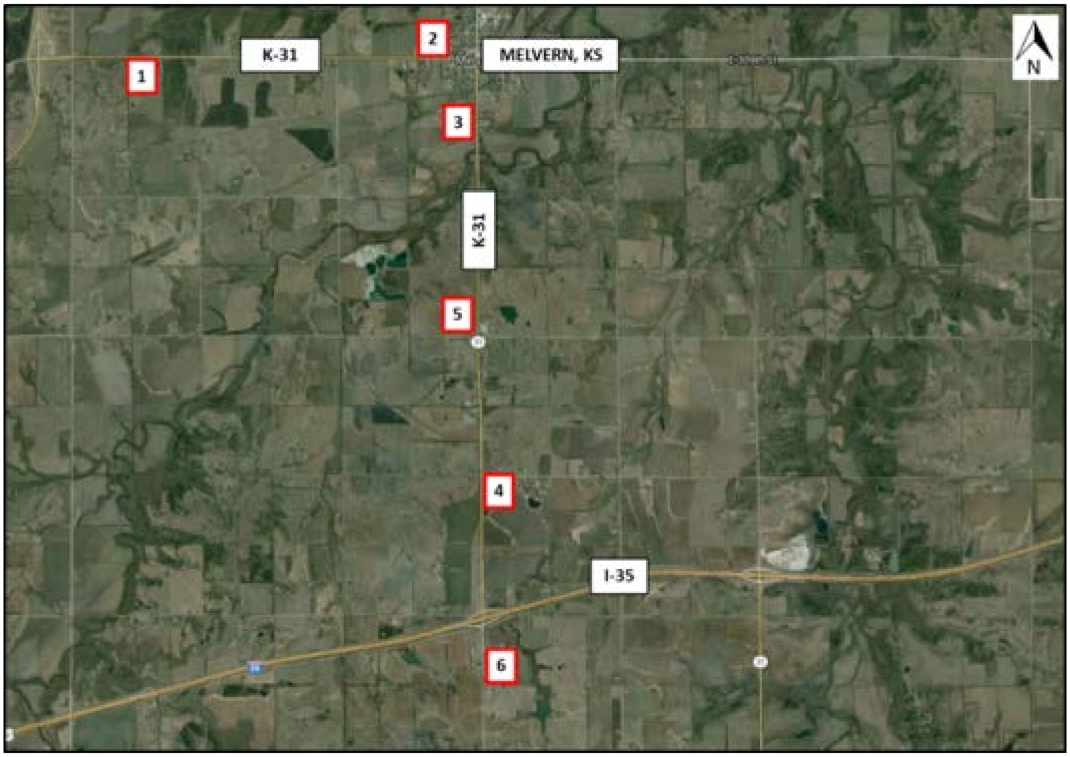

Figure 4.4: Map Showing Work Zone Ends at Test Location 2 on K-31

Table 4.5: Summary of Data Collection for Test Location 2

Date	Work Zone End	Condition	Start of Session	End of Session	Total Data Collected	Inactive Green Phases
8/12/2014	1	B	9:30 a.m.	11:33 a.m.	2 hours 03 mins	0
	2	C	8:32 a.m.	12:07 p.m.	3 hours 35 mins	1
8/13/2014	3	C	7:37 a.m.	12:07 p.m.	4 hours 30 mins	1
	4	C	8:30 a.m.	12:16 p.m.	3 hours 46 mins	3
	5	C	1:44 p.m.	5:40 p.m.	4 hours 06 mins	0
	6	C	12:45 p.m.	5:00 p.m.	4 hours 15 mins	0
8/14/2014	5	C	7:53 a.m.	1:35 p.m.	5 hours 42 mins	3
	6	C	7:21 a.m.	1:12 p.m.	5 hours 51 mins	2
	5	A	1:52 p.m.	5:39 p.m.	3 hours 47 mins	NA
	6	A	2:10 p.m.	5:18 p.m.	3 hours 08 mins	NA
Total					**40 hours 43 mins**	**10**

Note: "NA" – Not applicable because signal not used; "mins" – minutes.

4.3 Test Location 3: US-24 Beloit, KS

Data were collected at a work zone on US-24 near Beloit, KS, from August 19, 2014, to August 21, 2014, for the three conditions mentioned previously. Table 4.6 presents a summary of the site characteristics for the test location.

Table 4.6: Summary of Site Characteristics at Test Location 3

Location	**US-24, Mitchell County, KS, near Beloit**	
Roadway Characteristics	Type	Two-lane, two-way rural highway
	Surface	Asphalt
	Lane Width	12'-0"
	Speed Limits	45 to 65 mph
	AADT	2,750/380 to 3,890/385 vpd
Work Zone Characteristics	Contractor	Hall Brothers, Inc.
	Type of Work Activity	Hot Mix Asphalt (HMA) Overlay
	End-to-End Distance	2.2 to 2.8 miles
	Visibility of Activity Area	Activity area not visible to stopped traffic
PTS Characteristics	Minimum Green Interval	30 seconds
	Maximum Green Interval	60 seconds
	Gap to Red	5 seconds

Note: "AADT" – Average Annual Daily Traffic, "vpd" – vehicles per day.

Figure 4.5 shows a map of the Test Location 3 and all the work zone ends where data were collected.

As shown in Figure 4.5, data were collected at four work zone ends for the three study conditions. The following were the work zone sections where data were collected: 1 to 2, and 3 to 4. Table 4.7 presents a summary of the data collection at each of the work zone ends at the test location for the different study conditions.

As shown in Table 4.7, a total of approximately 48 hours of field video data were collected at the test location for the three study conditions. It was also found that the green phase on the signal was not activated eight times during the entire data collection period at this location. A detailed discussion of the possible reasons for inactivated signal green phases is presented in Chapter 7.

Figure 4.5: Map Showing Work Zone Ends at Test Location 3 on US-24

Table 4.7: Summary of Data Collection for Test Location 3

Date	Work Zone End	Condition	Start of Session	End of Session	Total Data Collected	Inactive Green Phases
8/19/2014	1	B	9:47 a.m.	5:00 p.m.	7 hours 13 mins	2
	2	B	9:21 a.m.	5:30 p.m.	8 hours 09 mins	2
8/20/2014	1	C	8:50 a.m.	5:00 p.m.	8 hours 10 mins	1
	2	B	8:30 a.m.	5:05 p.m.	8 hours 25 mins	2
8/21/2014	3	C	8:30 a.m.	12:30 p.m.	4 hours 00 mins	0
	3	A	12:30 p.m.	4:30 p.m.	4 hours 00 mins	NA
	4	C	8:25 a.m.	4:30 p.m.	8 hours 05 mins	1
Total					**48 hours 2 mins**	**8**

Note: "NA" – Not applicable because signal not used; "mins" – minutes.

4.4 Test Location 4: US-50 near Newton, KS

Data were collected at a work zone on US-50 near Newton, KS, from August 26, 2014, to August 27, 2014, for the three conditions mentioned previously. Table 4.8 presents a summary of the site characteristics for the test location.

Table 4.8: Summary of Site Characteristics for Test Location 4

Location	**US-50, Harvey County, KS, near Newton**	
Roadway Characteristics	Type	Two-lane, two-way rural highway
	Surface	Asphalt
	Lane Width	12'-0"
	Speed Limits	65 mph
	AADT	4,700/1,300 to 5,130/1,360 vpd
Work Zone Characteristics	Contractor	APAC, KS-MO
	Type of Work Activity	Mill and Hot Mix Asphalt (HMA) Overlay
	End-to-end Distance	2.6 miles
	Visibility of Activity Area	Activity area not visible to stopped traffic
PTS Characteristics	Minimum Green Interval	30 seconds
	Maximum Green Interval	240 seconds
	Gap to Red	12 seconds

Note: "AADT" – Average Annual Daily Traffic, "vpd" – vehicles per day.

Figure 4.6 shows a map of the Test Location 4 and all the work zone ends where data were collected. As shown in Figure 4.6, data were collected at 4 work zone ends for the three study conditions. The following were the work zone sections where data were collected: 1 to 2, and 3 to 4. Table 4.9 presents a summary of the data collection at each of the work zone ends at the test location for the different study conditions.

Figure 4.6: Map Showing Work Zone Ends at Test Location 4 on US-50

Table 4.9: Summary of Data Collection for Test Location 4

Date	Work Zone End	Condition	Start of Session	End of Session	Total Data Collected	Inactive Green Phases
8/26/2014	1	NA	NA	NA	NA	NA
	2	B	9:56 a.m.	3:10 p.m.	5 hours 14 mins	2
8/27/2014	3	B	9:00 a.m.	1:00 p.m.	4 hours 00 mins	1
	3	C	1:00 p.m.	6:00 p.m.	5 hours 00 mins	0
	4	B	8:18 a.m.	6:40 p.m.	10 hours 22 mins	3
8/28/2014	NA	NA	NA	NA	0	0
Total					**24 hours 36 mins**	**6**

Note: "NA" – Not applicable because signal not used and no data were collected; "mins" – minutes.

As shown in Table 4.9, a total of approximately 25 hours of field video data were collected at the test location for the three study conditions. It was also found that the green phase on the signal was not activated six times during the entire data collection period at this location. A detailed discussion of the possible reasons for inactivated signal green phases is presented in Chapter 7. Chapter 5 presents a detailed description of the data reduction and analyses conducted on the collected video data.

Chapter 5: Data Analysis

5.1 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 wait times 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 (KDOT, 2007). 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 cars, 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 was 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. Figure 5.1 shows a sample data reduction sheet developed for this research study.

Team Members	A and B
PTS Used	Y/N
Flagger Used	Y/N
Video Start Time	9:47:00 AM
Video End Time	4:29:10 PM

VIDEO DATA													**Red Light Running (RLR)**			**Type of Red Light Running**			
Cycle No.	**Arrival Time of First Vehicle**	**Departure Time of First Vehicle**	**Total Wait Time**		**Start of Green Interval**	**End of Green Interval**	**Total Green Time (seconds)**	**Number of Vehicles Cleared in the Queue**				**Queue Length (feet)**	**Type of Vehicle**	**Time of Day**	**Time on Video**	**Follow a Departed Queue**	**Leave the Stopped Queue**	**Waived by Flagger**	**Disregard the Signal**
			Minutes	**Seconds**				**Trucks**	**PC's**	**Two-Wheelers**	**Total**								
1	2'22"	10'06"	7'44"	464	9:57:06 AM	9:57:58 AM	52	4	6	0	10	520	Truck	10:20:34 AM	33'34"	-	-	Yes	-
2	11'14"	20'27"	9'13"	553	10:07:27 AM	10:08:01 AM	34	0	5	0	5	150	Car	10:20:38 AM	33'38"	Yes	-	-	-
3	22'27"	32'29"	10'02"	602	10:19:29 AM	10:20:29 AM	60	5	10	0	15	725							
4	36'57"	44'52"	7'55"	475	10:31:52 AM	10:32:52 AM	60	4	5	0	9	490							
Average Wait Time			**8'44"**	**523.5**	**Average Green Time**		**51.5**	**13**	**26**	**0**	**39**	**1,885**							

Figure 5.1: Sample Data Reduction Sheet

As shown in Figure 5.1, data were manually reduced to accurately record all the parameters described previously. The research team recorded information regarding the team members, use of a signal/flagger, and start and end of data collection periods to ensure accuracy in data reduction. Information regarding the average duration of wait time for the first vehicle in each queue, the average duration of the green interval, and the total number of vehicles of each type cleared in each queue was also calculated at the time of data reduction. With the help of the time recorded in the video cameras during the data collection, the time on video was interpolated to determine the corresponding time of day. RLR violations were categorized into four different categories, elaborated in the subsequent sections, and vehicle type and time of violation were also recorded for each individual violation under the appropriate category.

A total of 777 queues were recorded and reduced during the data reduction process. After reducing all the video data for the three study conditions, the following actions were performed:

1. 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.
2. 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.
3. 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 a guideline for the use of PTS systems in conjunction with pilot car operations at long work zones.

These actions performed were 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.

5.2 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.

5.2.1 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 starts at the end of the yellow time but the wait time starts with the arrival of the first vehicle in the queue. Table 5.1 provides a summary of the average vehicle wait time calculated for each queue at all the test locations.

Table 5.1: Summary of the Average Wait Time for All the Three Conditions

Test Location	Cycles Analyzed			Average Wait Time (minutes)		
	Flagger Only	PTS with a Flagger	PTS without a Flagger	Flagger Only	PTS with a Flagger	PTS without a Flagger
US-56	64	50	129	8.2	9.1	9.2
K-31	29	14	152	8.9	5.7	5.9
US-24	15	108	89	11.6	9.5	10.3
US-50	NA	99	28	NA	10.1	7.7
Total	**108**	**271**	**398**	**9.6**	**8.6**	**8.3**

Note: “NA” – Not Applicable because PTS unit was not used.

As shown in Table 5.1, the calculated average wait times had minimal difference when compared for the study three conditions. 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 results indicated that the PTS without the flagger condition was most effective in reducing the average wait time for the drivers approaching the work zone.

5.2.2 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 RVs 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 (AASHTO, 2011).

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 = 0.12 miles.

The lengths of queues were calculated for all the cycles that were reduced during the data reduction. Table 5.2 provides a summary of the average length of the queue calculated for each of the conditions at all the test locations.

Table 5.2: Summary of the Average Queue Length for All the Three Conditions

Test Location	Cycles Analyzed			Average Queue Length (miles)		
	Flagger Only	PTS with a Flagger	PTS without a Flagger	Flagger Only	PTS with a Flagger	PTS without a Flagger
US-56	64	50	129	0.05	0.05	0.05
K-31	29	14	152	0.02	0.01	0.01
US-24	15	108	89	0.1	0.07	0.08
US-50	NA	99	28	NA	0.25	0.26
Total	**108**	**271**	**398**	**0.06**	**0.1**	**0.1**

Note: “NA” – Not Applicable because PTS unit was not used.

As shown in Table 5.2, the calculated average queue lengths had minimal difference when compared for the three study conditions. The PTS with a flagger and the PTS without a flagger conditions served the longest average queue lengths, while the flagger only condition served the least average queue lengths over the entire duration of the data collection. The smaller average length of queues observed for the flagger only condition were attributed to the lower traffic volumes observed at test locations where data were collected. These results indicated that the length of the queues were a function of the traffic volumes and the traffic control methods that were used.

5.2.3 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 5.3 provides a summary of the average green time calculated for each of the conditions at all the test locations.

Table 5.3: Summary of the Average Green Time for All the Three Conditions

Test 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**
US-56	64	50	129	NA	37.0	38.9
K-31	29	14	152	NA	30.0	30.7
US-24	15	108	89	NA	44.2	49.5
US-50	NA	99	28	NA	145.7	138.7
Total	**108**	**271**	**398**	**NA**	**64.2**	**64.5**

Note: “NA” – Not Applicable because PTS unit was not used.

As shown in Table 5.3, the average duration of the green interval for the two conditions where the signal was used did not differ significantly. These results also indicated that the signal operations were independent of the presence or absence of a flagger with the signal unit since the pilot car drivers were responsible for activating the green phases on the signal unit at all test locations where data were collected. Appendix C provides detailed information regarding the signal timings and the corresponding number of cycles and percentages when the minimum green interval and green extensions were used.

5.2.4 Summary of Results

A total of 777 vehicle queues were recorded and reduced during the data reduction process for all the three study conditions. During the data reduction, vehicle arrival and departure times, signal timing operations, and queue information was recorded for each of the vehicle queues. 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 were some of the significant findings from results of the comparison of the operational parameters for each of the three study conditions:

- 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 results indicated that the PTS without a flagger condition was the most effective method in reducing the average wait time for the drivers approaching the work zone.
- The PTS with a flagger and the PTS without a flagger conditions served the longest average queue lengths, while the flagger only condition served the least average queue lengths over the entire duration of the data collection.
- There was no significant difference in the average duration of the green interval for the study conditions, indicating that the signal operations were independent of the presence or absence a flagger with the signal unit.
- Based on these results, it was concluded that since the three conditions did not significantly differ in the values for their operational parameters, they provided equivalent level of operational efficiency for controlling traffic at one-lane, two-way rural work zones.

5.3 Red Light Running Violations

Red light running (RLR) violations were the primary measure used to evaluate the effectiveness of the PTS system for controlling traffic at lane-closure type rural work zones. To conduct the statistical evaluation, the number of RLR violations for the three study 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 waved through by a flagger to enter the work zone and/or traveled in the direction of the work zone with no consent from the flagger and without being escorted by a pilot car.” Similarly, when a signal was used with a flagger or without a flagger, an RLR violation was defined as, “an event when a vehicle entered the work zone and/or traveled in the direction of the work zone when the signal 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 events.

RLR violations of the Types (a), (b), and (c) were observed when a signal was used without a flagger. Similarly, Type (d) RLR violations (d-1, d-2, and d-3) were observed when a signal was used with a flagger present. The following section provides a description for each type of these violations.

Type (a): *RLR when drivers were following an already departed queue*: These were the type of violations observed when a vehicle or a platoon of vehicles, not cleared in a certain green interval, immediately followed the departed queue into the work zone even after the signal turned red. In this type of violation, the back end of the departed queue was visible to the violating drivers who then made the decision to follow the queue on red signal indication.

Type (b): *RLR when drivers left a stopped queue*: These were the type of violations observed when a vehicle or a platoon of vehicles that were stopped at the flagger station/signal left the standing queue to travel in the direction of the work zone in the absence of a vehicle queue escorted by the pilot car and on red signal indication.

Type (c): *RLR when drivers completely disregarded the PTS system*: These were the types of violations observed when drivers completely disregarded the signal (red indication) to travel in the direction of the work zone without reducing their vehicle's speed.

Type (d): *RLR when drivers were waved through by the flagger*: These were the type of violations observed in the presence of a flagger with a signal unit and were further classified into the following categories.

Type (d-1): *When the drivers were waved to follow an already departed queue*: These were the type of violations observed when a vehicle or a platoon of vehicles, not cleared in a certain green interval, were waved through by the flagger to immediately follow the departed queue into the work zone even after the signal turned red. In this type of violation, the back end of the departed queue was visible to the flagger, who then made an informed judgement to direct the drivers to travel in the direction of the work zone on red signal indication.

Type (d-2): *When the drivers received the flagger's consent to enter the work zone at another time period*: These were the types of violations when a driver of the vehicle stopped at the flagger station, talked to the flagger, and obtained his/her consent to enter the work zone on red signal indication and unescorted by a pilot car.

Type (d-3): *RLR when drivers completely disregarded the flagger control*: These were the types of violations observed when drivers completely disregarded the flagger control (STOP paddle) to travel in the direction of the work zone without reducing their vehicle's speed.

The number of RLR vehicles was 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 5.3.1. RLR (%) were calculated by the Equation 5.1 given below:

$$RLR\ (\%) = \left(\frac{Number\ of\ RLR\ vehicles\ observed\ in\ x\ hours}{Total\ traffic\ volume\ observed\ in\ x\ hours}\right) * 100 \quad \textbf{Equation 5.1}$$

Table 5.4 provides a summary of the violations that were observed for the flagger only condition. It can be found that nine violations (about 1.1 percent) out of a total of 814 vehicles were observed for the flagger only condition. It was also found that all the observed nine violations were of the type when the driver obtained the flagger's consent to enter the work zone unescorted by a pilot car.

Table 5.5 provides a summary of the number of RLR vehicles for the PTS with a flagger condition.

Table 5.4: Summary of Violations for the Flagger Only Condition at All the Test Locations

Date	Test Site	Roadway AADT (vpd)	Observed Traffic Volume (vehicles)	Number of Violations	Percentage Violations (%)
7/30/2014	US-56	1,660/110	157	0	0
7/31/2014	US-56	1,010/60	363	2	0.6
8/14/2014	K-31	585/65	102	7	6.9
8/21/2014	US-24	3,890/385	192	0	0
Total			**814**	**9**	**1.1**

Note: “vpd” – vehicles per day and correspond to the work zone end where data were collected.

Table 5.5: Number of RLR Violations for the PTS with a Flagger Condition

Date	Test Site	Roadway AADT (vpd)	Observed Traffic Volumes (vehicles)	RLR Type		
				Follow a Departed Queue	Leave a Stopped Queue	Disregard the Flagger
8/5/2014	US-56	1,660/110 to 1,830/115	413	4	0	0
8/6/2014	US-56	NA	NA	NA	NA	NA
8/7/2014	US-56	NA	NA	NA	NA	NA
8/12/2014	K-31	490/65	20	0	0	0
8/13/2014	K-31	NA	NA	NA	NA	NA
8/14/2014	K-31	NA	NA	NA	NA	NA
8/19/2014	US-24	3,140/390 to 3,890/345	642	53*	13*	0
8/20/2014	US-24	3,140/390 to 3,890/345	300	12*	5*	0
8/21/2014	US-24	NA	NA	NA	NA	NA
8/26/2014	US-50	4,700/1,300	503	1	0	1
8/27/2014	US-50	5,130/1,360	2,471	3	0	1
8/28/2014	US-50	NA	NA	NA	NA	NA
Total			**4,349**	**73**	**18**	**2**
				93		

Note: “NA” – Not applicable because no data were collected; “*” – Four-leg intersection, “vpd” – vehicles per day.

As shown in Table 5.5, 93 violations (about 2 percent) out of a total of 4,349 vehicles were observed at all test locations for the PTS with a flagger condition. It can also be found that the number of RLR violations of the type when vehicles were waved through by the flagger to follow a departed queue were higher than the other two types. This was because on August 19 and August 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 5.2 in Section 5.4. The intersection geometry and traffic operations at that work zone end did not comply with the experimental design for this research explained in Section 3.3.2. Therefore, it was decided to exclude the data collected at that end of the work zone for conducting the test of proportions. Table 5.6 provides a summary of the number of RLR violations for the PTS with a flagger condition when data for the intersection at Beloit, KS, were excluded.

As shown in Table 5.6, the number of RLR violations of the type when vehicles were waved through by the flagger to follow a departed queue were higher than the other two types and constituted 90 percent of the total violations observed for the condition. It was also found that after the exclusion of the intersection data, the total number of violations reduced to 52 and the total average percentage of the number of RLR violations reduced to 1.3 percent. Table 5.7 provides a summary of the percentages of the number of RLR vehicles for the PTS with a flagger condition.

As shown in Table 5.7, the average percentage of RLR violations for the PTS with a flagger condition at all the three test locations for the RLR types, when following a departed queue, when leaving a stopped queue, and when disregarding the traffic control, were 90, 5.8, and 3.8 percent, respectively. The results indicated that when a signal was used with a flagger, it was more susceptible to violations that involved drivers following an already departed queue on red signal indication than the other two types of violations.

Table 5.8 provides a summary of the number of RLR violations for the PTS without a flagger condition. It can be found that a total of 2,944 vehicles and 92 violations (3.1 percent) were observed at all test locations when the PTS was used without a flagger. It was also found that the number of RLR violations of the type when vehicles left the stopped queue were higher than the other two types and constituted 48 percent of the total violations observed for the condition. Table 5.9 provides a summary of the percentages of the number of RLR vehicles for the PTS without a flagger condition.

Table 5.6: Number of RLR Violations for the PTS with a Flagger Condition Excluding the Intersection at Beloit, KS

Date	Test Site	Roadway AADT (vpd)	Observed Traffic Volumes (vehicles)	RLR Type		
				Follow a Departed Queue	Leave a Stopped Queue	Disregard the Flagger
8/5/2014	US-56	1,660/110 to 1,830/115	413	4	0	0
8/6/2014	US-56	NA	NA	NA	NA	NA
8/7/2014	US-56	NA	NA	NA	NA	NA
8/12/2014	K-31	490/65	20	0	0	0
8/13/2014	K-31	NA	NA	NA	NA	NA
8/14/2014	K-31	NA	NA	NA	NA	NA
8/19/2014	US-24	3,140/390 to 3,890/345	372	39	3	0
8/20/2014	US-24	NA	NA	NA	NA	NA
8/21/2014	US-24	NA	NA	NA	NA	NA
8/26/2014	US-50	4,700/1,300	503	1	0	1
8/27/2014	US-50	5,130/1,360	2,471	3	0	1
8/28/2014	US-50	NA	NA	NA	NA	NA
Total			**3,779**	**47**	**3**	**2**
				52		

Note: "NA" – Not applicable because no data collected for PTS with flagger condition, "vpd" – vehicles per day.

Table 5.7: Percentage of RLR Violations for the PTS with a Flagger Condition

Date	Test Site	Roadway AADT (vpd)	Observed Traffic Volumes (vehicles)	Follow a Departed Queue (%)	Leave a Stopped Queue (%)	Disregard the Flagger (%)
8/5/2014	US-56	1,660/110 to 1,830/115	413	0.1	0	0
8/6/2014	US-56	NA	NA	NA	NA	NA
8/7/2014	US-56	NA	NA	NA	NA	NA
8/12/2014	K-31	490/65	20	0	0	0
8/13/2014	K-31	NA	NA	NA	NA	NA
8/14/2014	K-31	NA	NA	NA	NA	NA
8/19/2014	US-24	3,140/390 to 3,890/345	372	10.5	0.8	0
8/20/2014	US-24	NA	NA	NA	NA	NA
8/21/2014	US-24	NA	NA	NA	NA	NA
8/26/2014	US-50	4,700/1,300	503	0.2	0	0.2
8/27/2014	US-50	5,130/1,360	2,471	0.1	0	0.04
8/28/2014	US-50	NA	NA	NA	NA	NA
Total			**3,779**	**90**	**5.8**	**3.8**

Note: "NA" – Not applicable because no data were collected, "vpd" – vehicles per day.

Table 5.8: Number of RLR Violations for the PTS without a Flagger Condition

Date	Test Site	Roadway AADT (vpd)	Observed Traffic Volumes (vehicles)	Follow a Departed Queue	Leave a Stopped Queue	Disregard the Signal
8/5/2014	US-56	NA	NA	NA	NA	NA
8/6/2014	US-56	1,830/115 to 1,670/115	343	0	4	3
8/7/2014	US-56	1,670/115 to 3,320/140	660	19	7	1
8/12/2014	K-31	490/65	17	0	0	0
8/13/2014	K-31	585/65	157	0	9	5
8/14/2014	K-31	585/65	87	0	2	0
8/19/2014	US-24	NA	NA	NA	NA	NA
8/20/2014	US-24	3,890/345	333	7	1	0
8/21/2014	US-24	2,750/380 to 3,890/385	553	10	21	2
8/26/2014	US-50	NA	NA	NA	NA	NA
8/27/2014	US-50		794	0	0	1
8/28/2014	US-50	NA	NA	NA	NA	NA
Total			**2,944**	**36**	**44**	**12**
				92		

Note: “NA” – Not applicable because no data were collected, “vpd” – vehicles per day.

Table 5.9: Percentage of RLR Violations for the PTS without a Flagger Condition

Date	Test Site	Roadway AADT (vpd)	Observed Traffic Volumes (vehicles)	Follow a Departed Queue (%)	Leave a Stopped Queue (%)	Disregard the Signal (%)
8/5/2014	US-56	NA	NA	NA	NA	NA
8/6/2014	US-56	1,830/115 to 1,670/115	343	0	0.9	0.9
8/7/2014	US-56	1,670/115 to 3,320/140	660	2.9	1.1	0.2
8/12/2014	K-31	490/65	17	0	0	0
8/13/2014	K-31	585/65	157	0.6	4.4	3.2
8/14/2014	K-31	585/65	87	0	1.2	1.2
8/19/2014	US-24	NA	NA	NA	NA	NA
8/20/2014	US-24	3,890/345	333	2.1	0	0
8/21/2014	US-24	2,750/380 to 3,890/385	553	1.8	3.8	0.4
8/26/2014	US-50	NA	NA	NA	NA	NA
8/27/2014	US-50		794	0	0	0.1
8/28/2014	US-50	NA	NA	NA	NA	NA
Total			**2,944**	**39**	**48**	**13**

Note: “NA” – Not applicable because no data were collected, “vpd” – vehicles per day.

As shown in Table 5.9, the average percentage of RLR violations for the PTS without a flagger condition at all the three test locations for the RLR types, when following a departed queue, when leaving a stopped queue, and when disregarding the traffic control, were 39, 48, and 13 percent, respectively. The results indicated that when a signal was used without a flagger, it was more susceptible to violations that involved drivers leaving a stopped queue on red signal indication than the other two types of violations. The numbers of RLR violations described in this section were then used in conducting the statistical evaluation and comparison of the three study conditions.

5.3.1 Test of Proportions

A test of proportions was conducted to determine whether there was a statistically significant difference between the numbers of RLR violations for each of three study conditions: flagger only, PTS with a flagger, and PTS without a flagger (Ramsey & Schafer, 2002). For conducting the analysis, the total number of vehicles observed for the condition was used as sample sizes and the number of RLR vehicles was 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:

$$Pooled\ Sample\ Proportion\ (p) = \left(\frac{p_1+p_2}{n_1+n_2}\right) \quad \textbf{Equation 5.2}$$

$$Standard\ Error\ (SE) = sqrt\left\{p * (1-p) * \left[\left(\frac{1}{n_1}\right) + \left(\frac{1}{n_2}\right)\right]\right\} \quad \textbf{Equation 5.3}$$

$$Test\ Statistic\ or\ z-score\ (z) = \left(\frac{p_1-p_2}{SE}\right) \quad \textbf{Equation 5.4}$$

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 the flagger only condition at Test Location 4 (near Newton on US-50). Therefore the test of proportions was conducted using the data for Test Locations 1, 2, and 3 for Case 1 and Case 2. Table 5.10 provides the results of the test of proportions for the Case 1.

Table 5.10: Results of the Test of Proportions 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		
US-56	520	413	2	4	0.18	Do Not Reject
K-31	102	20	7	0	0.99	Do Not Reject
US-24	192	372	0	42	< 0.001	Reject
Total	**814**	**805**	**9**	**46**	**< 0.001**	**Reject**

As shown in Table 5.10, 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 concluded that the number of RLR violations 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. Therefore, it was concluded that flagger only operations were statistically more effective in reducing the number of RLR violations than a PTS unit with a flagger. Table 5.11 provides the results of the test of proportions for the Case 2.

Table 5.11: Results of the Test of Proportions 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		
US-56	520	1,003	2	35	< 0.001	Reject
K-31	102	261	7	16	0.60	Do Not Reject
US-24	192	886	0	40	0.001	Reject
Total	**814**	**2,150**	**9**	**91**	**< 0.001**	**Reject**

As shown in Table 5.11, 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 violations 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. Therefore, it was concluded that flagger only operations were statistically more effective in reducing the number of RLR violations than a PTS unit without a flagger. Table 5.12 provides the results of the test of proportions for the Case 3.

As shown in Table 5.12, 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 violations 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, it was concluded the PTS unit with a flagger was statistically more effective in reducing the number of RLR violations than a PTS unit without a flagger.

Table 5.12: Results of the Test of Proportions 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		
US-56	413	1,003	4	35	0.004	Reject
K-31	20	261	0	16	0.13	Do Not Reject
US-24	372	886	42	40	0.99	Do Not Reject
US-50	2,974	794	6	1	0.67	Do Not Reject
Total	**3,779**	**2,944**	**52**	**92**	**< 0.001**	**Reject**

A more in-depth statistical analysis was conducted to determine whether there was a statistically significant difference between the number of RLR violations for the four different types of violations for the conditions PTS with a flagger and PTS without a flagger. Since the data collected for the flagger only condition were less compared to the other two conditions, no further analysis was conducted for the condition. Table 5.13 provides the results of the test of proportions that compared the number of RLR violations when vehicles followed an already departed queue.

As shown in Table 5.13, there was no statistically significant difference between the numbers of RLR vehicles for the two conditions. This meant that the number of vehicles following a departed queue at a PTS unit were statistically equivalent in the presence and absence of a flagger. It was also concluded that the presence of a flagger with a PTS unit was not more effective in reducing the number of violations when the vehicles followed the back of an already departed queue as compared to the number of violations in the absence of a flagger. Table 5.14 provides the results of the test of proportions that compared the number of RLR violations when vehicles left the stopped queue.

Table 5.13: Results of the Test of Proportions for the RLR Violations when Drivers 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		
US-56	413	1,003	4	19	0.11	Do Not Reject
K-31	20	261	0	0	0.52	Do Not Reject
US-24	372	886	39	17	0.99	Do Not Reject
US-50	2,974	794	4	0	0.85	Do Not Reject
Total	**3,779**	**2,944**	**47**	**36**	**0.53**	**Do Not Reject**

Table 5.14: Results of the Test of Proportions for the RLR Violations when Drivers Left the Stopped Queue

Test Location	Traffic Volumes		Leave a Stopped Queue		p-value	Null Hypothesis
	PTS with a Flagger	PTS without a Flagger	PTS with a Flagger	PTS without a Flagger		
US-56	413	1,003	0	11	0.02	Reject
K-31	20	261	0	11	0.18	Do Not Reject
US-24	372	886	3	22	0.03	Reject
US-50	2,974	794	0	0	0.50	Do Not Reject
Total	**3,779**	**2,944**	**3**	**44**	**< 0.001**	**Reject**

As shown in Table 5.14, there was a statistically significant difference between the numbers of RLR vehicles for the two conditions. This meant that the drivers were more likely to leave a queue at a PTS unit in the absence of a flagger. It was also concluded that the presence of a flagger with a PTS unit was more effective in reducing the number of violations when the vehicles left a stopped queue as compared to the number of violations in the absence of a flagger. Table 5.15 provides the results of the test of proportions that compared the RLR events where vehicles disregarded the traffic control.

Table 5.15: Results of the Test of Proportions for the RLR Violations when Drivers 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		
US-56	413	1,003	0	4	0.099	Do Not Reject
K-31	20	261	0	5	0.27	Do Not Reject
US-24	372	886	0	2	0.18	Do Not Reject
US-50	2,974	794	2	1	0.30	Do Not Reject
Total	**3,779**	**2,944**	**2**	**12**	**< 0.001**	**Reject**

As shown in Table 5.15, there was a statistically significant difference between the numbers 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. It was also concluded that the presence of a flagger with a PTS unit was more effective in reducing the number of violations when the vehicles disregarded the traffic control as compared to the number of violations in the absence of a flagger. All results obtained from the test of proportions were used to make suitable conclusions and recommendations described in subsequent chapters.

5.3.2 Summary of Results

Red light running violations (RLR) were the primary measure used to evaluate the effectiveness of the PTS systems for controlling traffic at lane-closure type rural work zones. To conduct the analysis, the number of RLR violations for the three study conditions were calculated and then compared between all the test locations. The following were some of the significant findings obtained from the RLR violation analysis and the results of the test of proportions:

- A total of nine violations (about 1.1 percent) out of 814 vehicles were observed for the flagger only condition. It was also found that all the observed nine violations were of the type when the driver obtained the flagger’s consent to enter the work zone unescorted by a pilot car.

- A total of 52 violations (about 1.3 percent) out of 3,779 vehicles were observed at all test locations for the PTS with a flagger condition. It was also found that the average percentage of RLR violations for the PTS with a flagger condition at all the three test locations for RLR the types, when following a departed queue, when leaving a stopped queue, and when disregarding the traffic control, were 90, 5.8, and 3.8 percent, respectively. The results indicated that when a signal was used with a flagger, it was more susceptible to violations that involved drivers following an already departed queue on red signal indication than the other two types of violations.
- A total of 92 violations (3.1 percent) out of 2,944 vehicles were observed at all test locations for the PTS without a flagger condition. It was also found that the average percentage of RLR violations for the PTS without a flagger condition at all the three test locations for the RLR types, when following a departed queue, when leaving a stopped queue, and when disregarding the traffic control, were 39, 48, and 13 percent, respectively. The results indicated that when a signal was used without a flagger, it was more susceptible to violations that involved drivers leaving a stopped queue on red signal indication than the other two types of violations.
- 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 significant and higher than the condition when flagger only operations were used.
- The results of the test of proportions indicated that the number of violations when a PTS was used without a flagger were statistically significant and higher than the condition when a PTS was used with a flagger.
- The results of the test of proportions indicated that there was no statistically significant difference between the number of RLR violations when vehicles followed an already departed queue between the PTS with a flagger and PTS without a flagger conditions.

- Finally, it was also found that there was a statistically significant difference between the number of RLR vehicles that left the stopped queue and the number of vehicles that disregarded the PTS control between the PTS with a flagger and PTS without a flagger conditions.

5.4 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 5.2 presents a ground view of the intersection and the data collection setup at Beloit, KS.

Figure 5.2: Ground View of the Eastbound PTS Leg of the Intersection at Beloit, KS

As shown in Figure 5.2, 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 waved 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 of the type when drivers are waved 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 waved 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 10 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 waved 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 5.7 and Table 5.8.

- 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 waved 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 10 vehicles observed in the actual scenario. The arrival rate was found to be 40 seconds and was used in developing the values in Table 5.8.

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 a 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 5.16 provides the arrival time for all the vehicle positions in the queue considered in the actual scenario. It can be found that similar to the existing scenario, a uniform arrival rate of 40 seconds was used to develop the arrival times. 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. 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.

Table 5.16: Sample Arrival Times for the Actual and Hypothetical Scenarios

Actual Scenario		Hypothetical Scenario	
Arrival time (a.m.)	**Vehicle Position (i)**	**Arrival time (a.m.)**	**Vehicle Position (i)**
11:06:16	0	11:02:16	0
11:06:56	1	11:02:56	1
11:07:36	2	11:03:36	2
11:08:16	3	11:04:16	3
11:08:56	4	11:04:56	4
11:09:36	5	11:05:36	5
11:10:16	6	11:06:16	6
11:10:56	7	11:06:56	7
11:11:36	8	11:07:36	8
11:12:16	9	11:08:16	9
11:12:56	10	11:08:56	10
11:13:51	0	11:09:36	11
NA	NA	11:10:16	12
NA	NA	11:10:56	13
NA	NA	11:11:36	14
NA	NA	11:12:16	15
NA	NA	11:12:56	16
NA	NA	11:14:24	0

Note: "NA" – Not Applicable because vehicles were not present for the actual scenario.

Figure 5.3 shows the chart generated by plotting the values for vehicle position against the arrival times using the data from Table 5.16.

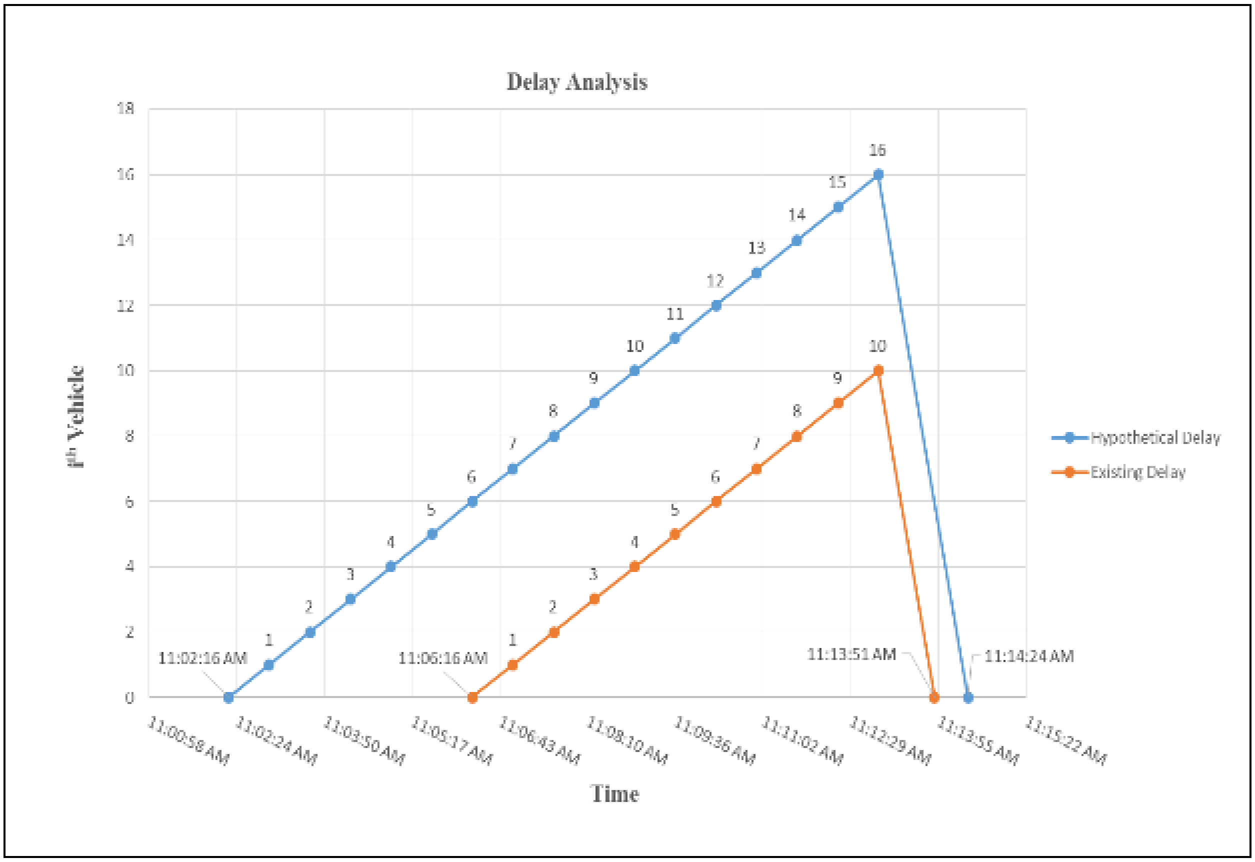

Figure 5.3: Graph Illustrating a Sample Delay Analysis

As shown in Figure 5.3, a chart was developed using the values from Table 5.16. 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 Equation 5.5 was used to compute the total delay for each of the conditions:

$$Total\ Delay = (Area\ of\ triangle) = 0.5 * Base * Height \qquad \textbf{Equation 5.5}$$

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 Equation 5.5 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 5.17 provides a summary of the total delay that was calculated for all 31 cycles analyzed for all the test locations.

Table 5.17: Summary of the Delay Analysis

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**

From Table 5.17, 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. The total delay observed for the PTS with a flagger condition was calculated using Equation 5.6.

$$\boldsymbol{Total\ Delay = 0.5 * Wait\ time\ for\ first\ vehicle * Number\ of\ vehicles}$$ **Equation 5.6**

Table 5.18 provides a summary of the total delay observed when a flagger was present with a PTS unit calculated using Equation 5.6.

Table 5.18: 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	US-56	119,588.5	1,993.1	33.2
8/6/2014	US-56	-	-	-
8/7/2014	US-56	-	-	-
8/12/2014	K-31	4,097.5	68.3	1.1
8/13/2014	K-31	-	-	-
8/14/2014	K-31	-	-	-
8/19/2014	US-24	189,926.5	3,165.4	52.7
8/20/2014	US-24	88,903	1,481.7	24.7
8/21/2014	US-24	-	-	-
8/26/2014	US-50	175,554	2,925.9	48.8
8/27/2014	US-50	569,317	9,488.6	158.1
8/28/2014	US-50	-	-	-
Total		**1,147,386.5**	**19,123.1**	**318.7**

From Table 5.18, 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 5 percent of the total vehicle delay.

5.4.1 Summary of Results

An exploratory delay analysis was conducted to determine the change in total delay by the presence of a flagger with a signal unit in comparison to the signal only condition. At all the test locations, the flagger used his/her judgement to waive a few vehicles to travel in the direction of the work zone on red signal indication and unescorted by a pilot car. Two scenarios were compared to obtain an estimate of the total reduction in vehicular delay—the actual scenario and the hypothetical scenario. The total delay was determined based on the information available for arrival and departure times of the vehicles in each of the queues. After analyzing the available data, it was found that a total of 16.8 hours (approximately 5 percent) of the 318 hours of total delay was reduced in the presence of a flagger. The researchers do not promote these actions as a valid means to reduce the total vehicular delay and have not based any recommendations using the results from this part of the analysis. Since these actions were only observed from video during the data reduction process, the research team explored the possibilities of delay reduction that could be brought by the presence of a flagger when using a signal in conjunction with pilot car operations.

5.5 Model Development for Volume Thresholds and Appropriate Green Interval

The video data reduction provided information regarding the duration of green intervals and the number of vehicles that were served in each of those intervals. With the help of this information, equations were 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 relevant calculations.

5.5.1 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 (TRB, 2010):

- 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 (TRB, 2010). 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 10 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" (Ott, 1998). 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 5.4 shows the chart presenting the raw data for all the 30 queues for vehicle positions against the corresponding average vehicle headways.

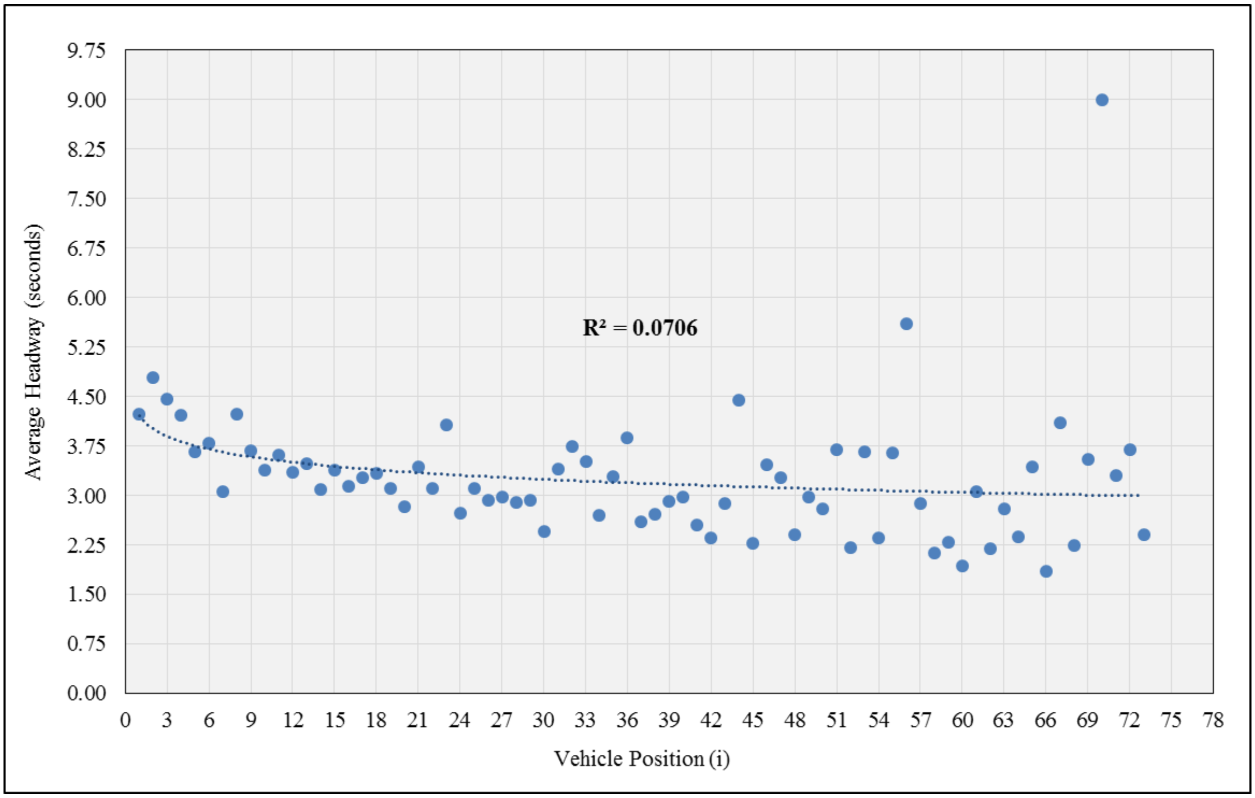

Figure 5.4: Plot of the Vehicle Headway Data against Vehicle Position for All the 30 Queues

As shown in Figure 5.4, 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 the 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 5.5 shows the chart for the average vehicle headways against the vehicle positions represented by a minimum of 15 vehicles.

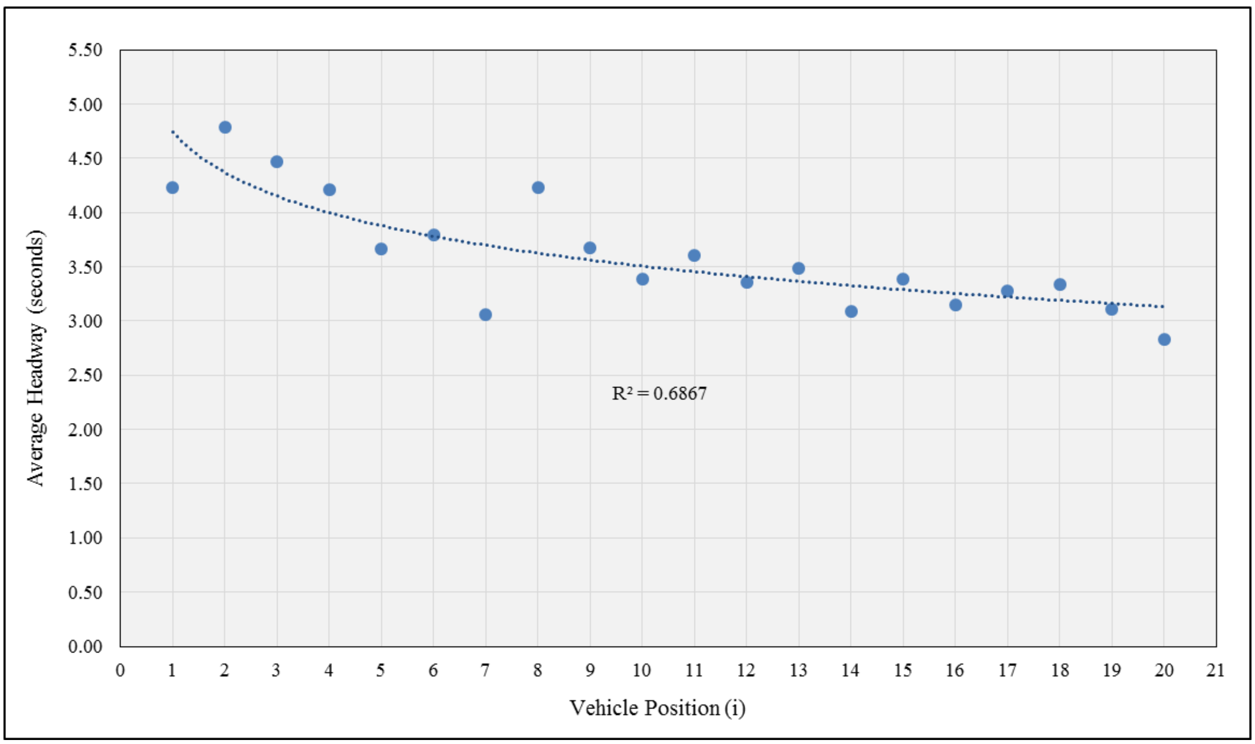

Figure 5.5: Plot for the Vehicle Headway Data against First 20 Vehicle Positions

As shown in Figure 5.5, 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 5.5. Although from Figure 5.5 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 eighth 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.

$$Saturation\ Headway\ (h_S) = \left[\frac{h(i)+h(i+1)+\cdots+h(n)}{n-i+1}\right] \quad \textbf{Equation 5.7}$$

$$Saturation\ Flow\ Rate\ (s) = \left[\frac{3600}{h_S}\right] \quad \textbf{Equation 5.8}$$

$$Startup\ Lost\ Time\ (t_S) = \left[\sum_1^{(i-1)}(h - h_S)\right] \quad \textbf{Equation 5.9}$$

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

Table 5.19: 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 5.19, 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 (TRB, 2010). 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 5.6 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.

As shown in Figure 5.6, 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 5.19 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.

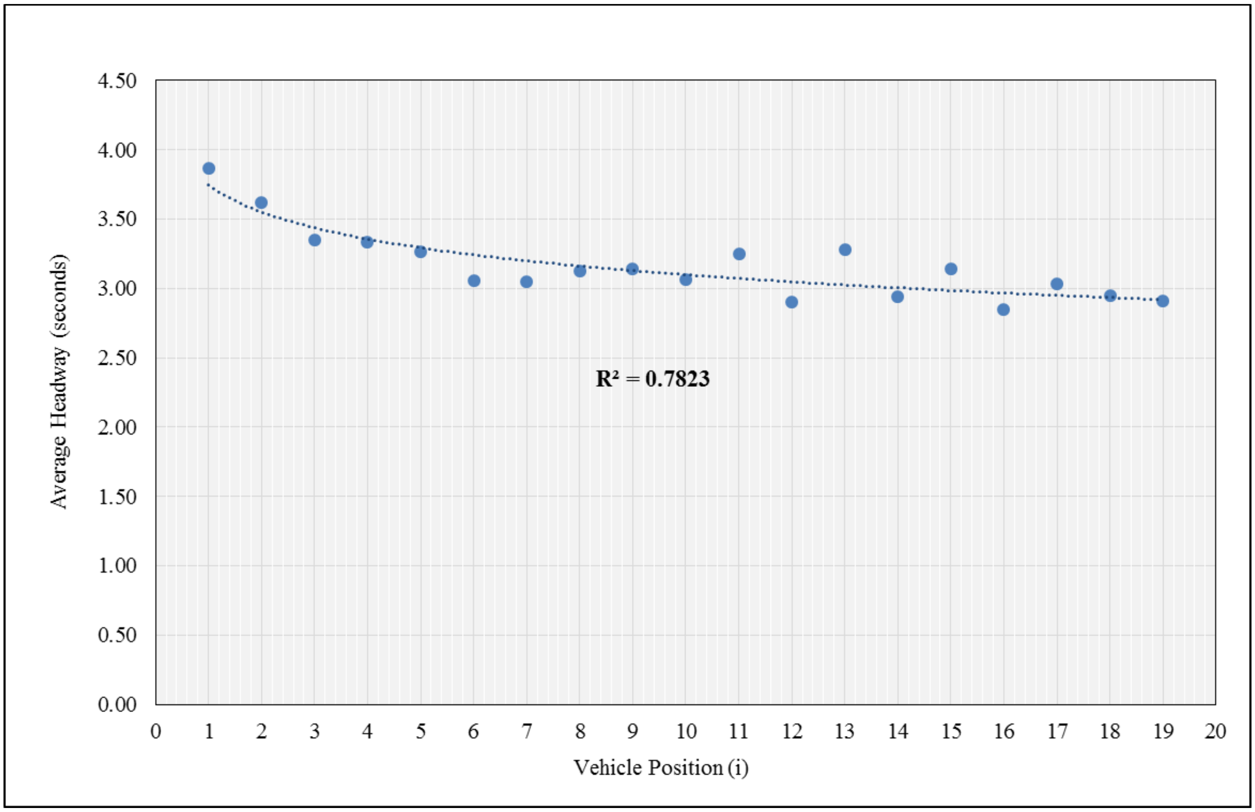

Figure 5.6: Plot for the Headway Data against Vehicle Position Excluding the Trucks and Heavy Vehicles

5.5.2 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 turn around and begin escorting the queue back. This time will be referred to as the Platoon Clearance Time (P_t) in the following sections.

The 30 longest vehicle queues were considered in the calculation of h_s and t_s, and it was found that P_t varied significantly for all the three test locations and no significant correlation could be determined. The 10 longest queues from US-56, US-24, and US-50 were used for this analysis—no queues from K-31 were used due to the low overall volumes and correspondingly shorter queues. 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 5.20 provides a summary of the P_t and the turnaround time.

Table 5.20: Summary of Average Platoon Clearance Time and Turnaround Time for the 30 Longest Observed Queues

Test Location	Roadway AADT (vpd)	Average Green Time (second)*	Average P_t (second)	Percent Difference (%)	Average Turnaround time (second)
US-56	1,010/60 to 3,320/140	65	64	1.5	12
US-24	2,750/380 to 3,890/385	64	52	19	25
US-50	4,700/1,300 to 5,130/1,360	204	174	15	37
Total		**113**	**98**	**13**	**25**

Note: All numbers are rounded-off for simplicity of calculations.
* These are the averages of the 10 longest observed queues for each location, not the averages of all observed queues.

As shown in Table 5.20, 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. Although no specific conclusions were made from these results, determining clearance times could be beneficial for future research needs.

5.5.3 Development of the Model to Determine Appropriate 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 lists 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 5.5.1.

Figure 5.7 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.

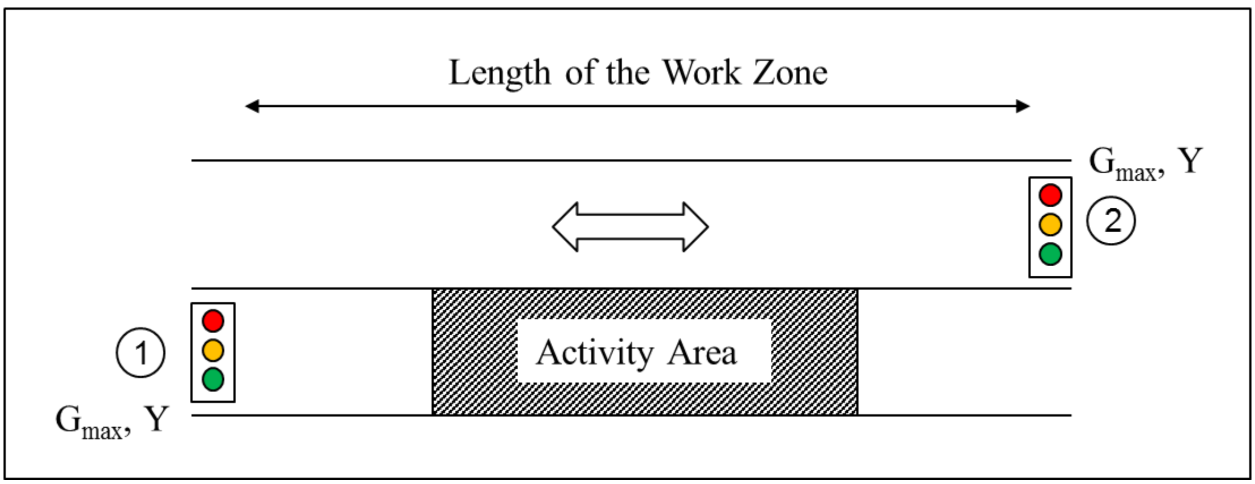

Figure 5.7: General End-to-End Layout of the Work Zone at All Test Locations

As shown in Figure 5.7, 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, Equations 5.10 and 5.11 were developed to calculate the total round trip time in minutes:

$$T_r = \left[\left\{2 * \left(\frac{L_w}{S_p}\right) * 60\right\} + \left\{2 * \left(\frac{G_{max}+Y}{60}\right)\right\}\right]$$ **Equation 5.10**

$$T_r = \left[\left\{120 * \left(\frac{L_w}{S_p}\right)\right\} + \left(\frac{G_{max}+Y}{30}\right)\right]$$ **Equation 5.11**

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).

Equations 5.12 and 5.13 for calculating the maximum feasible green interval and the length of work zone were obtained by rearranging the terms from Equation 5.11:

$$G_{max} = \left[30 * \left\{T_r - \left(\frac{120 * L_w}{S_p}\right)\right\}\right] - Y$$ **Equation 5.12**

$$L_w = \left[\left\{T_r - \left(\frac{G_{max}+Y}{30}\right)\right\} * \left(\frac{S_p}{120}\right)\right]$$ **Equation 5.13**

Equation 5.14 was developed to calculate the number of vehicles cleared in a certain green interval and was a function of h_s and t_s.

$$V_{max} = \left[\frac{(G_{max} - t_s)}{h_s}\right] \quad \textbf{Equation 5.14}$$

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" (TRB, 2010). 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. Equation 5.15 given below was developed for calculating the capacity in vehicles per hour per direction.

$$C = (V_{max} * Number\ of\ Round\ Trips\ per\ hour) \quad \textbf{Equation 5.15}$$

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 Equation 5.11.

$$C = \left[V_{max} * \left(\frac{60}{T_r}\right)\right] \quad \textbf{Equation 5.16}$$

Substituting the value of V_{max} from Equation 5.14 in Equation 5.16:

$$C = \left[\frac{(G_{max} - t_s)}{h_s}\right] * \left(\frac{60}{T_r}\right) \quad \textbf{Equation 5.17}$$

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" (TRB, 2010). Assuming the Peak Hour Volume (PHV) to be 15 percent of the AADT and a 50/50 directional distribution of the traffic volume, Equation 5.18 was developed for calculating the capacity:

$$C = (0.15 * 0.5 * AADT) \qquad \textbf{Equation 5.18}$$

Where:
AADT = Average Annual Daily Traffic (vehicles per day)

The terms in Equation 5.18 were rearranged to obtain the equation for calculating the AADT given in Equation 5.19.

$$AADT = \left[2 * \left(\frac{C}{0.15}\right)\right] \qquad \textbf{Equation 5.19}$$

Substituting the value of *C* from Equation 5.17 in Equation 5.19:

$$AADT = \left[\frac{(G_{max} - t_s)}{h_s}\right] * \left(\frac{60}{T_r}\right) * \left(\frac{2}{0.15}\right) \qquad \textbf{Equation 5.20}$$

Simplifying the Equation 5.20:

$$AADT = \left[\frac{(G_{max} - t_s)}{h_s}\right] * \left(\frac{800}{T_r}\right) \qquad \textbf{Equation 5.21}$$

Using the value of h_s = 3.31 seconds and t_s = 5.98 seconds obtained from Section 5.5.1 in Equation 5.21:

$$AADT = \left[\frac{(G_{max} - 5.98)}{T_r}\right] * 241.7 \qquad \textbf{Equation 5.22}$$

The terms in Equation 5.22 were rearranged to obtain the final equation for calculating the maximum feasible green interval given in Equation 5.23.

$$G_{max} = \left[\left(\frac{AADT * T_r}{241.7}\right) + 5.98\right]$$ **Equation 5.23**

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 5.5.3.

Using the equations mentioned earlier, three charts shown in Figures 5.8, 5.9, and 5.10 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 40 mph to determine the volume thresholds and other corresponding values (KDOT, 2007). 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 5.8 shows a plot of the AADT against the maximum feasible green interval.

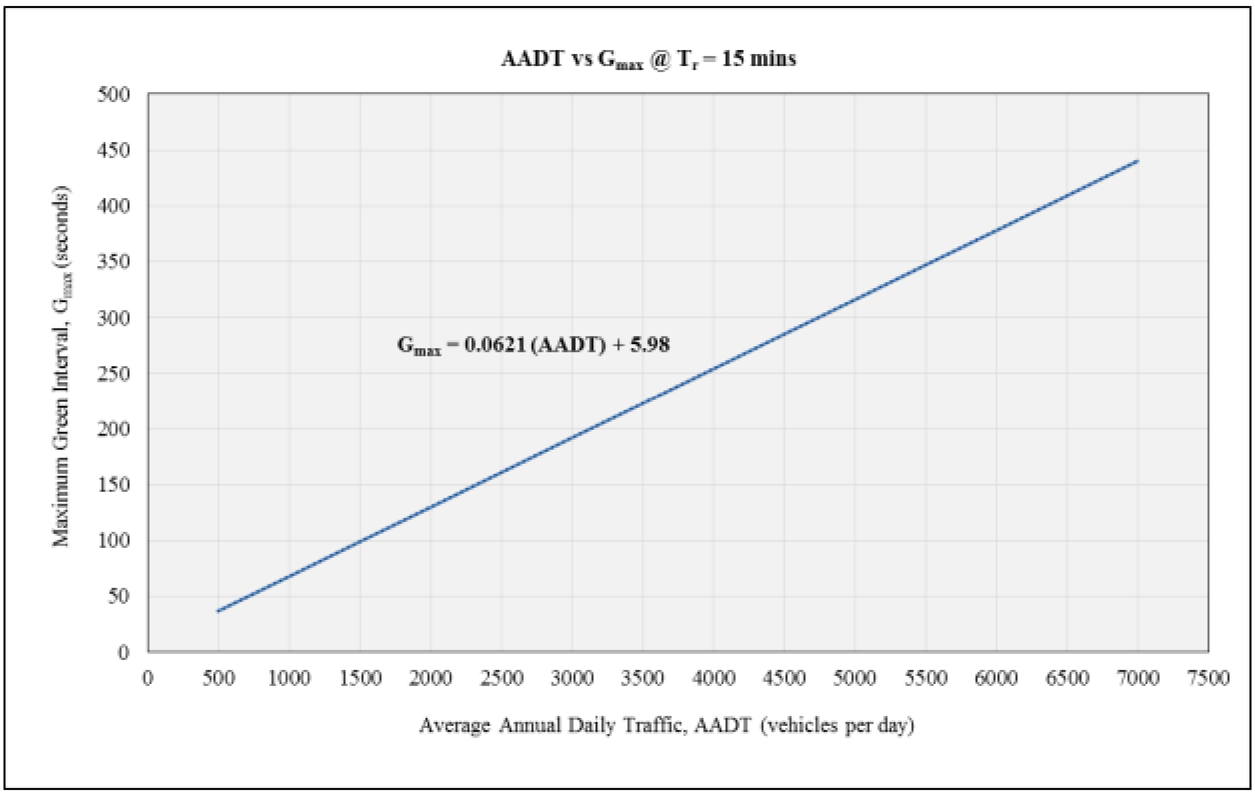

Figure 5.8: Plot for the AADT against the Maximum Green Interval

As shown in Figure 5.8, the AADT values were plotted against the maximum feasible green interval for a constant T_r of 15 minutes and using Equation 5.23. 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 5.9 shows a plot of the maximum feasible green interval against the number of vehicles that could be cleared in that corresponding green interval.

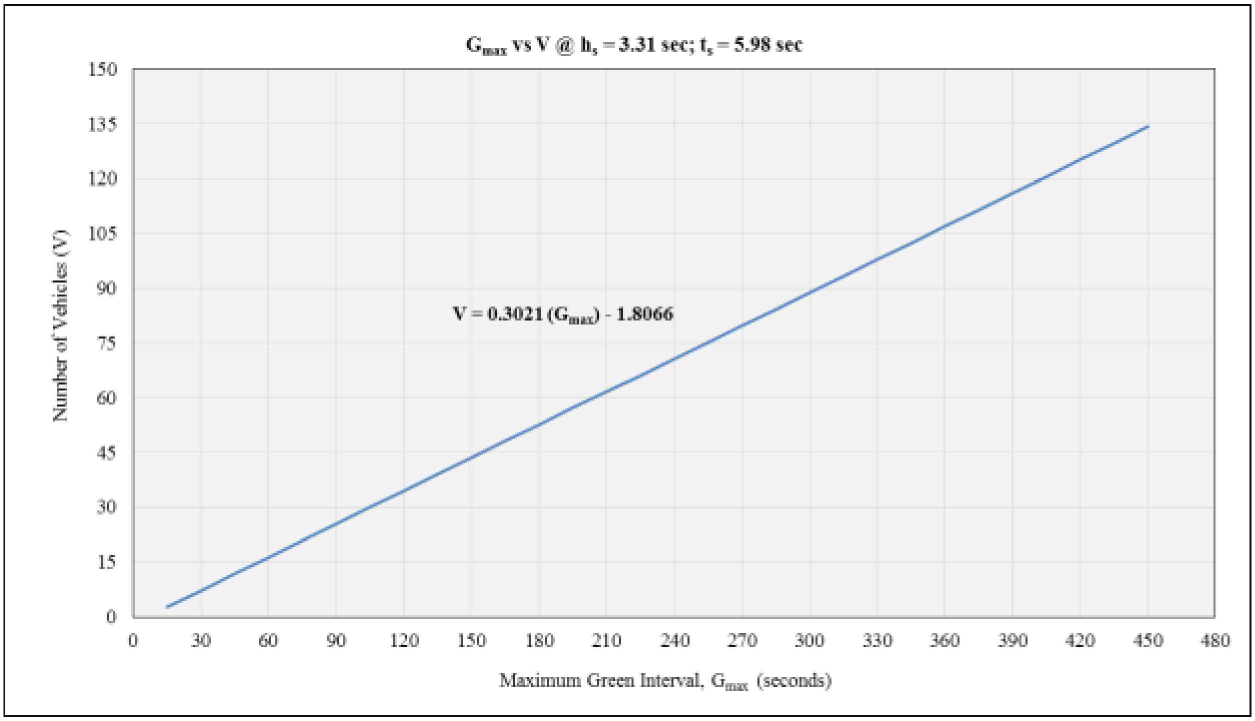

Figure 5.9: Plot for Maximum Green Time against Number of Vehicles

As shown in Figure 5.9, the maximum feasible green interval was plotted against the number of vehicles that could be cleared in that corresponding green interval using Equation 5.14. 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 5.10 shows the plot for the maximum feasible green interval against the maximum feasible length of the work zone.

As shown in Figure 5.10, the maximum feasible green interval was plotted against the maximum feasible length of the work zone using Equation 5.13. 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 5.8. Chapter 6 presents a detailed description of the use of the charts shown in Figures 5.8, 5.9, and 5.10. Table 5.21 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 Equations 5.13, 5.14, 5.16, and 5.19.

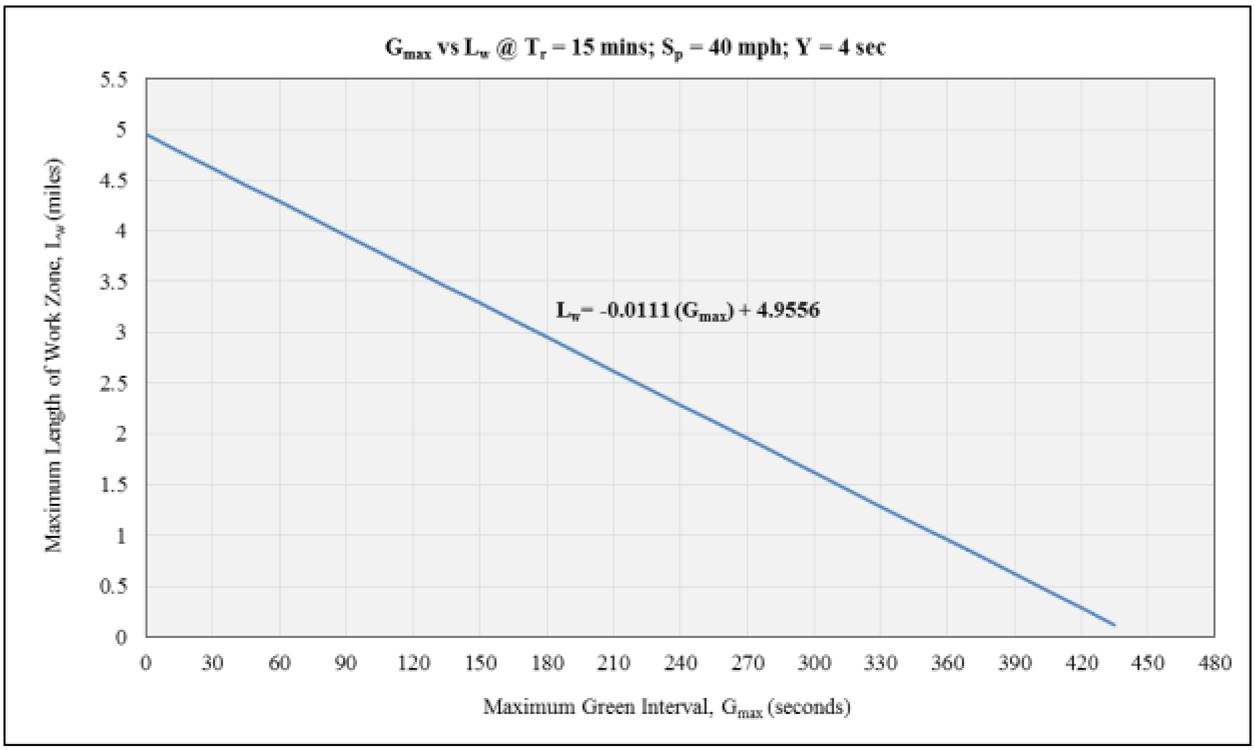

Figure 5.10: Plot for Maximum Green Interval against Maximum Length of Work Zone

As shown in Table 5.21, 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.

Table 5.21: 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)**
< = 1,000	4.20	70	19
1,000 to 2,000	3.51	130	38
2,000 to 3,000	2.82	195	56
3,000 to 4,000	2.13	255	75
4,000 to 5,000	1.44	320	94
5,000 to 6,000	0.75	380	113
6,000 to 7,000	0.06	440	131
S_p = 35 mph			
< = 1,000	3.70	70	19
1,000 to 2,000	3.07	130	38
2,000 to 3,000	2.47	195	56
3,000 to 4,000	1.86	255	75
4,000 to 5,000	1.26	320	94
5,000 to 6,000	0.66	380	113
6,000 to 7,000	0.05	440	131
S_p = 30 mph			
< = 1,000	3.15	70	19
1,000 to 2,000	2.63	130	38
2,000 to 3,000	2.12	195	56
3,000 to 4,000	1.60	255	75
4,000 to 5,000	1.08	320	94
5,000 to 6,000	0.56	380	113
6,000 to 7,000	0.05	440	131

5.5.4 Summary of Results

The video data reduction provided information regarding the duration of green intervals and the number of vehicles that were served in each of those intervals. With the help of this information, equations were 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 guidelines presented in the HCM were used to determine the values of h_s and t_s. Based on the charts developed using the available data, it was found that saturated headway conditions started from the ninth vehicle position. From further analysis, it was found that the values for h_s and t_s were 3.3 seconds and 6 seconds, respectively. The P_t and pilot car turnaround times were calculated to determine the presence of a correlation between those values and the green intervals. Data were reduced and compared for three test locations and no significant correlation and/or conclusions were obtained from the analysis due to the varying nature of the results. Finally, the model was developed using the available information, and it was found that the use of a signal system would fail at an AADT of 7,083 vehicles per day and at a corresponding maximum green interval of 446 seconds. Using the several equations developed as a part of this research, agencies can determine guidance regarding the volume thresholds for the failure of the system, the length of the work zone, and appropriate signal timing information.

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 6, Chapter 7, and Chapter 8.

Chapter 6: Research Findings

A Portable Traffic Signal (PTS) system is designed to control two-way traffic at temporary work zones where only one lane is available. 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 at shorter work zones. 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 (FHWA, 2012). However, there was minimal guidance provided regarding the use of the 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 long two-lane, two-way 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 valid 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 controlling one-lane, two-way traffic at long work zones. First, an operational evaluation and comparison of the three study 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 into different types and compared for the three study conditions using a 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 serve as a practical tool and provide some guidelines for the use of PTS systems at long and temporary rural work zones.

6.1 Summary of Findings

6.1.1 Safety and Visibility

In comparison to a flagger, the PTS units were highly visible from a long distance when observed from the upstream end. A major disadvantage of using only a flagger is his/her small size as compared to a signal unit and thereby the inability of drivers to identify the downstream traffic operations. Therefore, vehicles at the upstream end of a queue would be made more aware of the presence of a work zone downstream. In some cases visibility of the signal could be diminished by the presence of an oversized truck or a semi-trailer in front of a passenger car or a motorcycle. Therefore, providing adequate signage and informing 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 report) that the use of a PTS system could minimize the ever-increasing risk of flaggers being victims of inattentive and rash driving at work zones.

6.1.2 Field Operations

The signal units were user-friendly and had several practical features that assisted in their easy operation. The PTS units were easy to install with setup and teardown times approximately between 7 and 10 minutes each. When in use, the procedure to operate the signals was easy to understand and the units were easily operated by the pilot car drivers using the handheld remote control device (GFR) even though they had no prior experience in using these devices. Signal timings such as green interval, yellow interval, and gap time were easily entered, stored, and adjusted on the PTS units and did not require any special training and/or guidance.

6.1.3 Evaluation of 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. A total of 777 vehicle queues were recorded and reduced during the data reduction process for the three study conditions. During the data reduction, vehicle arrival and departure times, signal timing operations, and queue information were recorded for each observed vehicle queue. The following were some of the significant findings from results of the comparison of the operational parameters for each of the three study conditions:

- 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 results indicated that the PTS without a flagger condition was the most effective method in reducing the average wait time for the drivers approaching the work zone.
- The PTS with a flagger and the PTS without a flagger conditions served the longest average queue lengths, while the flagger only condition served the least average queue lengths over the entire duration of the data collection.
- There was no significant difference in the average duration of the green interval for the study conditions, indicating that the signal operations were independent of the presence or absence of a flagger with the signal unit.

Based on these results, it was concluded that since the three conditions did not significantly differ in the values for their operational parameters, they provided equivalent level of operational efficiency for controlling traffic at one-lane, two-way rural work zones.

6.1.4 RLR or Violation Analysis

Red light running violations (RLR) were the primary measure used to evaluate the effectiveness of the PTS systems for controlling traffic at lane-closure type rural work zones. Based on field observations and video evidence, RLR violations were divided into different categories for the purpose of the study. The following were the four types of RLR violations, and data were reduced to record each of these following events:

a. RLR when drivers were following an already departed queue.

b. RLR when drivers left a stopped queue unescorted by a pilot car.

c. RLR when drivers completely disregarded the PTS system.

d. RLR when drivers were waved through by the flagger to travel towards the work zone:

   (d-1) When the drivers were catching up with a departed queue.

   (d-2) When the drivers received the flagger’s consent to enter the work zone at another time period.

   (d-3) When the drivers completely disregarded the flagger control.

To conduct the analysis, the number of RLR violations for the three study conditions were calculated and then compared between all the test locations. The following were some of the significant findings obtained from the RLR violation analysis and the results of the test of proportions:

- A total of nine violations (about 1.1 percent) out of 814 vehicles were observed for the flagger only condition. It was also found that all the observed nine violations were of the type when the driver obtained the flagger’s consent to enter the work zone unescorted by a pilot car.
- A total of 52 violations (about 1.3 percent) out of 3,779 vehicles were observed at all test locations for the PTS with a flagger condition. It was also found that the average percentage of RLR violations for the PTS with a flagger condition at all the three test locations for the RLR types, when following a departed queue, when leaving a stopped queue, and when disregarding the traffic control, were 90, 5.8, and 3.8 percent, respectively. The results indicated that when a signal was used with a flagger, it was more susceptible to violations that involved drivers following an already departed queue on red signal indication than the other two types of violations.

- A total of 92 violations (3.1 percent) out of 2,944 vehicles were observed at all test locations for the PTS without a flagger condition. It was also found that the average percentage of RLR violations for the PTS without a flagger condition at all the three test locations for the RLR types, when following a departed queue, when leaving a stopped queue, and when disregarding the traffic control, were 39, 48, and 13 percent, respectively. The results indicated that when a signal was used without a flagger, it was more susceptible to violations that involved drivers leaving a stopped queue on red signal indication than the other two types of violations.
- 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 significant and higher than the condition when flagger only operations were used.
- The results of the test of proportions indicated that the number of violations when a PTS was used without a flagger were statistically significant and higher than the condition when a PTS was used with a flagger.
- The results of the test of proportions indicated that there was no statistically significant difference between the number of RLR violations when vehicles followed an already departed queue between the PTS with a flagger and PTS without a flagger conditions.
- Finally, it was also found that there was a statistically significant difference between the number of RLR vehicles that left the stopped queue and the number of vehicles that disregarded the PTS control between the PTS with a flagger and PTS without a flagger conditions.

6.1.5 Delay Analysis

An exploratory delay analysis was conducted to determine the change in total delay by the presence of a flagger with a signal unit in comparison to the signal only condition. At all the test locations, the flagger used his/her judgement to waive a few vehicles to travel in the direction of the work zone on red signal indication and unescorted by a pilot car. Two scenarios were compared to obtain an estimate of the total reduction in vehicular delay—the actual scenario and the hypothetical scenario. The total delay was determined based on the information available for arrival and departure times of the vehicles in each of the queues. After analyzing the available data, it was found that a total of 16.8 hours (approximately 5 percent) of the 318 hours of total delay was reduced in the presence of a flagger.

6.1.6 Model for Volume Thresholds and Appropriate Green Interval

As mentioned previously, the 2009 MUTCD provided limited guidance regarding the use of signals in conjunction with pilot car operations. Therefore, a model was developed to provide additional guidance prior to the application of the PTS units at two-lane, two-way work zones with pilot car operations and obtain estimates of the volume thresholds for the failure of these systems and appropriate green intervals that needed to serve a certain queue length. The guidelines presented in the HCM were used to determine the values of h_s and t_s. Based on the charts developed using the available data, it was found that saturated headway conditions started from the ninth vehicle position. From further analysis it was found that the values for h_s and t_s were 3.3 seconds and 6 seconds, respectively. The three charts shown in Figures 5.8, 5.9, and 5.10 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 5.8, 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 5.9, 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 5.10, the corresponding length of the work zone or end-to-end distance could be determined. It is noteworthy to mention that these charts could be used in a reverse order if a certain length of the work zone is desired to be established by the contractor. With the help of the model, the researchers found that the PTS systems would fail at an AADT of approximately 7,083 vehicles per day if the total pilot car round trip time is 15 minutes and the speed of the pilot car is 40 mph. Also, the corresponding maximum green time that could be set on the PTS is 446 seconds. Therefore, if the signal system is desired to be used at higher volume locations at the same speed and round trip time, the length of the work zone will have to be shortened to accommodate the increased volume. 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 7 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 7: Recommendations

Based on field observations and data analyses, it was found that the PTS without a flagger provided equivalent levels of operational efficiency as the flagger only and the PTS with a flagger conditions. Although there was a statistical difference in the number of red light running violations, it was believed that the difference in the number of violations was not practically significant, and so would not invalidate the use of PTS units with pilot car operations to control traffic at lane-closure type work zones. Therefore, the researchers recommend the use of PTS units without a flagger with pilot car operations and the most appropriate location to deploy them as a two-lane, two-way rural highway with an AADT of less than 7,083 vehicles per day. Since not every location has similar topography and roadway geometry, the following section describes a few recommendations and potential measures that can be adopted for better efficiency and work zone traffic control operations.

7.1 Use of PTS Units in Conjunction with Pilot Car Operations

It is recommended that the use of a PTS unit without a flagger should be avoided at major intersections with heavy cross-traffic and complex geometry. If a PTS unit is desired to be used without a flagger at rural intersections, proper storage lengths should be provided on the PTS leg of the intersection by altering the length of the work zone to accommodate the approaching traffic and to ensure efficient work zone traffic control operations. At locations with higher traffic volumes and longer vehicle queues, a PTS unit would prove beneficial for improved driver visibility and understanding, providing the road users with additional information regarding the presence of a traffic control device and downstream work zone conditions.

It is recommended that prior to installation of the PTS unit at any work zone end, the contractor or agency should plan for the space that would be needed for pilot car operations such as the U-turn maneuver and provide those drivers with the ability to identify and coordinate the signal operations. 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 pilot car queue has embarked and the signal was not in the green phase, it will cause severe driver confusion and drivers approaching the STOP line might entirely disregard the signal, creating a safety issue within the work zone. Therefore, to provide ample spacing between the PTS unit and the STOP line, the PTS unit should preferably be located close to a driveway so that the pilot car driver can easily perform the U-turn maneuver and be informed on the correct functioning of the signal operations.

To improve the safety at work zones, the researchers recommend using a trained flagger to control the signal operations and act as signal controller. A potential benefit in having a trained flagger act as the signal controller would be that he/she could conduct flagging operations in case of an emergency or an event of a signal failure. For shorter work zones in which the two signal units are visible to each other, a single flagger can control both the signal units and provide efficient traffic control operations. Although this might not be a suitable alternative for longer work zones in terms of reducing the costs and making additional manpower available, it could improve the safety of the flaggers by moving them away from the flagger station and also assist in controlling the likelihood of RLR violations.

It is recommended to use portable temporary rumble strips to reduce the speeds of red light running vehicles when approaching the activity area. As per the KDOT specifications, speed within the work zone was to be a maximum of 40 mph (KDOT, 2007). Pilot car operations prove to be effective as they are able to guide traffic at a consistent and safe speed through the entire work zone; yet, in the event when a driver runs the red light and travels in the direction of the work zone, safety can be compromised.

Meyer (2000) 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. Sun, Edara, and Ervin (2011) 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. Wang, Schrock, Bai, and Rescot (2013) 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 by 5.0 to 11.7 mph. Therefore, for RLR vehicles, a potential safety measure could be the use of portable temporary rumble strips that help in reducing the vehicle speeds within the work zone especially near the activity area. Reduction in the speed of a RLR vehicle could assist in reducing the severity of potential crashes and provide the work crew and other drivers some additional time to react to the hazardous situations.

It is recommended to use a static sign indicating the maximum anticipated wait time and the length of the work zone to decrease driver anxiety and control the number of red light running violations when a PTS is used without a flagger. All the work zones investigated during this research were long and temporary, in which the far end of the work zone was not visible to the traffic stopped at the flagger stations. It was found from the data reduction 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 2 and 3 miles. Furthermore, approximately 48 percent of the violations when a PTS was used without a flagger were of the type when the drivers left a stopped queue to travel in the direction of the work zone. Although no specific trend could be identified for the vehicle departures after the onset of the red indication, the researchers speculate that lack of information on the wait time or delay was an important variable. Therefore, 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 violations in the absence of a flagger.

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 and equations developed in this research, the site superintendent can estimate the maximum feasible green interval and length of the work zone needed at any particular pilot car speed and desired pilot car round trip time. This will assist the pilot car driver to provide appropriate green time to the number of stopped vehicles in the queue.

It is recommended to install the CONSTRUCTION VEHICLE – DO NOT FOLLOW sign on the back of the construction vehicles that will be moving in and out of the work zone during pilot car operations. 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. Therefore, in the absence of a flagger with a PTS unit, it is recommended that a sign should be installed on the back of all the work vehicles indicating that those were not the pilot car to discourage drivers stopped in the queue at the work zone end stations from following them into the work zone and to reduce driver confusion by providing additional information.

It is recommended to provide the clearance height on the PTS units to serve as additional guidance to the drivers of the oversize vehicles. Since rural roads and highways are generally free from vertical and horizontal obstructions such as flyover bridges, oversize vehicles can be found commonly in rural environments and could be a hindrance when deploying a PTS unit. Figure H.1 in Appendix H shows an oversize vehicle passing around the PTS unit observed during the data collection. If deployed correctly, a fully extended PTS unit has a clearance height of 17 feet and oversize loads are generally around 15.5 feet (15'6''). The PTS units should be stationed on the roadway shoulder in such a manner that the mast arm does not extend beyond the centerline. At locations where shoulders are not available, the mast arm might protrude beyond the roadway centerline and having a sign indicating the maximum clearance height would provide the drivers some additional guidance.

A single traffic control device demands greater respect from the drivers. A major portion of the five percent reduction in total delay was brought about by disregarding another traffic control device (PTS) when the flaggers waved vehicles through to travel in the direction of the work zone on red signal indication and unescorted by a pilot car. Reduction in vehicular delay is not a valid justification for disregarding a traffic control device. The most efficient way of reducing the total wait time is to reduce the queue size by increasing the number of cycles during the entire day the work zone is in operation. Furthermore, the KDOT (2008) *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 in conjunction with pilot car operations—would demand greater respect from the drivers towards the traffic control and eliminate the effect of contradiction generated by the use of a multiple traffic control devices. Therefore, the researchers recommend using either a PTS or a flagger in conjunction with pilot car operations to control traffic at lane-closure type work zones and discourage vehicles from entering the work zone on red signal indication.

7.2 Measures to Adopt for Potential Problems Due to Signal Failure

Signal failure events could occur at any point during the work activity. Signal failure events can be of several types: unable to level the trailer, unable to activate or connect the signal remote control device, loss of battery power, detection failure, and unable to activate the green extension time. The following are some measures believed to minimize effects of undesirable scenarios and to 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, 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.

7.3 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; or
- 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 with 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 members 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. Also, it is recommended for the manufacturers to develop newer systems that avoid using the Red Rest button to activate the maximum green phase which will further simplify the use of these signal systems for work zone traffic control operations.

At Newton (US-50), all 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, 2014, 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 by taking charge and stopping 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. Therefore, frequent checks of the signal unit should be conducted to ensure safe and efficient traffic control operations.

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 5 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 5 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 lengths 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, it was believed that the occurrence of such events was a function of the wait time at a PTS or 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 8 provides a few areas for future research that could help in improving the overall effectiveness of the system.

Chapter 8: 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 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 one 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, RVs, 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 A.1 shows the two PTS units used for the research.

Figure A.1: Two PTS Units Used for the Study

As shown in Figure A.1, 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 A.2 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 A.2: 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 A.3 shows the signal heads on a single PTS unit.

Figure A.3: 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 A.4 shows the batteries provided in a single PTS unit.

- 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.

Figure A.4: Batteries Provided (Source: Procurement Specifications PTS-2000)

Photo Voltaic Solar Array

Figure A.5 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 A.5: 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 A.6 shows the handheld remote control used to operate the PTS unit.

1. Electrical Specifications
   - External Power Supply Voltage: 10-18 VDC
   - Temperature: 30 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

Figure A.6: PTS Handheld Remote Control with External Plug-In Charger

Controls

Figure A.7 shows the main control box on a single PTS unit.

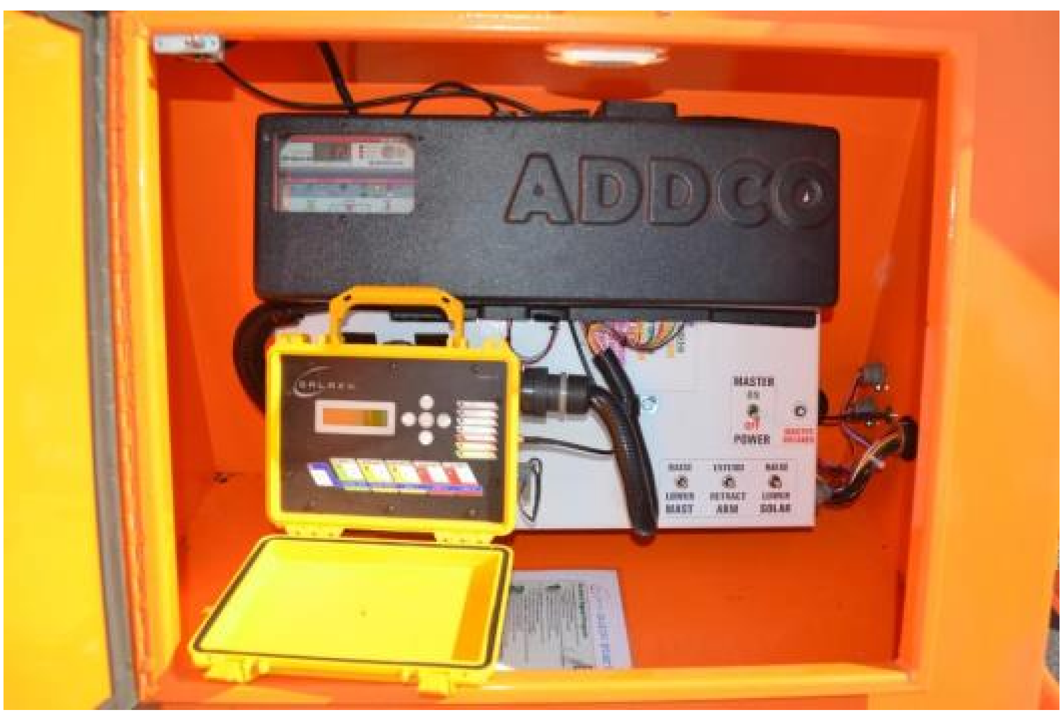

Figure A.7: PTS Control Box

As shown in Figure A.7, 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 Departments of Transportation (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 DOTs.

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 State Highway and Transportation Department

The Arkansas State Highway and Transportation Department (AHTD) referred to the MUTCD guidelines and used the temporary traffic signals without flaggers in its work zones. The department used pilot car operations for bridge work, 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 Department of Transportation

The Connecticut Department of Transportation 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 the department believes that they 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 Department of Transportation

The Florida Department of Transportation 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 no more than 2 to 3 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 Transportation Department

The Idaho Transportation Department 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 5 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 5 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 Department of Transportation

The Illinois Department of Transportation 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 1.5 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 closure 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 Department of Transportation

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 nighttime operations. The length of work zone for the pilot car operations varied from 0.5 to 8 miles. The department considered a queue length of 1.5 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 Department of Transportation

The Iowa Department of Transportation 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 works that were not very long in length. Temporary traffic signals and pilot car operations were used in work zones of length up to 2.5 miles. 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 Transportation Cabinet 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 Department of Transportation

The Maryland Department of Transportation 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 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 1 mile in length. If necessary, flaggers were used for nighttime operations with appropriate lighting in the work zone.

Michigan Department of Transportation

The Michigan Department of Transportation 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 2 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 nighttime operations and pilot cars during the daytime operations.

Minnesota Department of Transportation

The Minnesota Department of Transportation 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 Department of Transportation

The Montana Department of Transportation 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 2 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 10 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 Department of Roads

The Nebraska Department of Roads 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 Department of Transportation

The Nevada Department of Transportation 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 zero to 5 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 Department of Transportation

The Ohio Department of Transportation 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 temporary traffic signals for both the daytime and nighttime operations.

Oklahoma Department of Transportation

The Oklahoma Department of Transportation 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 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 Department of Transportation

The Tennessee Department of Transportation occasionally used the temporary traffic signals or PTS in its work 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 1 to 1.5 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 Department of Transportation

The Texas Department of Transportation 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 2 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 5 to 10 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 10 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 urban areas with ADTs in the range of 2,500 to 3,000.

Wyoming Department of Transportation

The Wyoming Department of Transportation 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: Signal Timing Data

Table C.1: Signal Timing Information for Test Location 1 on US-56 near Burlingame, KS

Date	WZ End	DCC	Total No. of Cycles	Minimum Green Time Used		Green Extension Time Used		Inactive Green Phases	
				Cycles	Percent (%)	Cycles	Percent (%)	Cycles	Percent (%)
8/5/2014	5	B	12	5	42	5	42	2	17
	6	NA	NA	NA	NA	NA	NA	NA	NA
	7	B	19	4	21	12	63	3	16
	8	B	19	5	26	10	53	4	21
8/6/2014	9	C	29	11	38	17	59	1	3
	10	C	24	10	42	12	50	3	13
8/7/2014	11	C	17	8	47	9	53	0	0
	12	C	16	12	75	3	19	1	6
	13	C	19	4	21	15	79	0	0
	14	C	24	5	21	19	79	0	0
Total			**179**	**64**	**36**	**102**	**57**	**14**	**8**

Note: "WZ" – Work zone end information from Figure 4.3, "DCC" – Data collection condition, "B" – PTS with a flagger condition, "C" – PTS without a flagger condition, "NA" – Not applicable because no data were collected.

Table C.2: Signal Timing Information for Test Location 2 on K-31 near Melvern, KS

Date	WZ End	DCC	Total No. of Cycles	Minimum Green Time Used		Green Extension Time Used		Inactive Green Phase	
				Cycles	Percent (%)	Cycles	Percent (%)	Cycles	Percent (%)
8/12/2014	1	B	14	13	93	0	0	1	7
	2	C	10	9	90	1	10	0	0
8/13/2014	3	C	21	17	81	3	14	1	5
	4	C	19	15	79	1	5	3	16
	5	C	24	23	96	1	4	0	0
	6	C	26	25	96	1	4	0	0
8/14/2014	5	C	26	22	85	1	4	3	12
	6	C	26	23	88	1	4	2	8
Total			**166**	**147**	**89**	**9**	**5**	**10**	**6**

Note: "WZ" – Work zone end information from Figure 4.4, "DCC" – Data collection condition, "B" – PTS with a flagger condition, "C" – PTS without a flagger condition, "NA" – Not applicable because no data were collected.

Table C.3: Signal Timing Information for Test Location 3 on US-24 near Beloit, KS

Date	WZ End	DCC	Total No. of Cycles	Minimum Green Time Used		Green Extension Time Used		Inactive Green Phase	
				Cycles	Percent (%)	Cycles	Percent (%)	Cycles	Percent (%)
8/19/2014	1	B	34	2	6	30	88	2	6
	2	B	34	6	18	26	76	2	6
8/20/2014	1	C	39	3	8	35	90	1	3
	2	B	40	17	43	21	53	2	5
8/21/2014	3	C	18	3	17	15	83	0	0
	4	C	32	2	6	29	91	1	3
Total			**197**	**33**	**17**	**156**	**79**	**8**	**4**

Note: “WZ” – Work zone end information from Figure 4.5, “DCC” – Data collection condition, “B” – PTS with a flagger condition, “C” – PTS without a flagger condition, “NA” – Not applicable because no data were collected.

Table C.4: Signal Timing Information for Test Location 4 on US-50 near Newton, KS

Date	WZ End	DCC	Total No. of Cycles	Minimum Green Time Used		Green Extension Time Used		Inactive Green Phase	
				Cycles	Percent (%)	Cycles	Percent (%)	Cycles	Percent (%)
8/26/2014	1	NA	NA	NA	NA	NA	NA	NA	NA
	2	B	19	0	0	17	89	2	11
8/27/2014	3	B	23	0	0	22	96	1	4
	3	C	28	0	0	28	100	0	0
	4	B	57	0	0	54	95	3	5
8/28/2014	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total			**127**	**0**	**0**	**121**	**95**	**6**	**5**

Note: “WZ” – Work zone end information from Figure 4.6, “DCC” – Data collection condition, “B” – PTS with a flagger condition, “C” – PTS without a flagger condition, “NA” – Not applicable because no data were collected.

Appendix D: Data for Delay Analysis

Table D.1: 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 D.2: 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 D.3: 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 D.4: 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 D.5: 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 D.6: 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 D.7: 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 D.8: 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 D.9: 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 D.10: 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 D.11: 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 D.12: 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 D.13: 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 D.14: 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 D.15: 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 D.16: 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 D.17: 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 D.18: 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 D.19: 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 D.20: 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 D.21: 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 D.22: 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 D.23: 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 D.24: 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 D.25: 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 D.26: 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 D.27: 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 D.28: 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 D.29: 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 D.30: 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 E: Charts for Delay Analysis

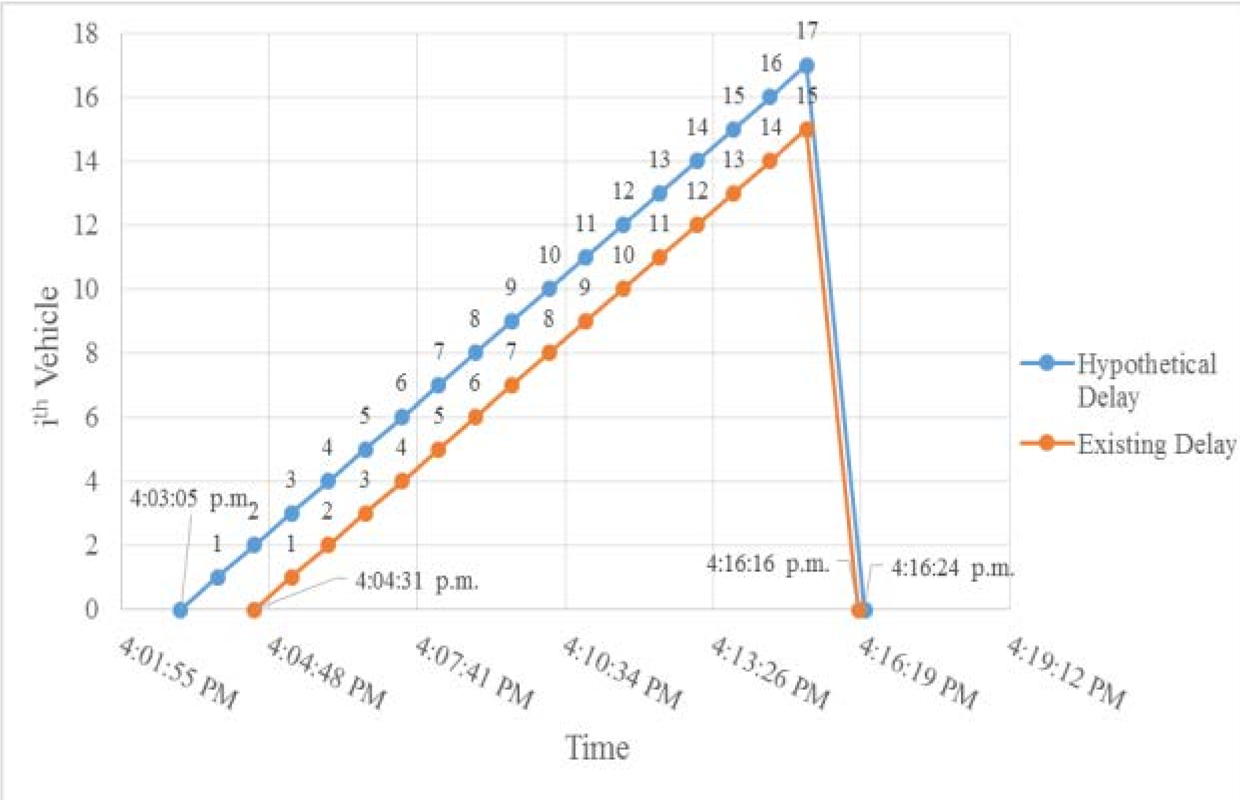

Figure E.1: Delay Analysis 1

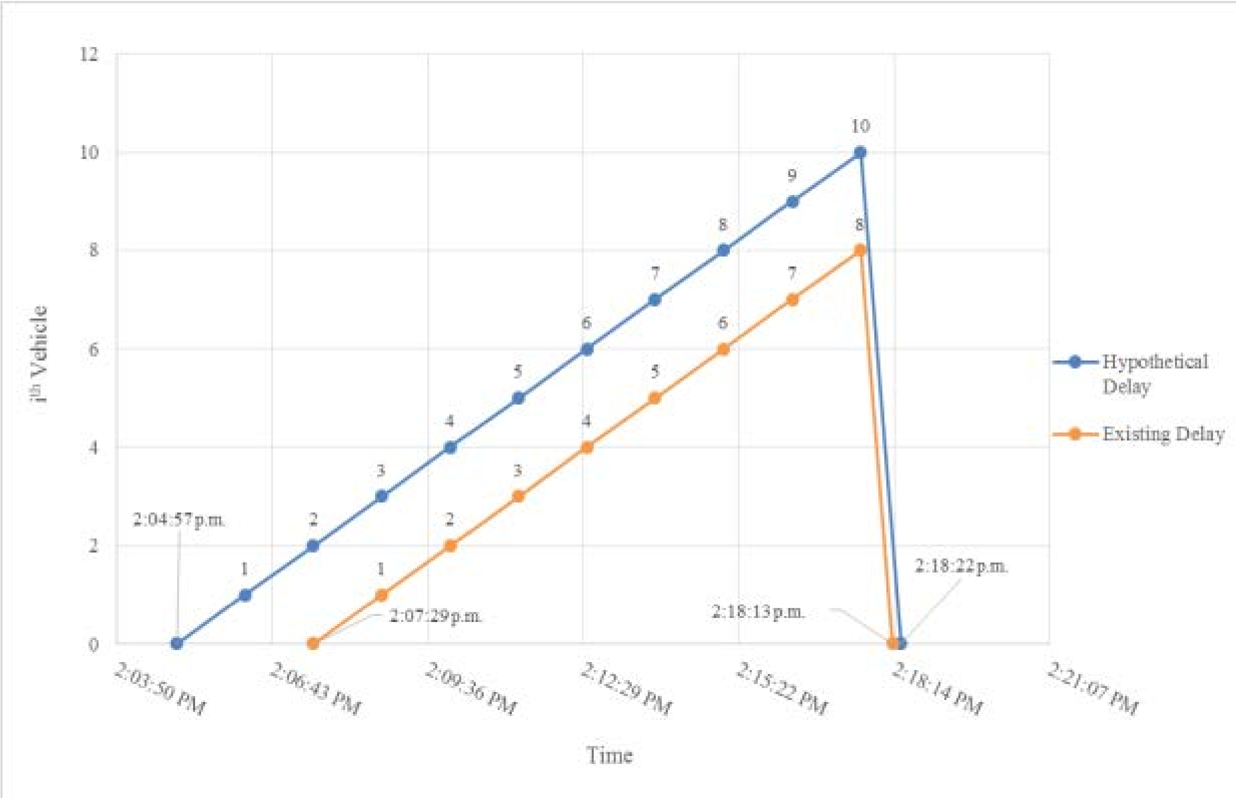

Figure E.2: Delay Analysis 2

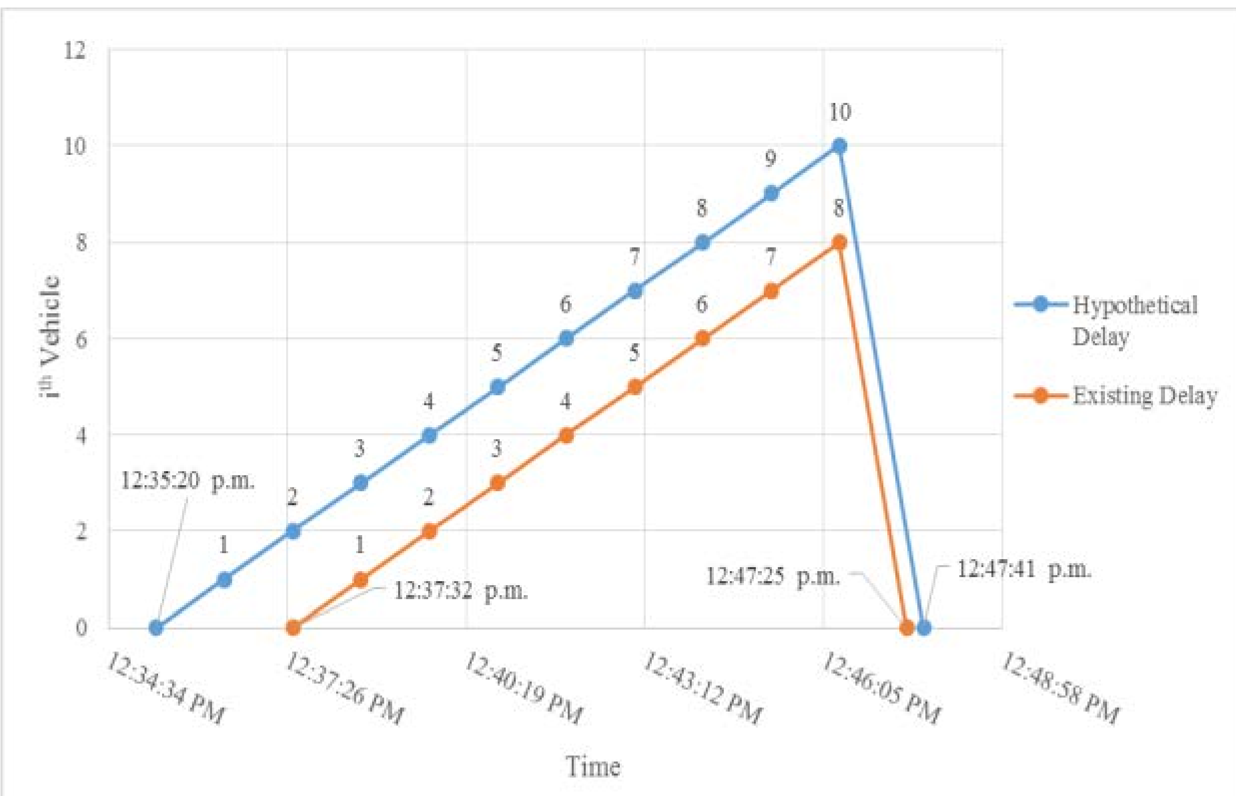

Figure E.3: Delay Analysis 3

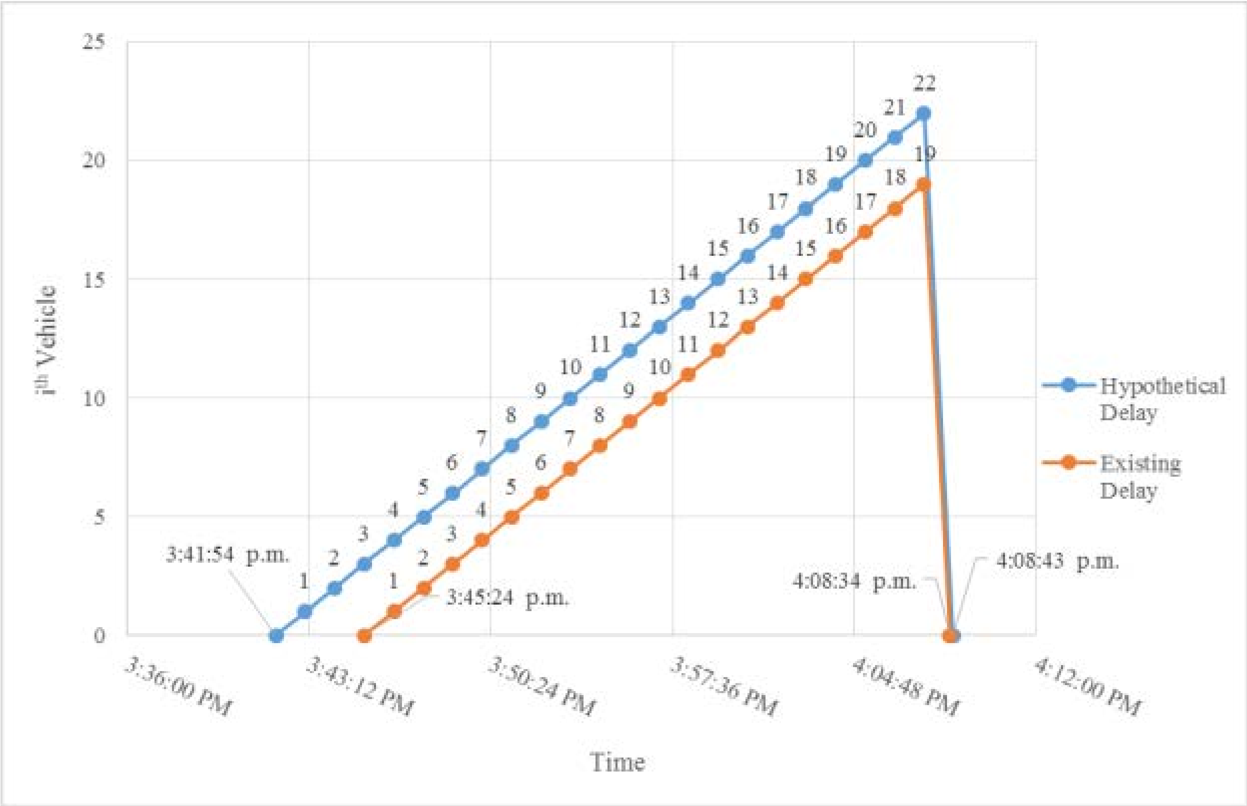

Figure E.4: Delay Analysis 4

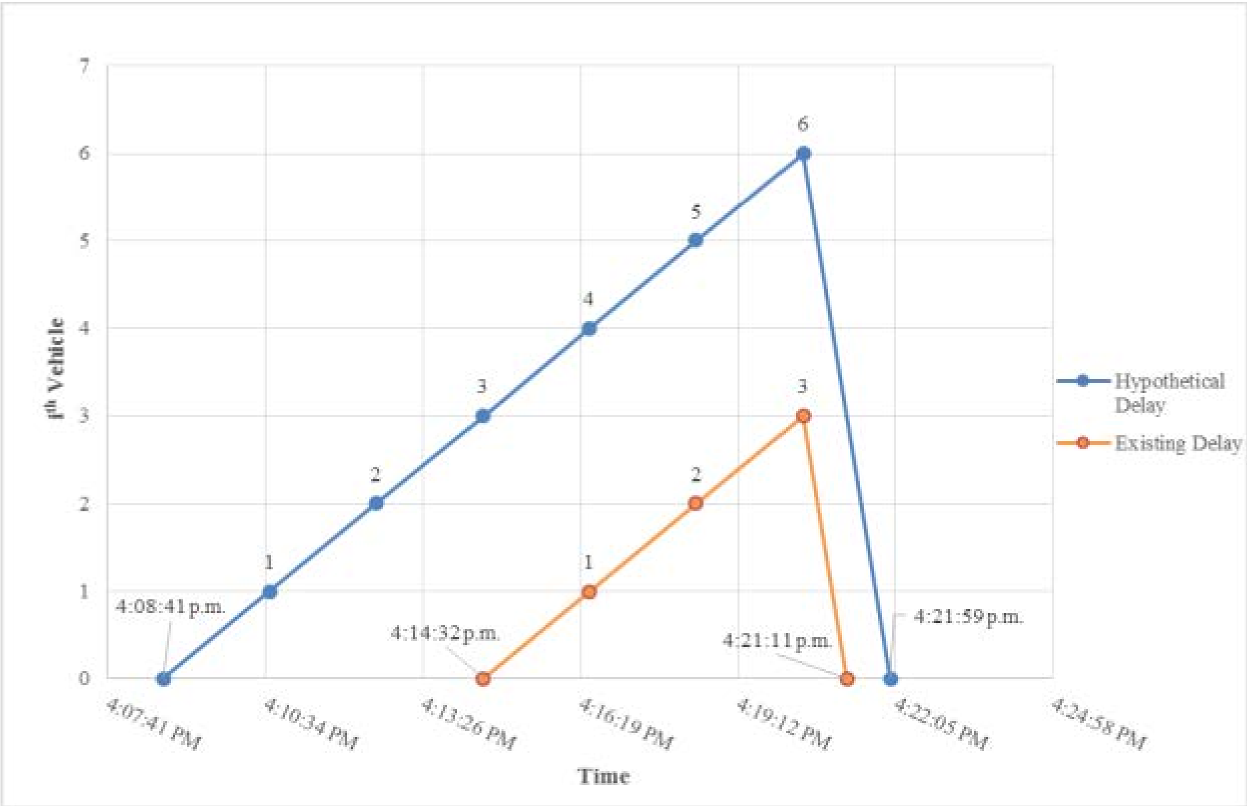

Figure E.5: Delay Analysis 5

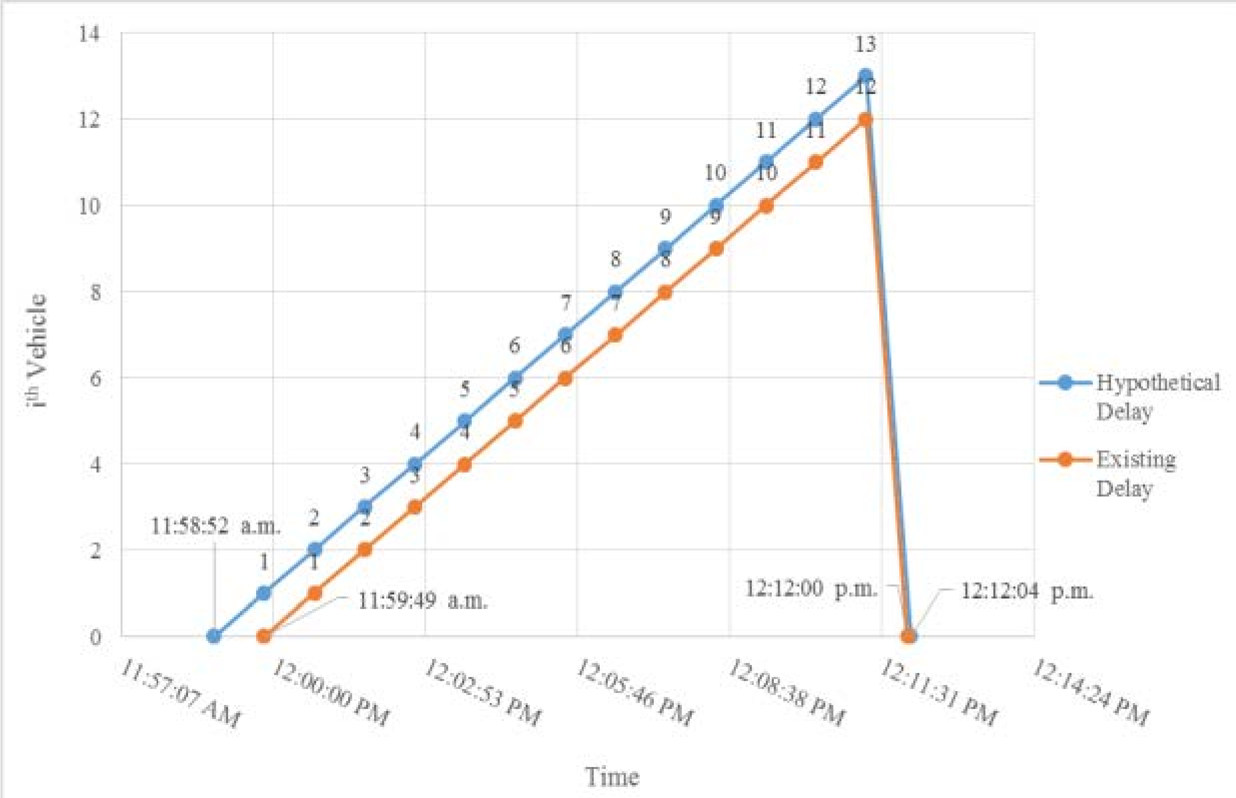

Figure E.6: Delay Analysis 6

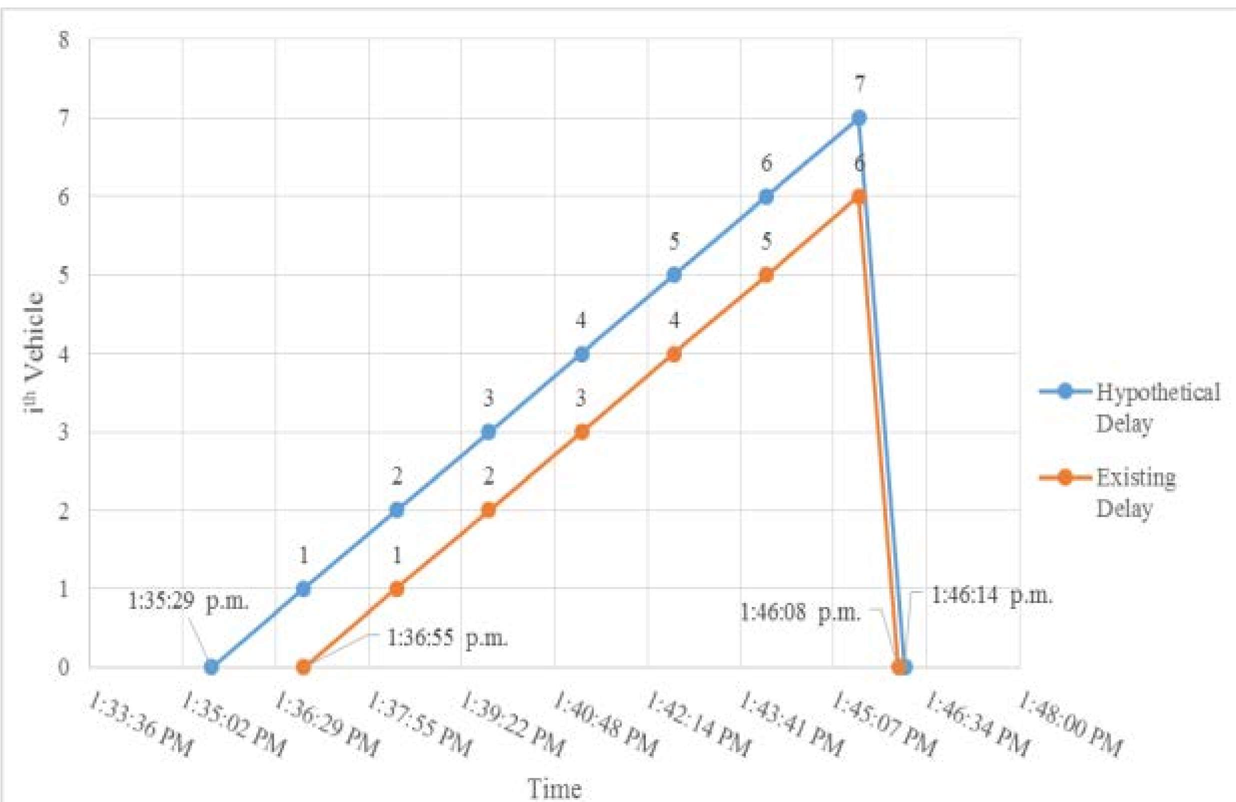

Figure E.7: Delay Analysis 7

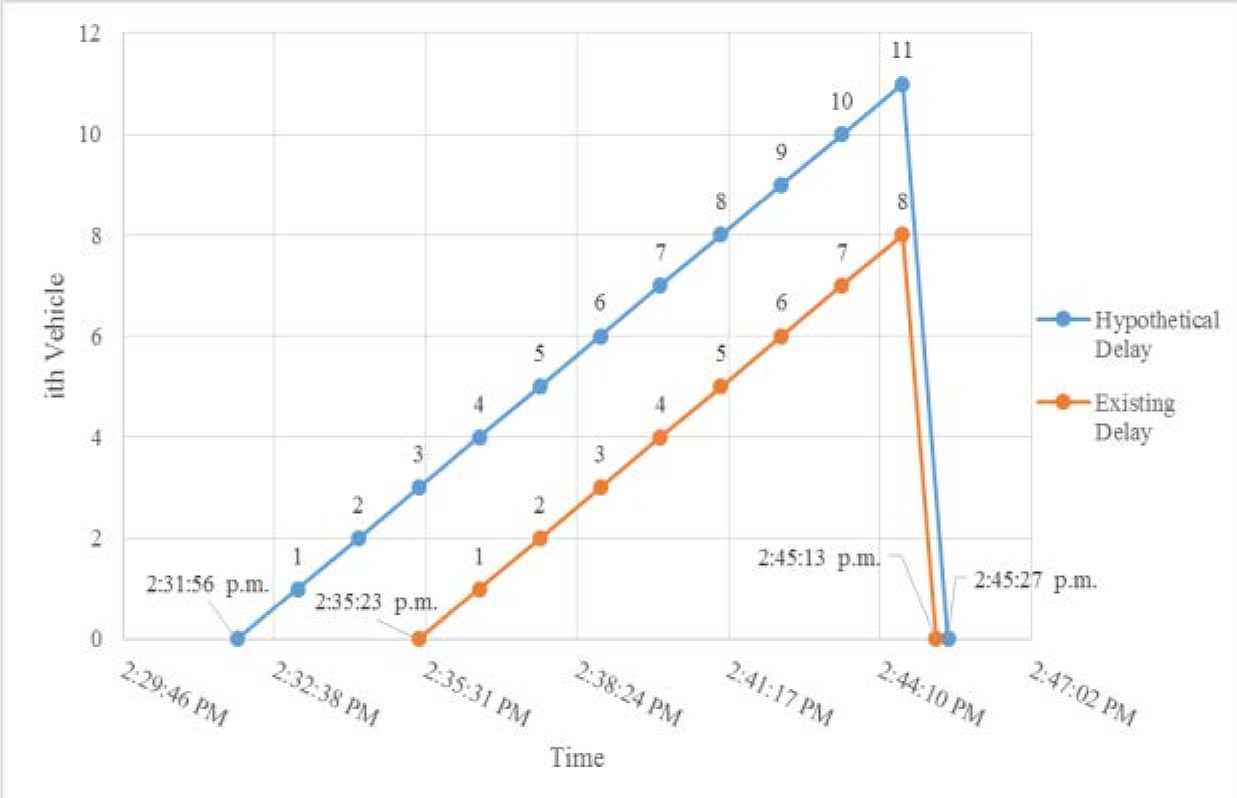

Figure E.8: Delay Analysis 8

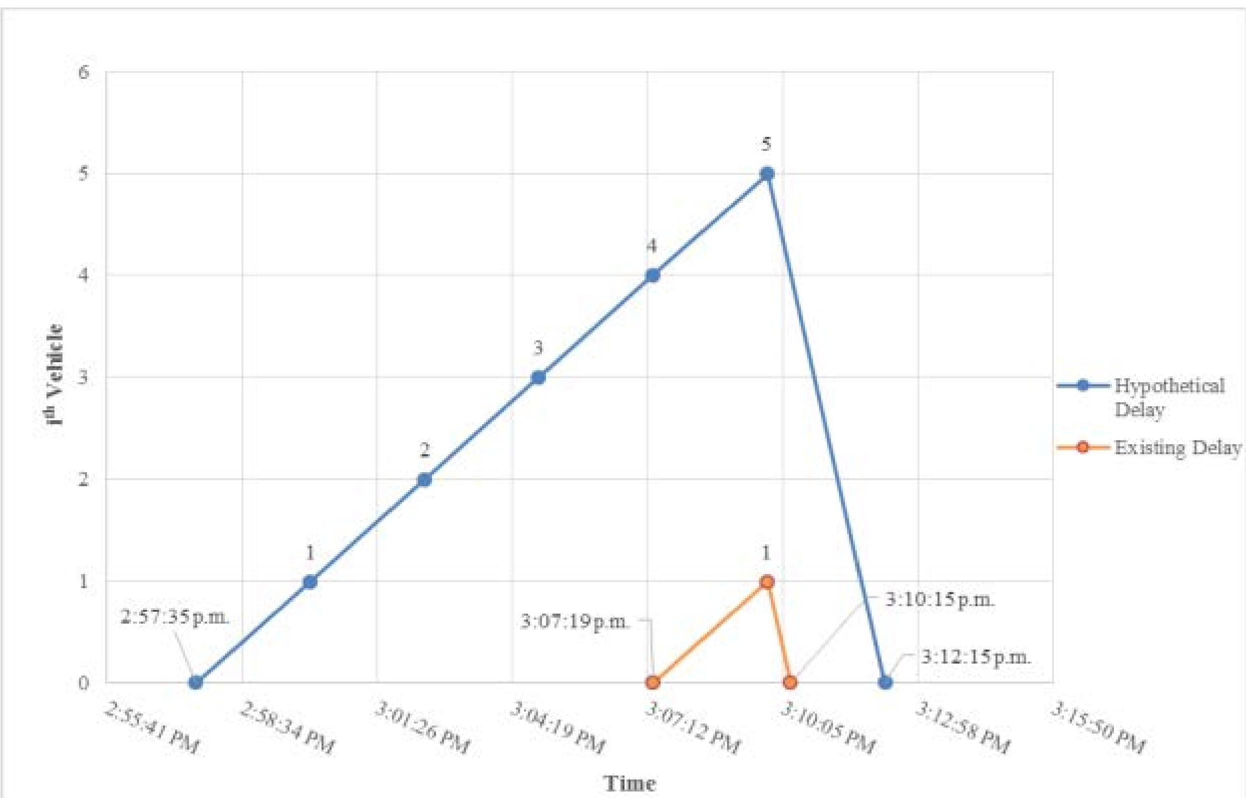

Figure E.9: Delay Analysis 9

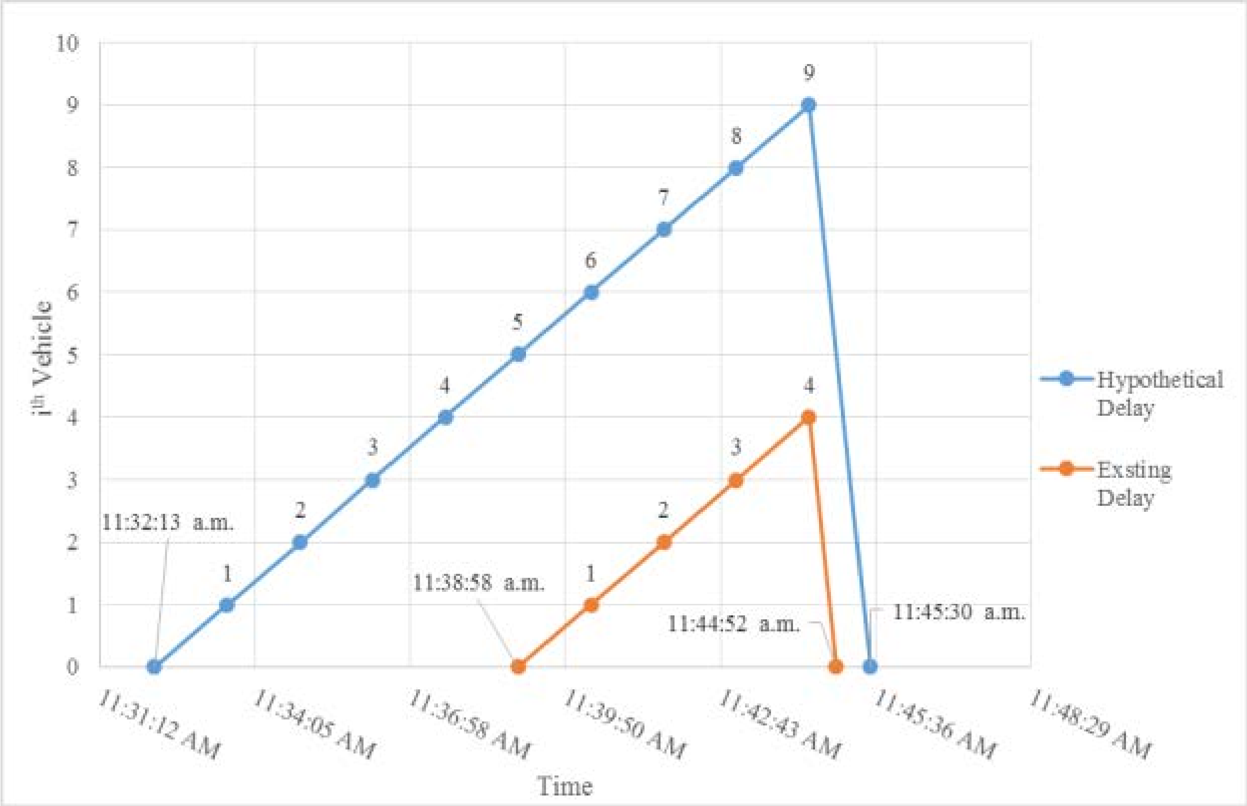

Figure E.10: Delay Analysis 10

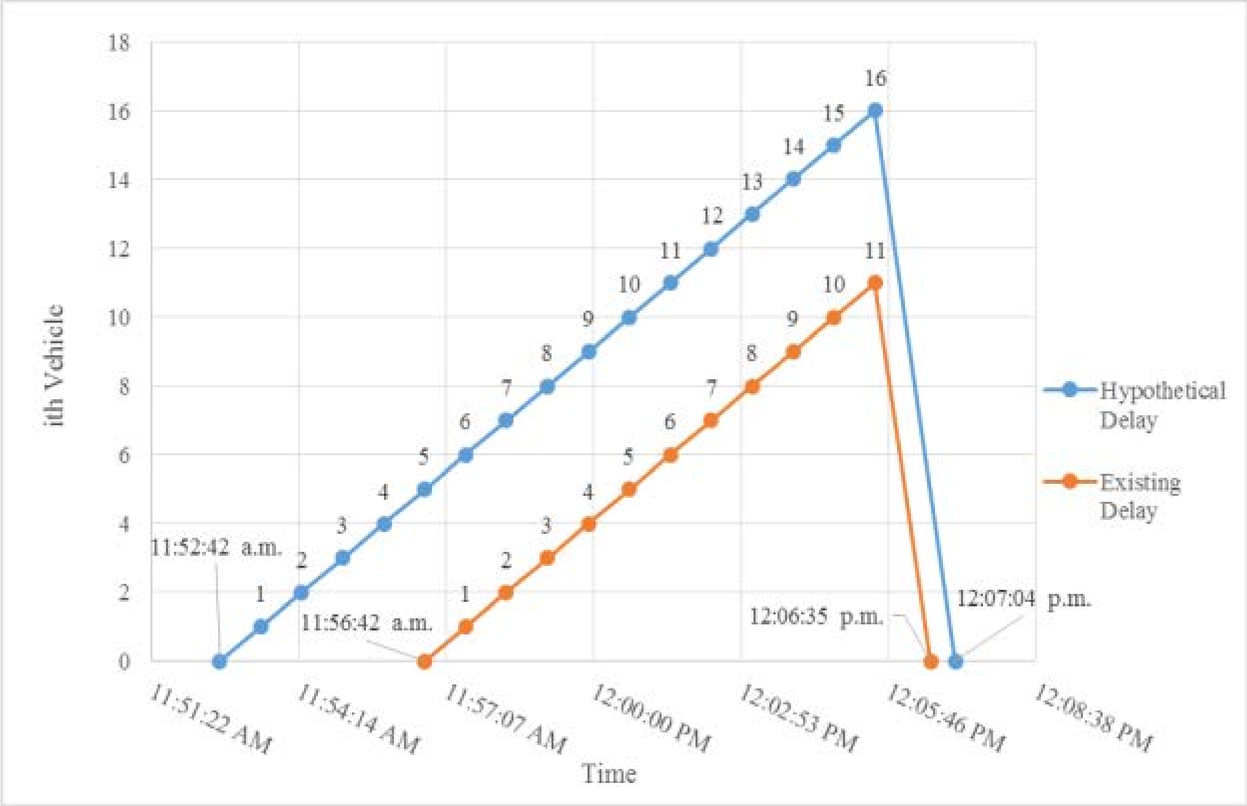

Figure E.11: Delay Analysis 11

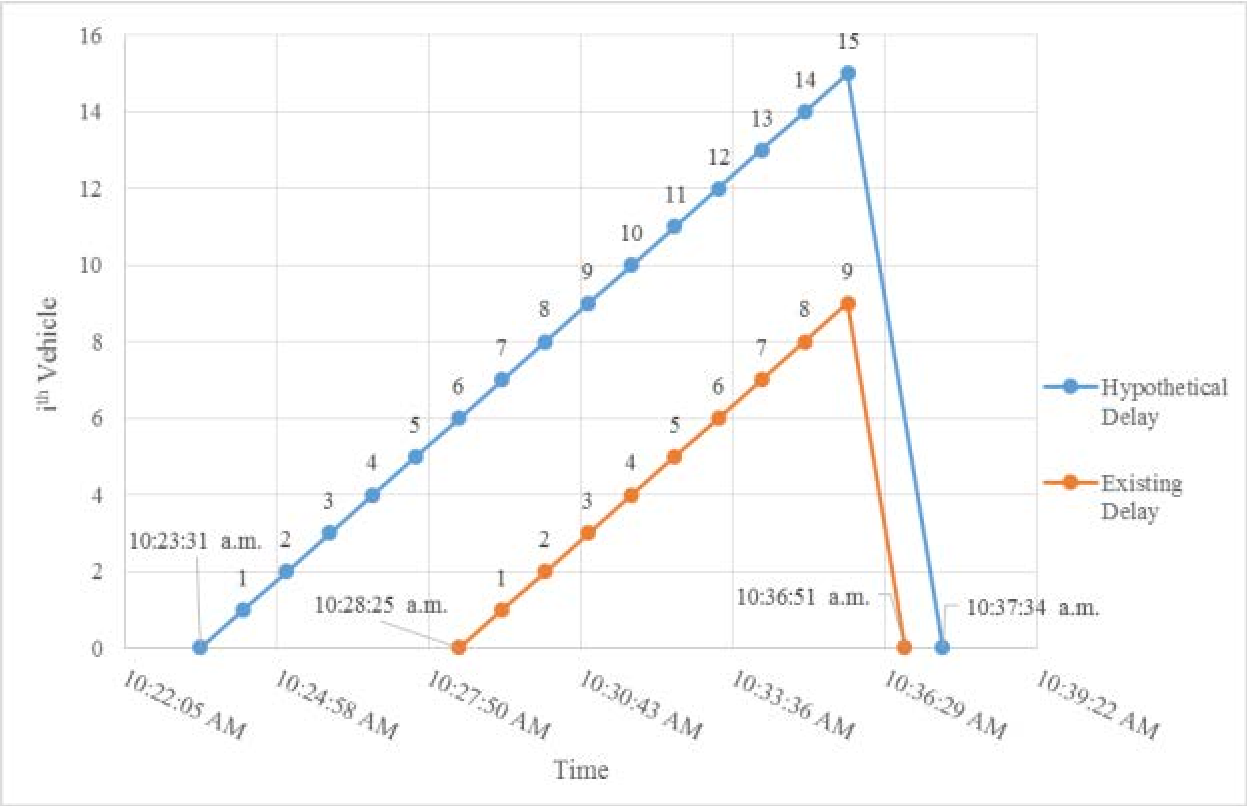

Figure E.12: Delay Analysis 12

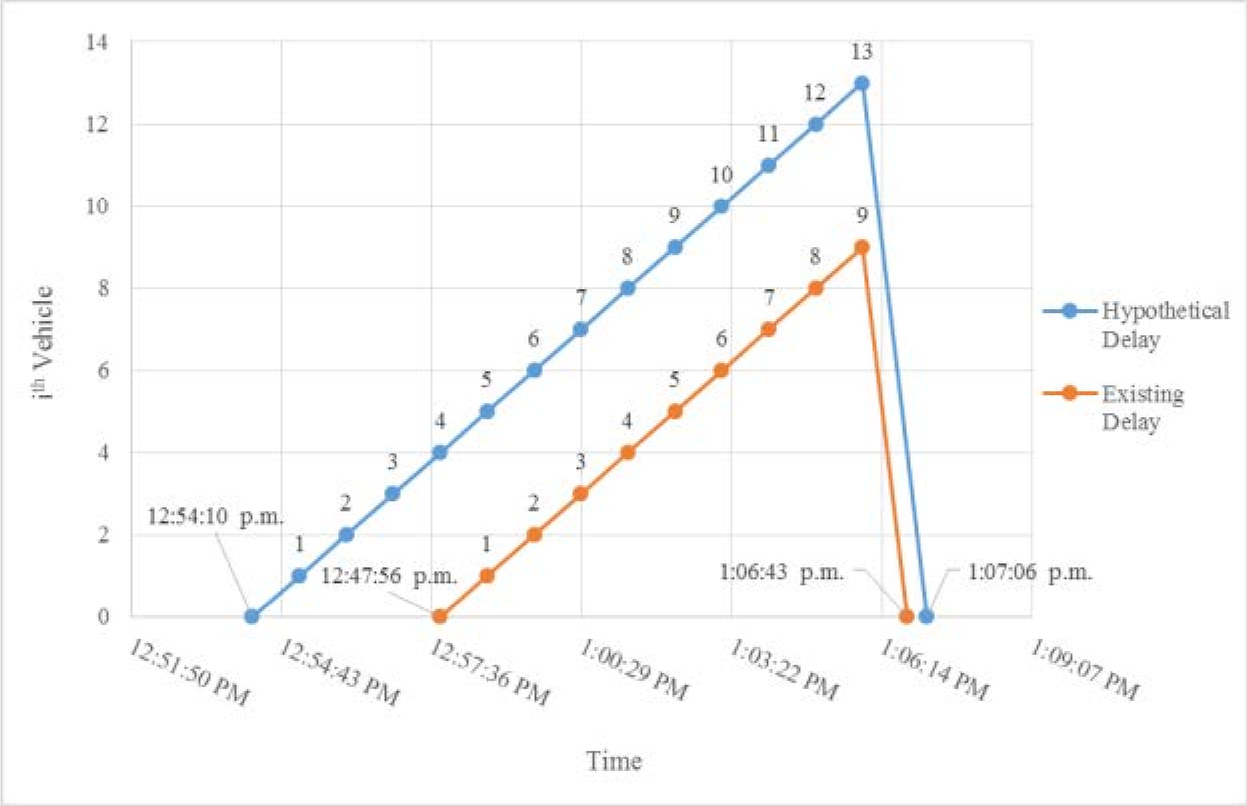

Figure E.13: Delay Analysis 13

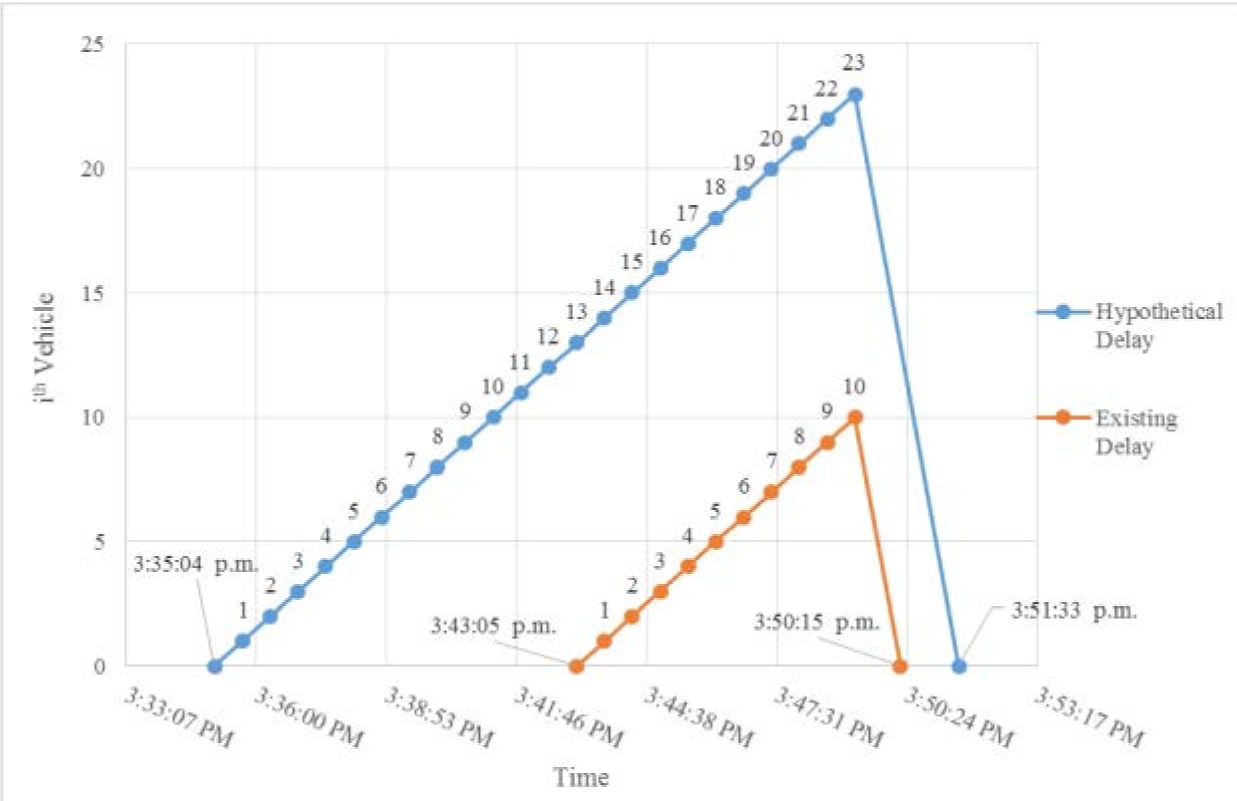

Figure E.14: Delay Analysis 14

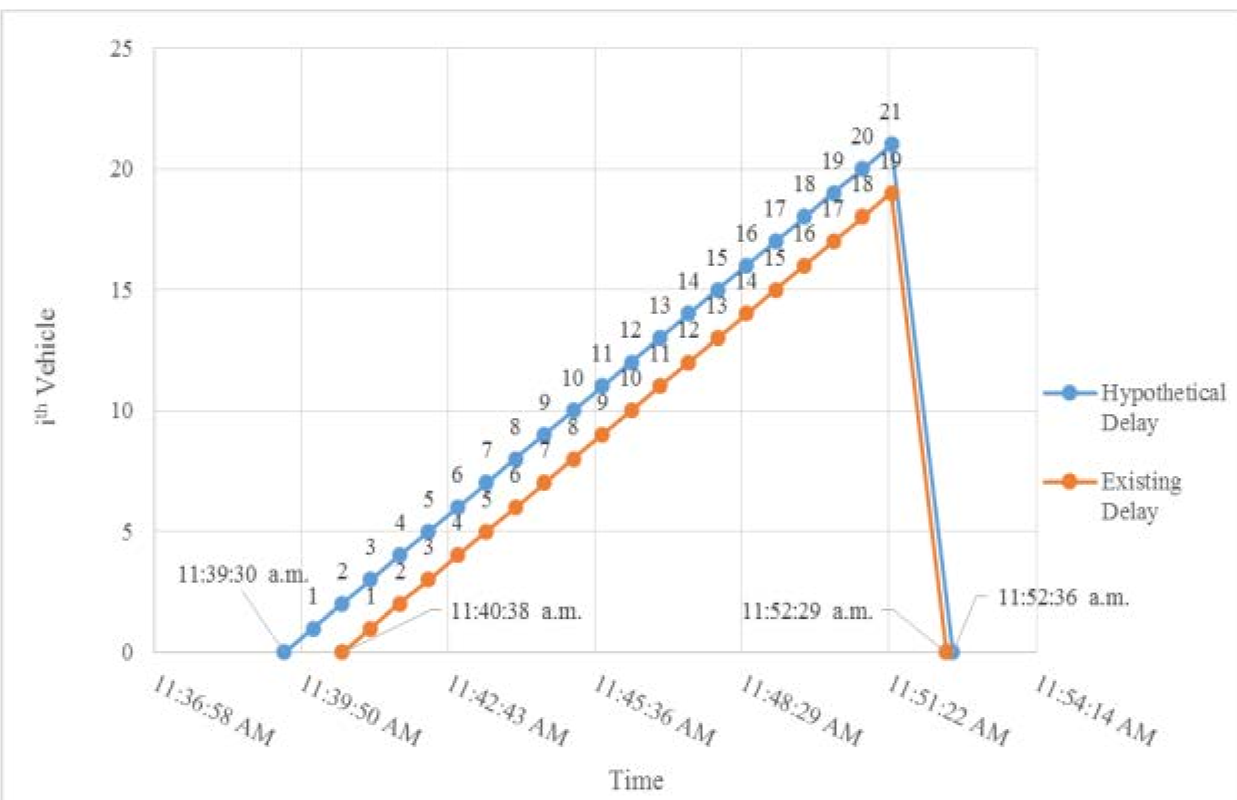

Figure E.15: Delay Analysis 15

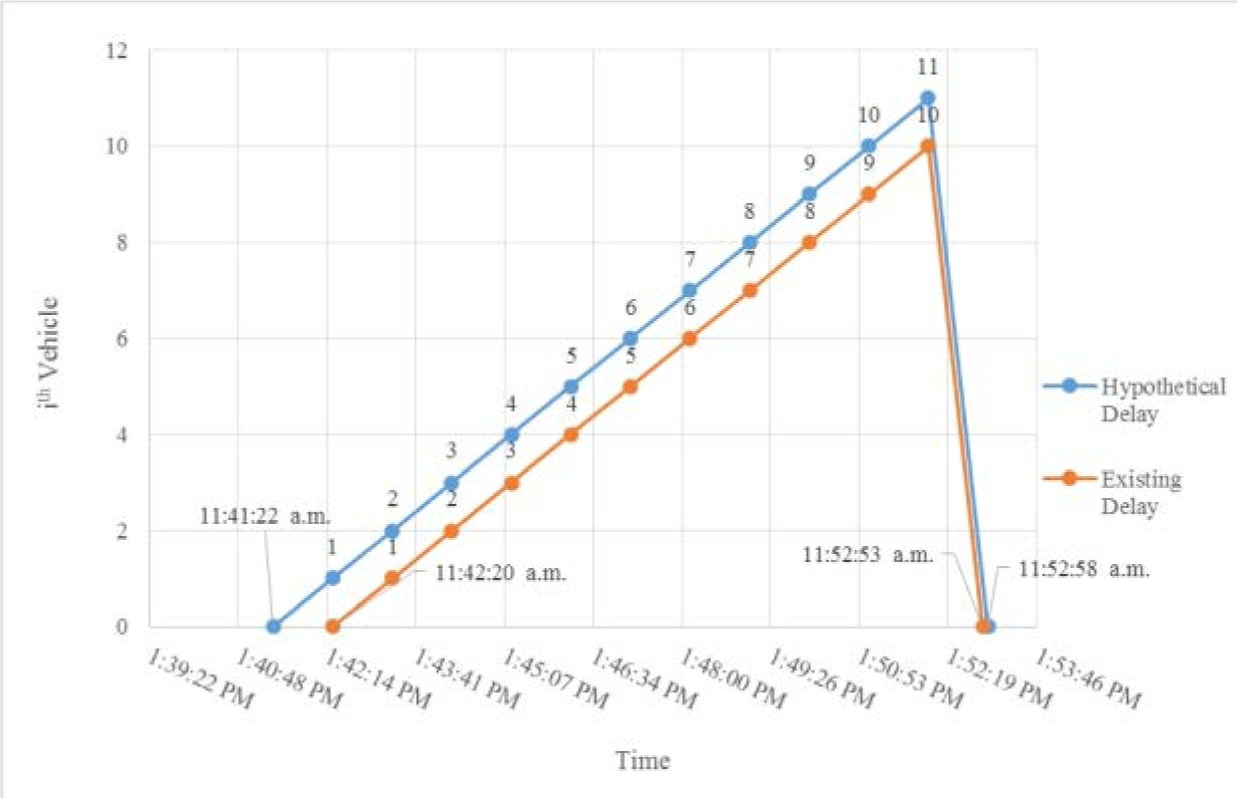

Figure E.16: Delay Analysis 16

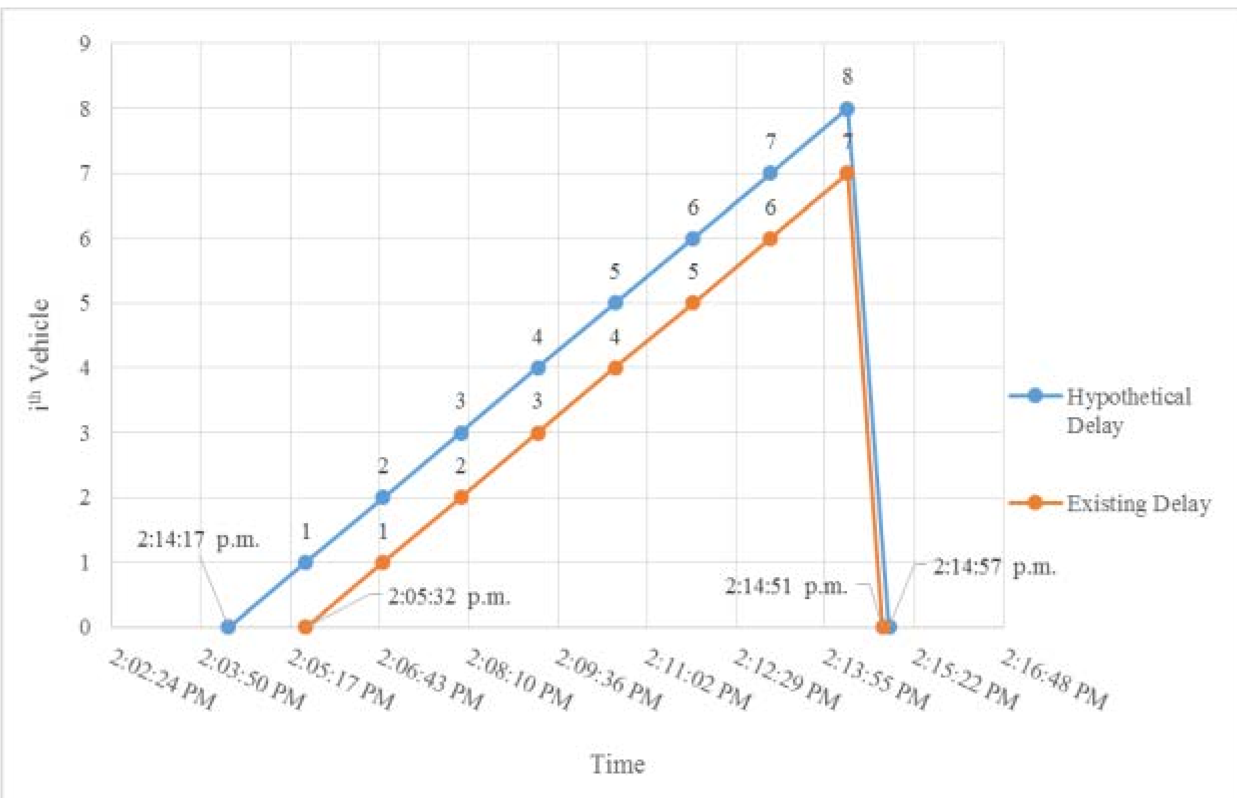

Figure E.17: Delay Analysis 17

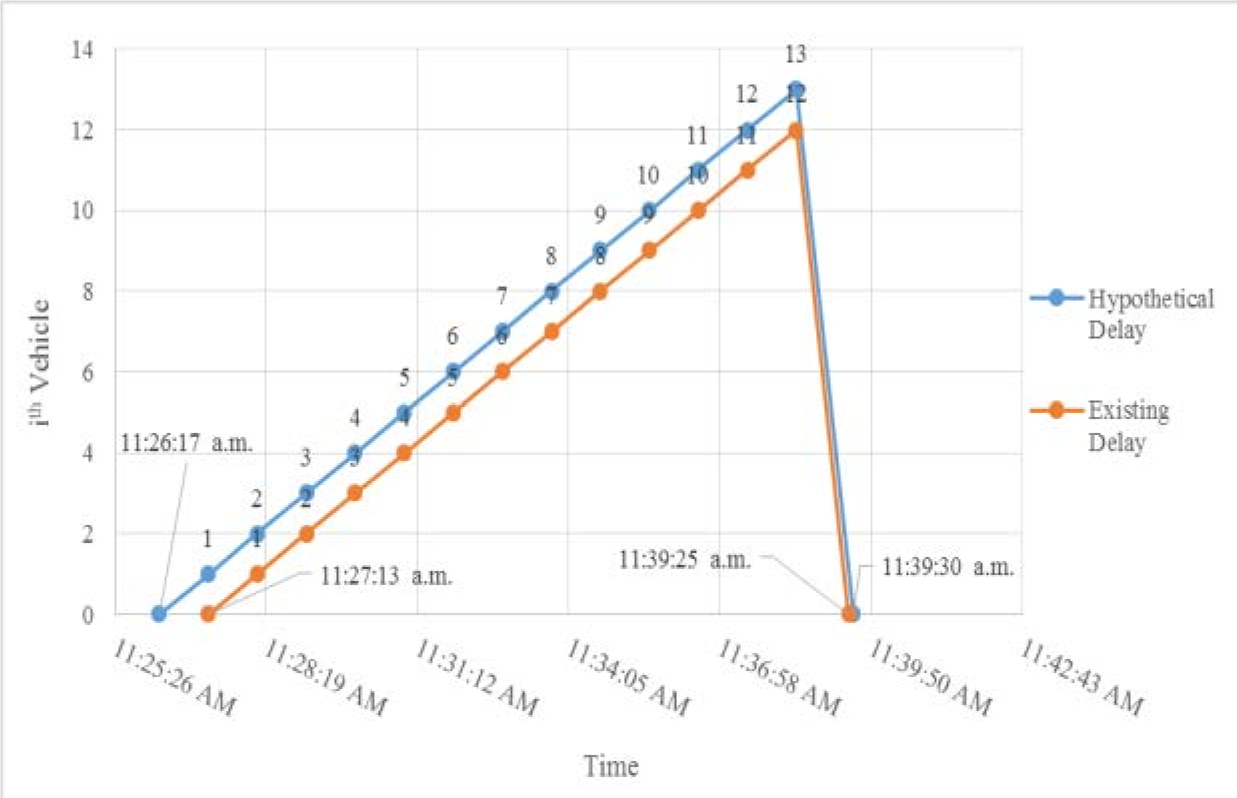

Figure E.18: Delay Analysis 18

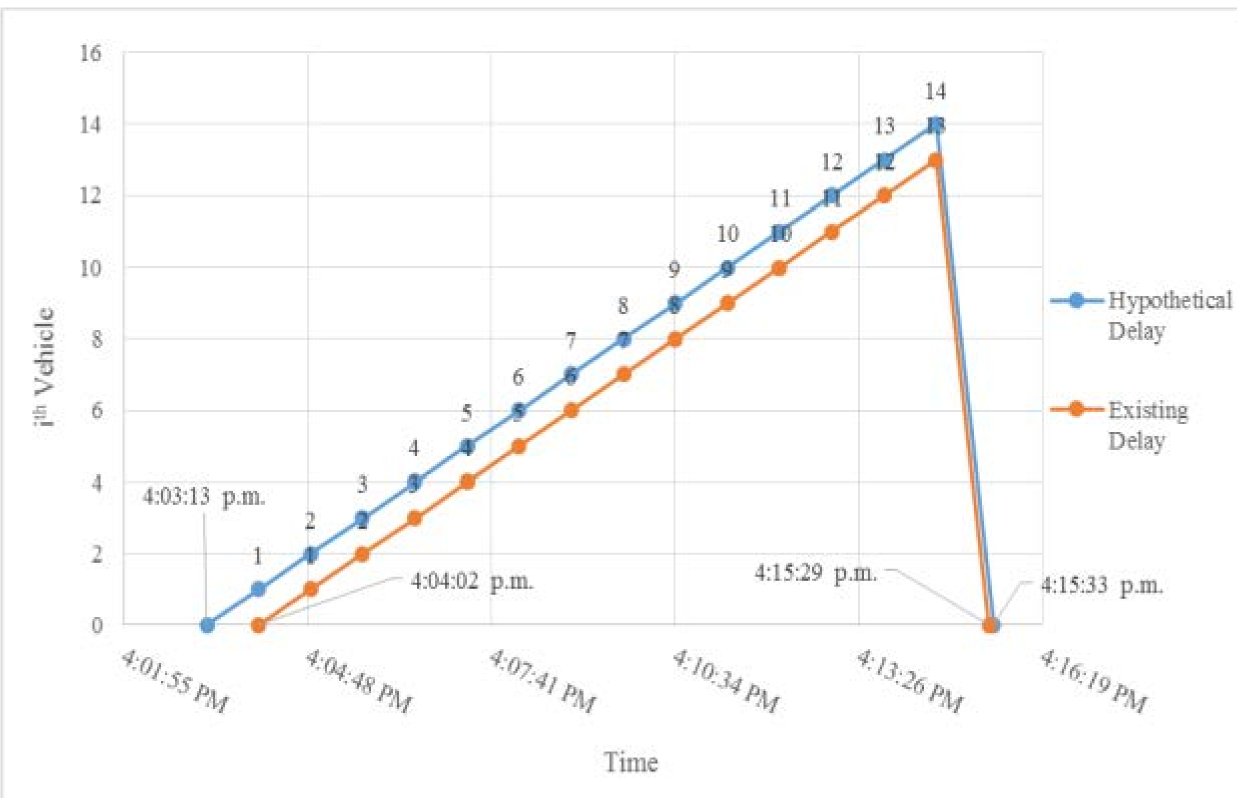

Figure E.19: Delay Analysis 19

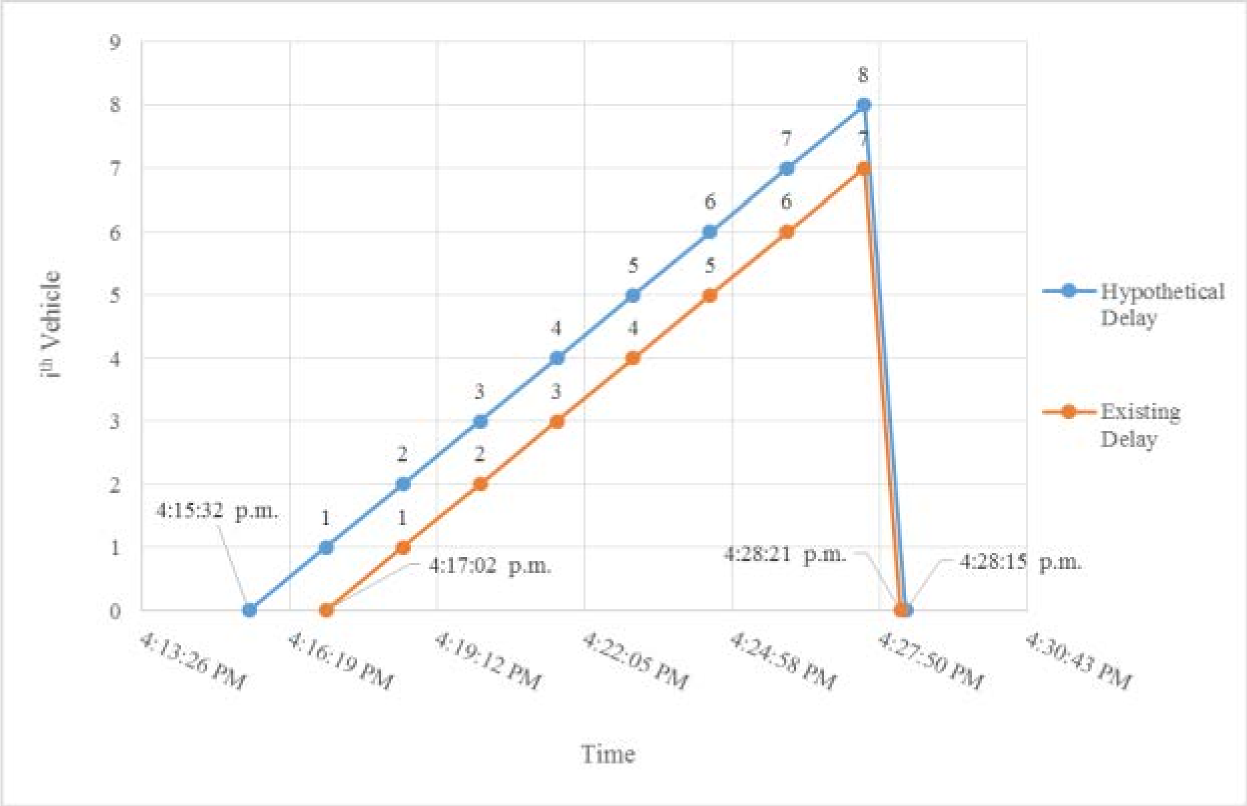

Figure E.20: Delay Analysis 20

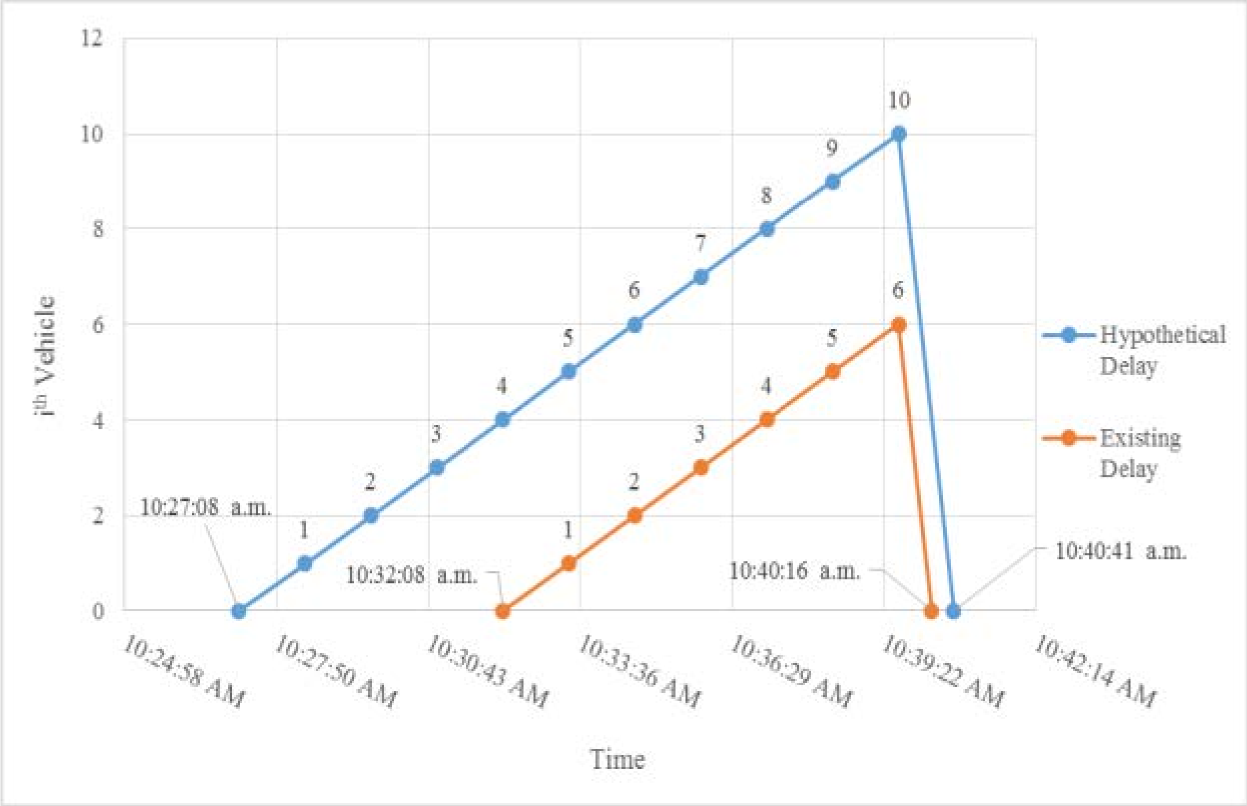

Figure E.21: Delay Analysis 21

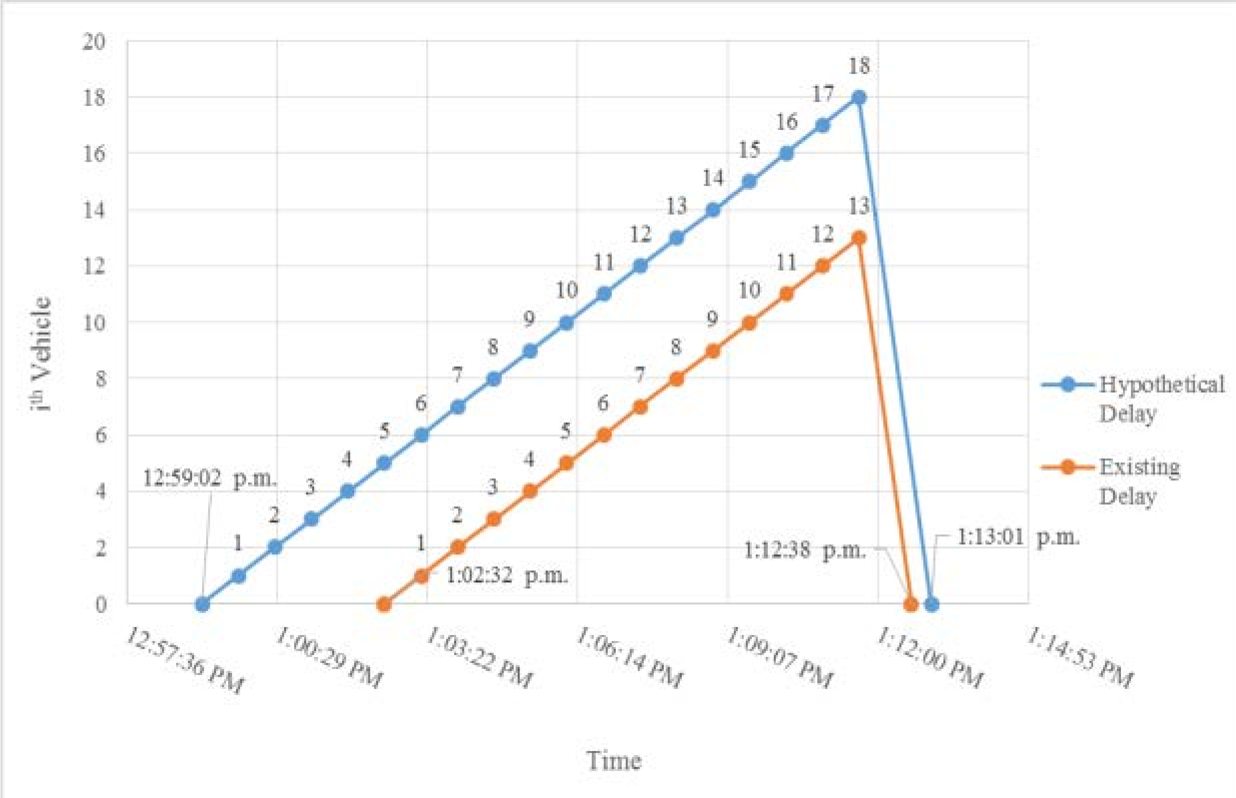

Figure E.22: Delay Analysis 22

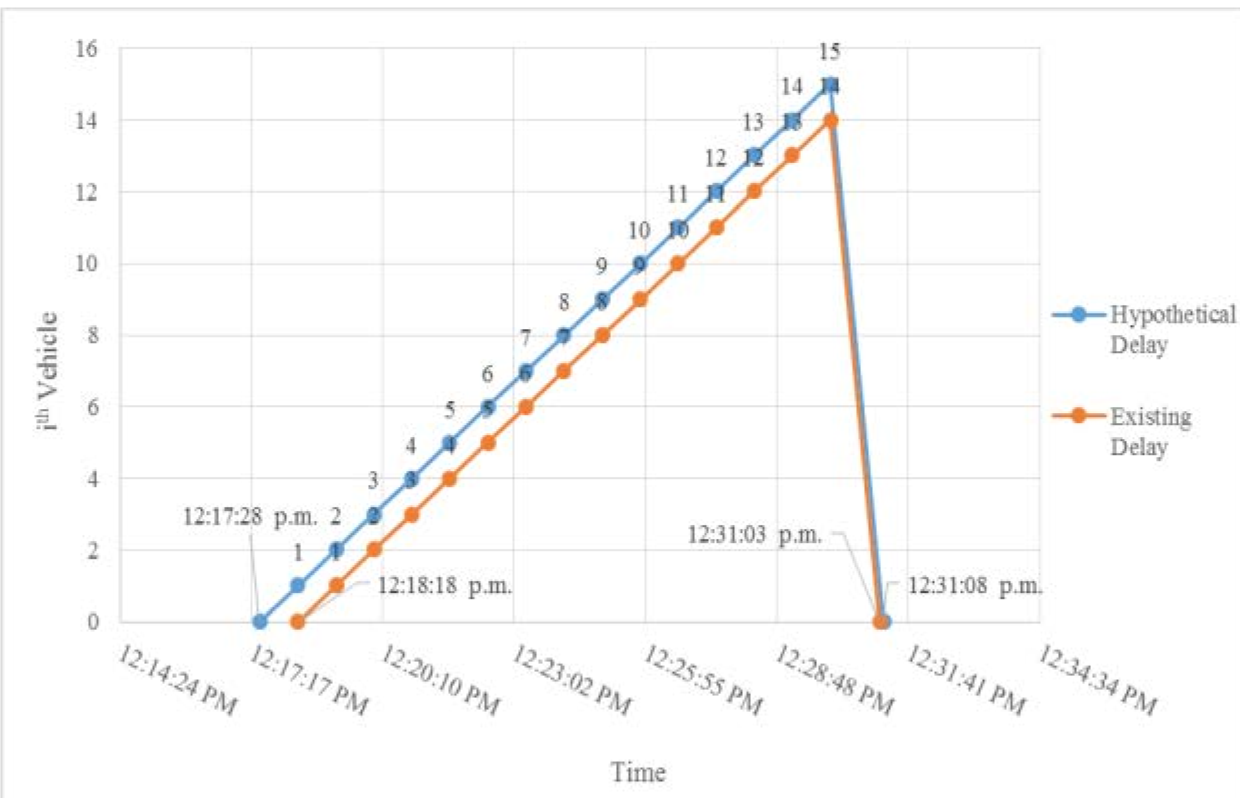

Figure E.23: Delay Analysis 23

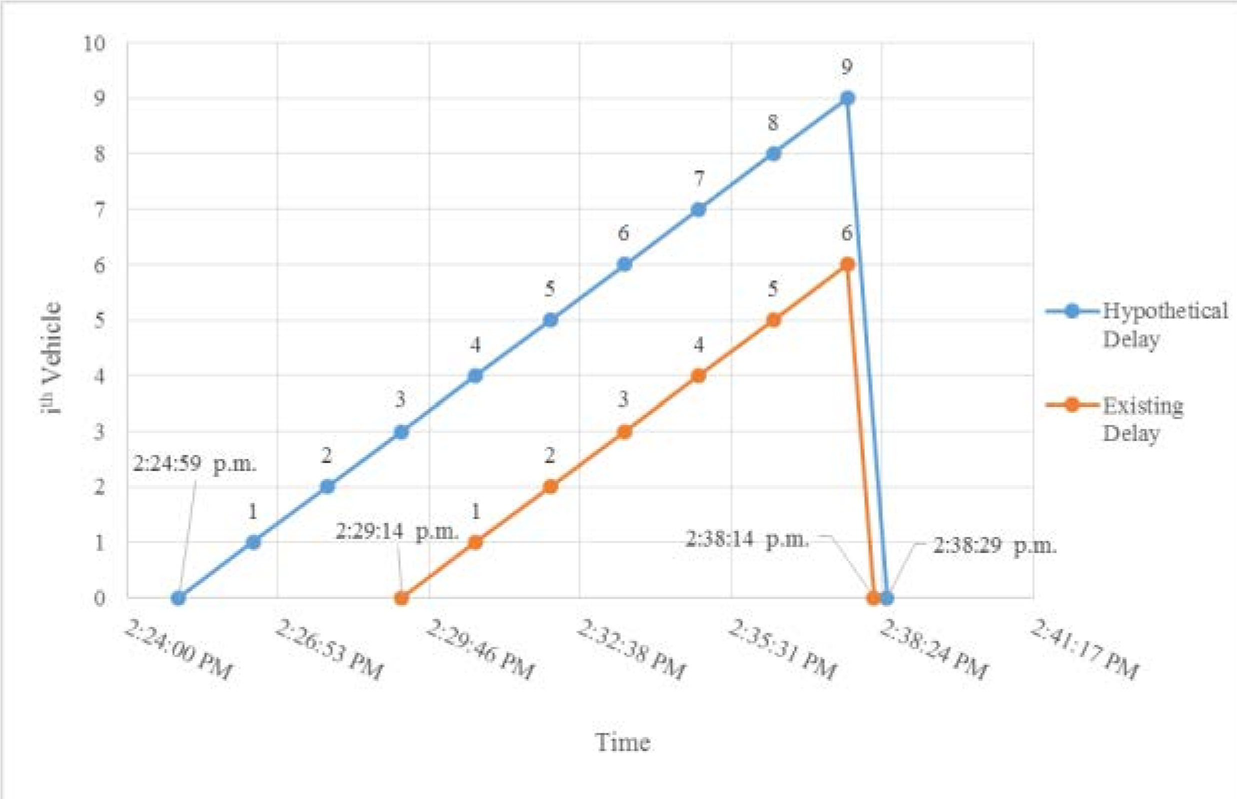

Figure E.24: Delay Analysis 24

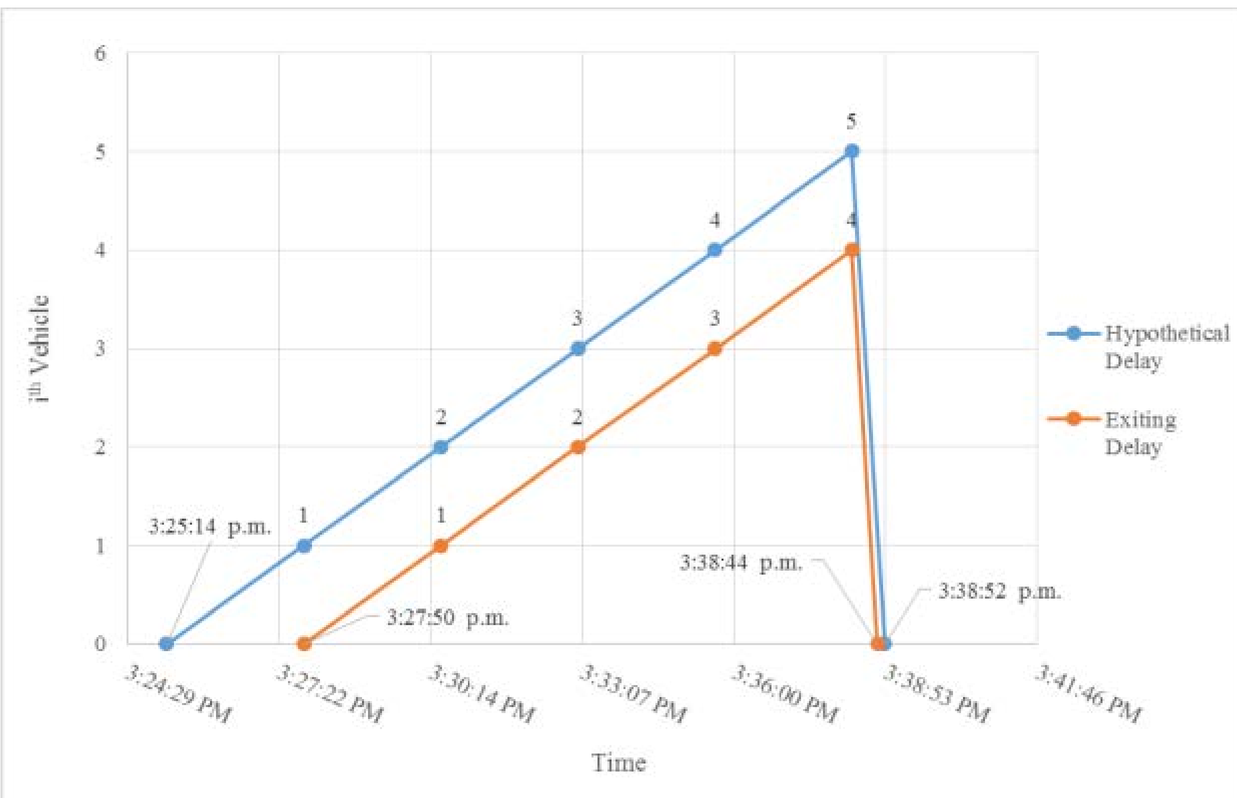

Figure E.25: Delay Analysis 25

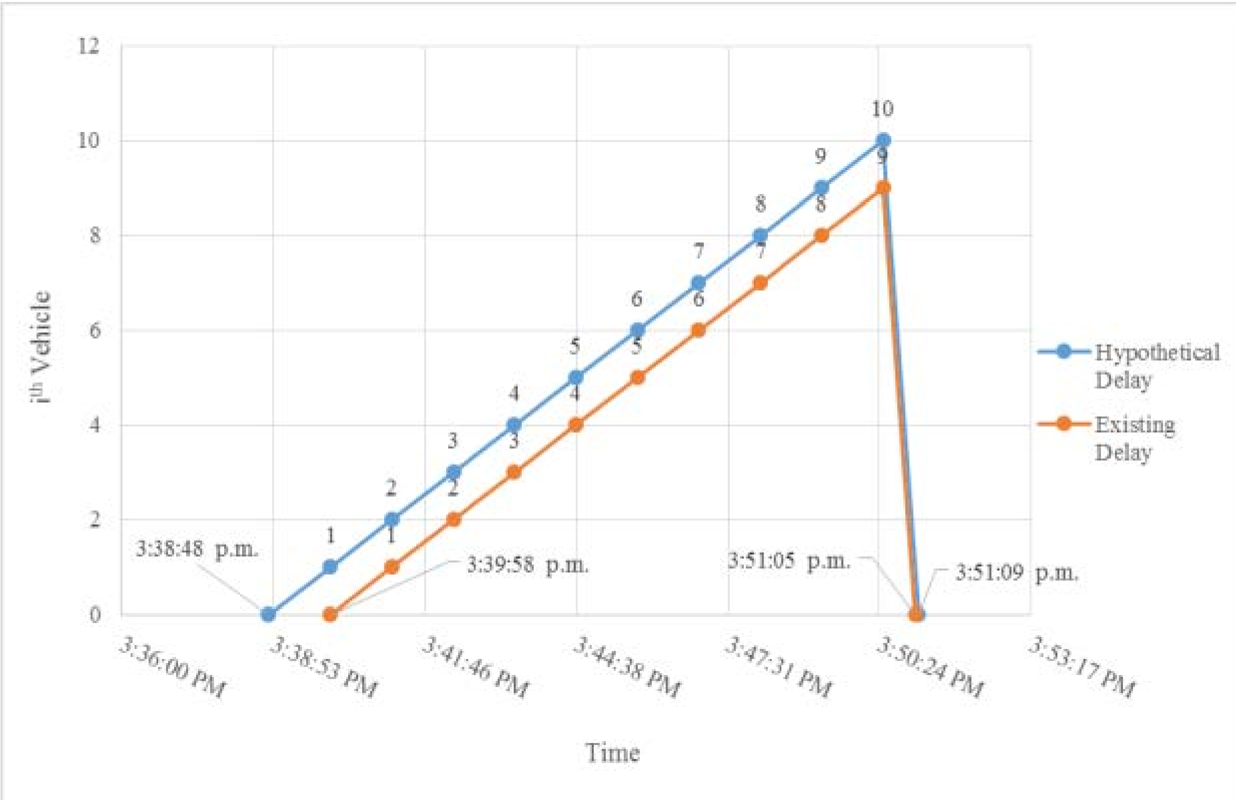

Figure E.26: Delay Analysis 26

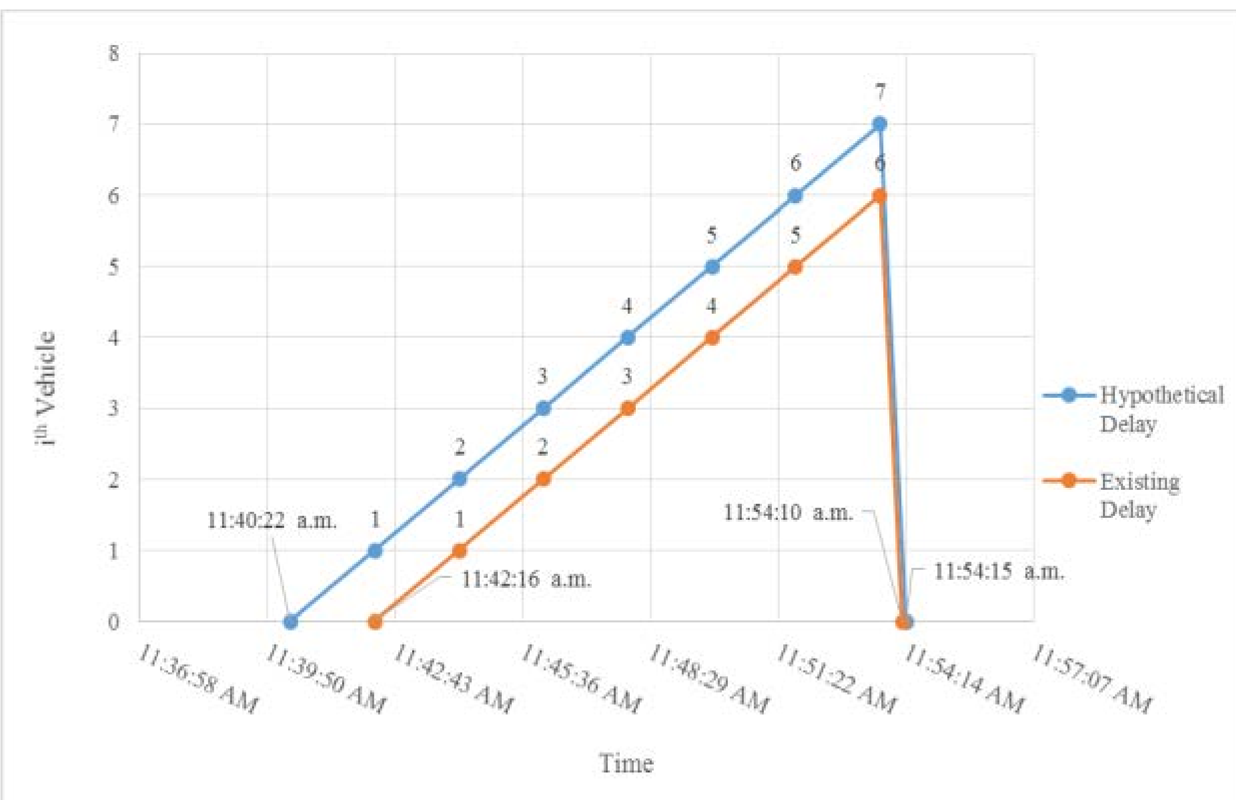

Figure E.27: Delay Analysis 27

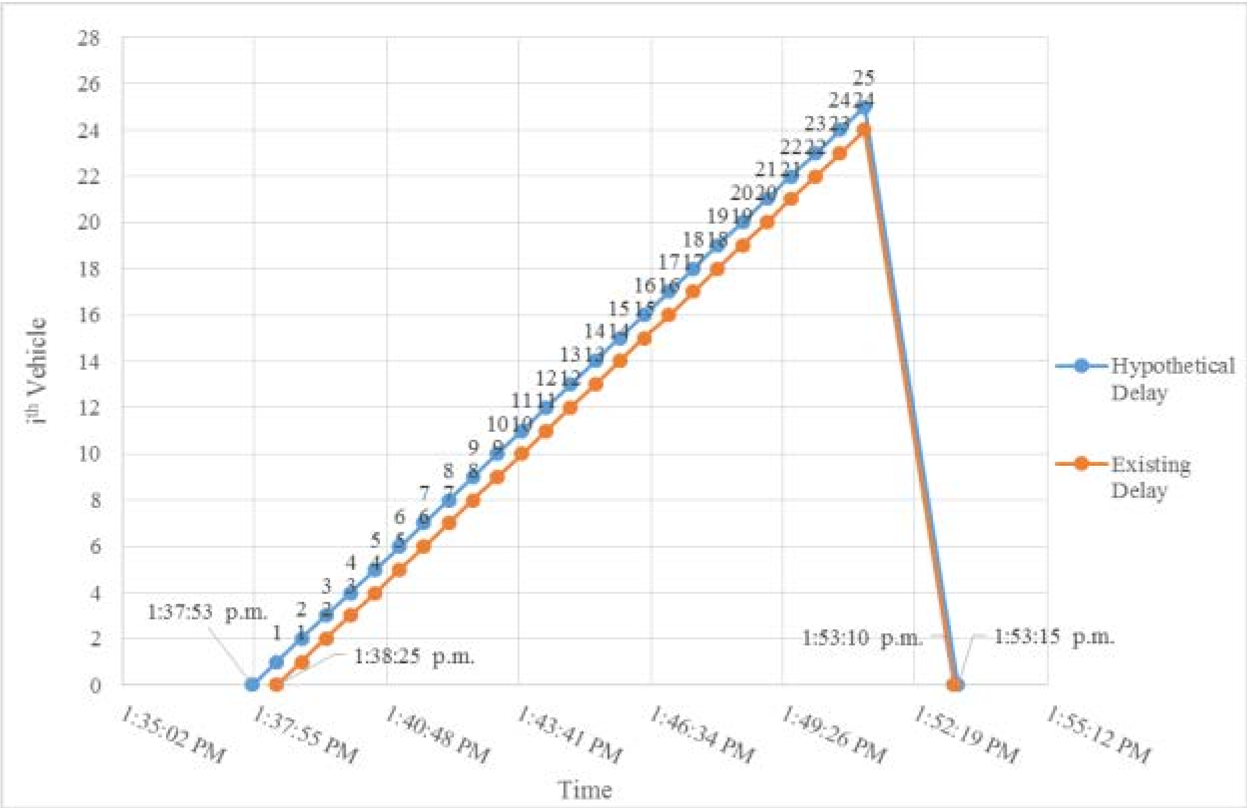

Figure E.28: Delay Analysis 28

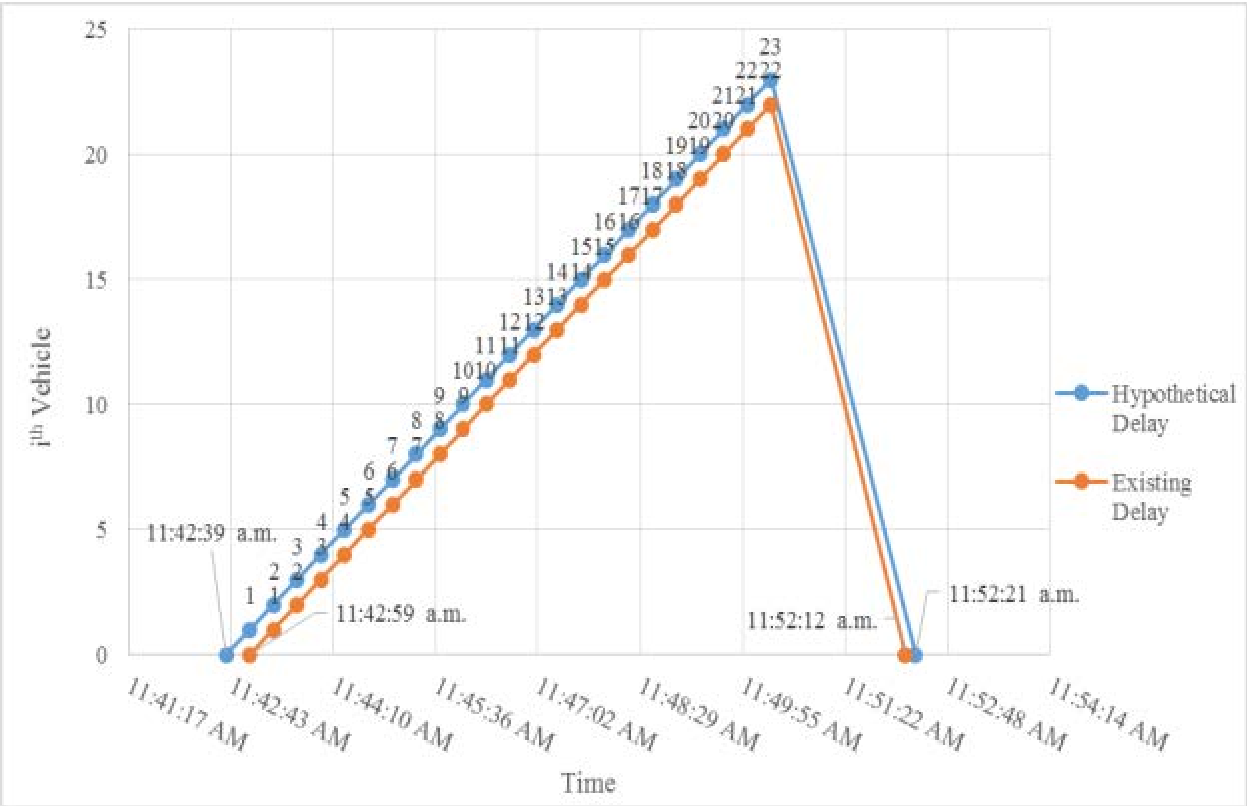

Figure E.29: Delay Analysis 29

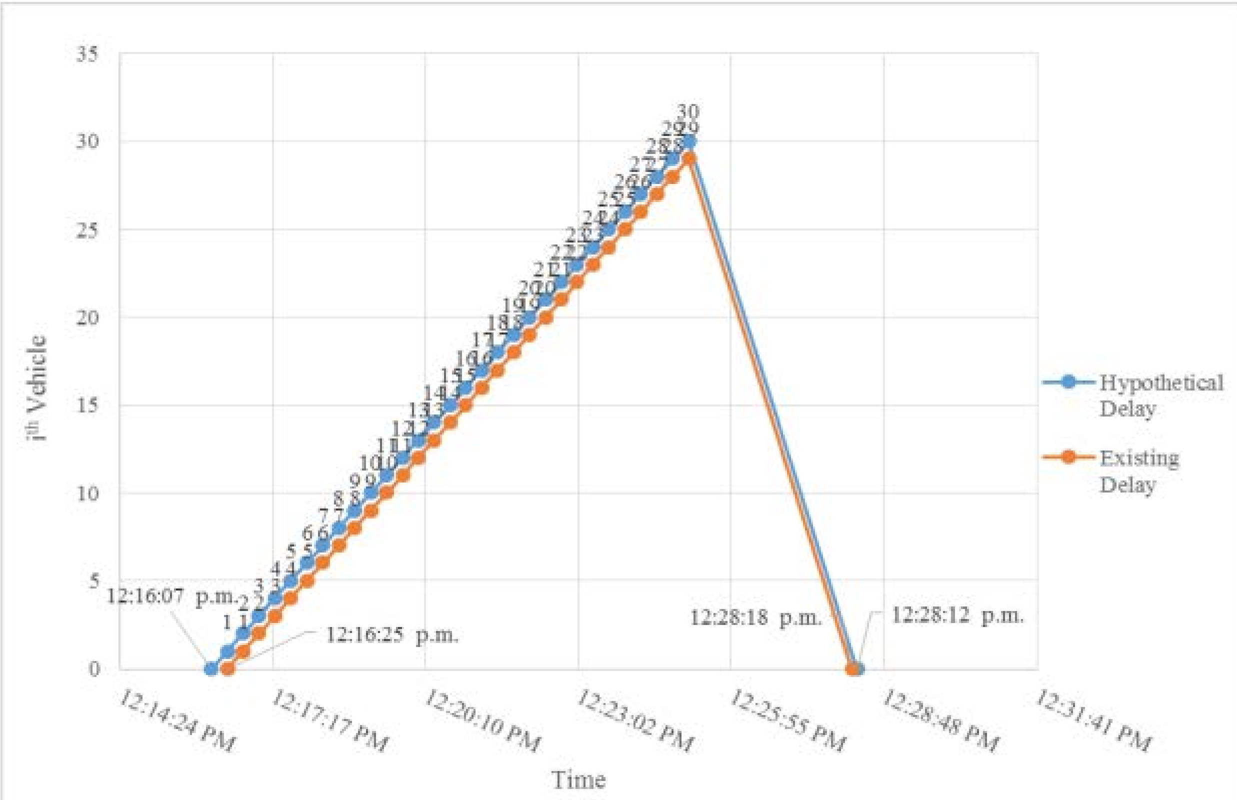

Figure E.30: Delay Analysis 30

Appendix F: Temporary Traffic Control Plans

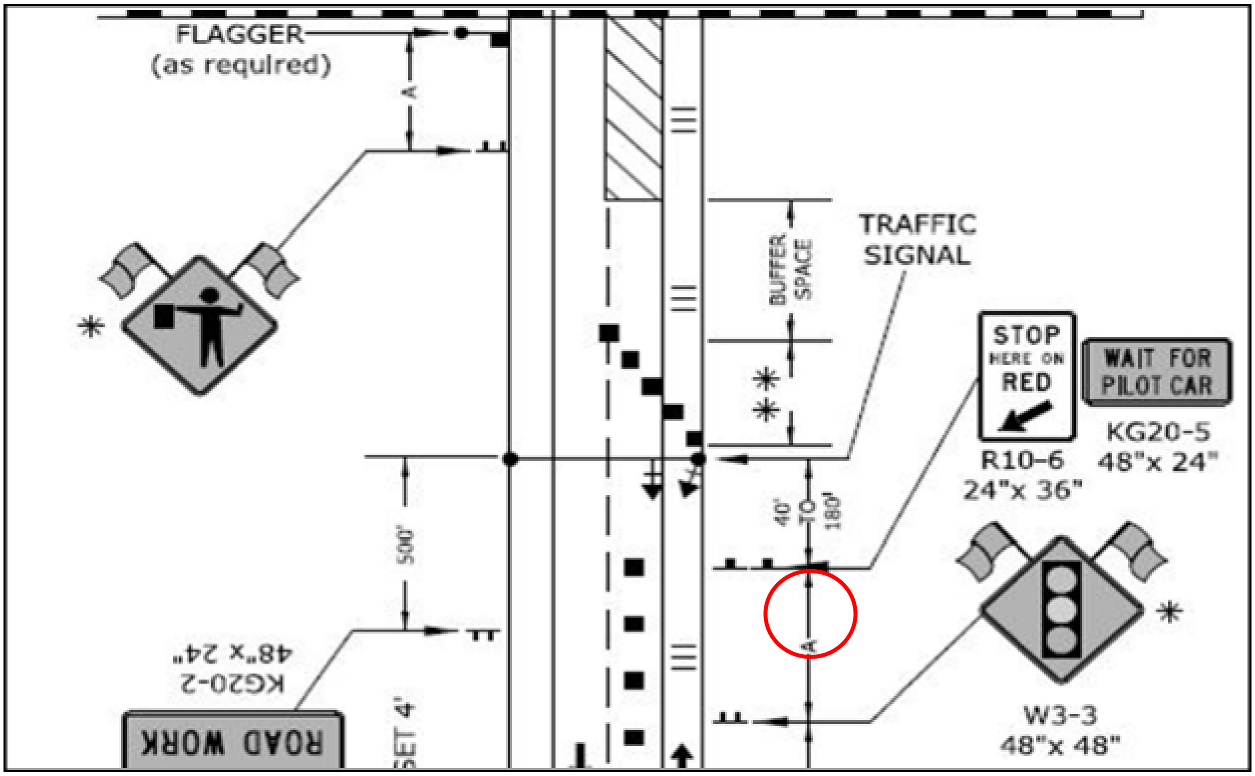

Figure F.1: Snapshot of the Temporary Traffic Control Plan used for Locating the Traffic Signs
Source: KDOT

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 F.2: Snapshot of TE-710 used for Determining the Distance 'A'

Source: KDOT

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

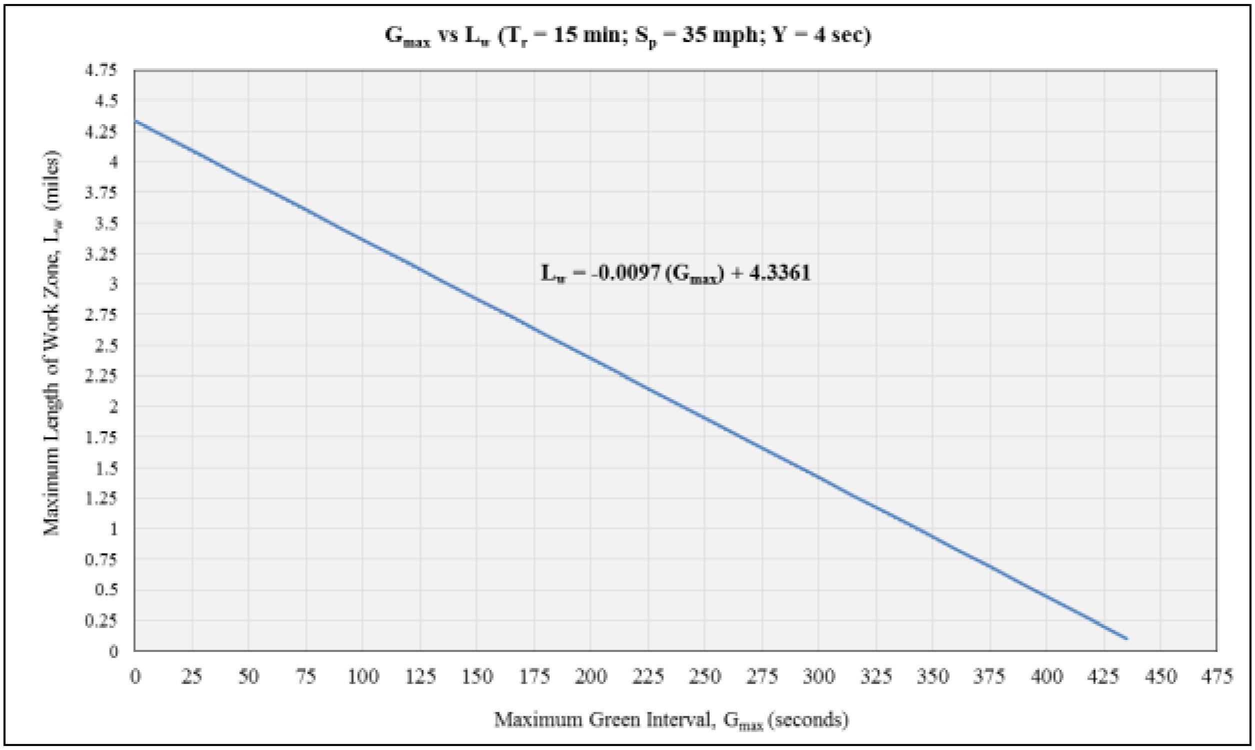

Figure G.1: Plot for G_{max} against L_w at T_r = 15 mins; S_p = 35 mph; Y = 4 sec.

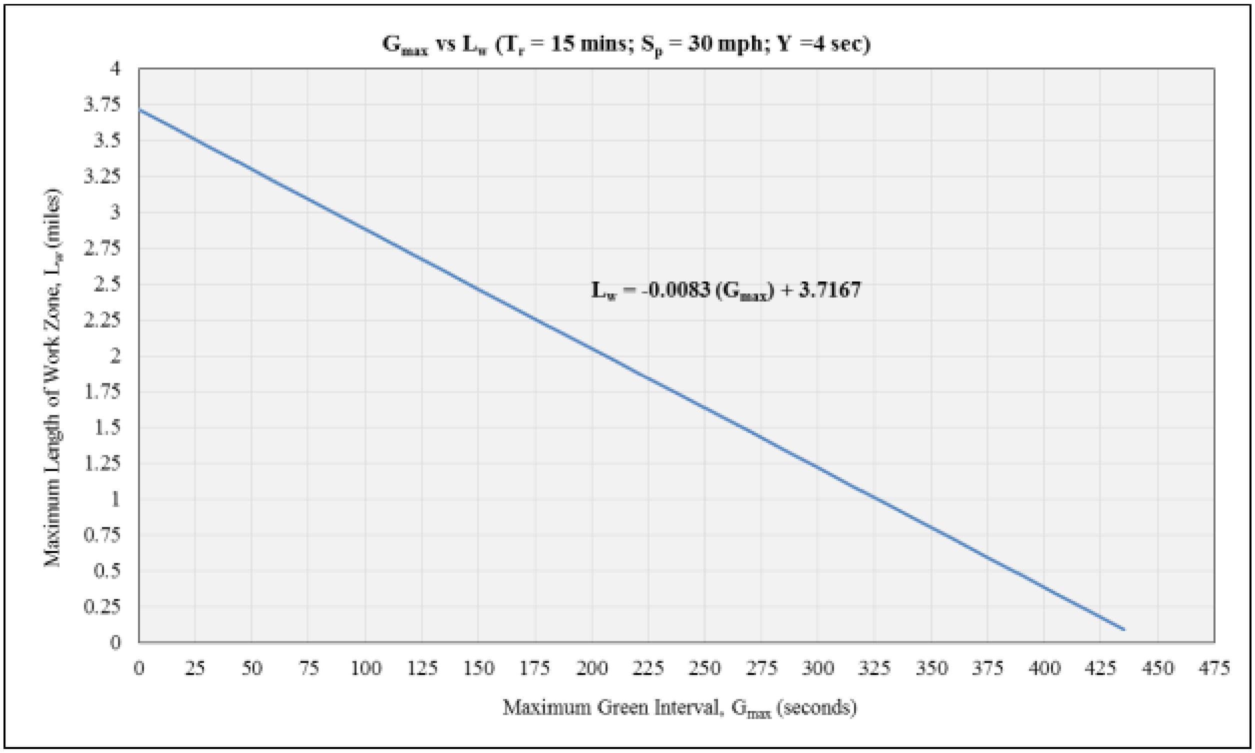

Figure G.2: Plot for G_{max} against L_w at T_r = 15 mins; S_p = 30 mph; Y = 4 sec.

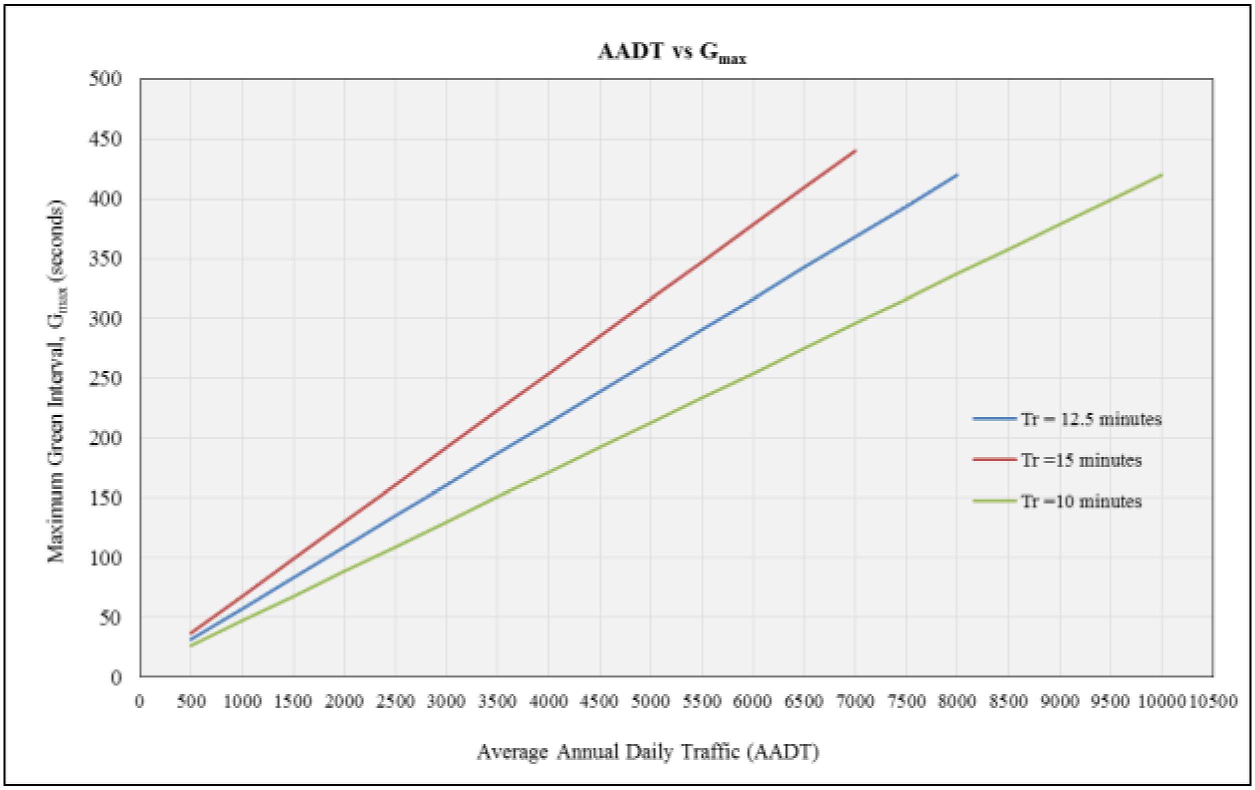

Figure G.3: Comparison of the AADT against G_{max} for Different T_r

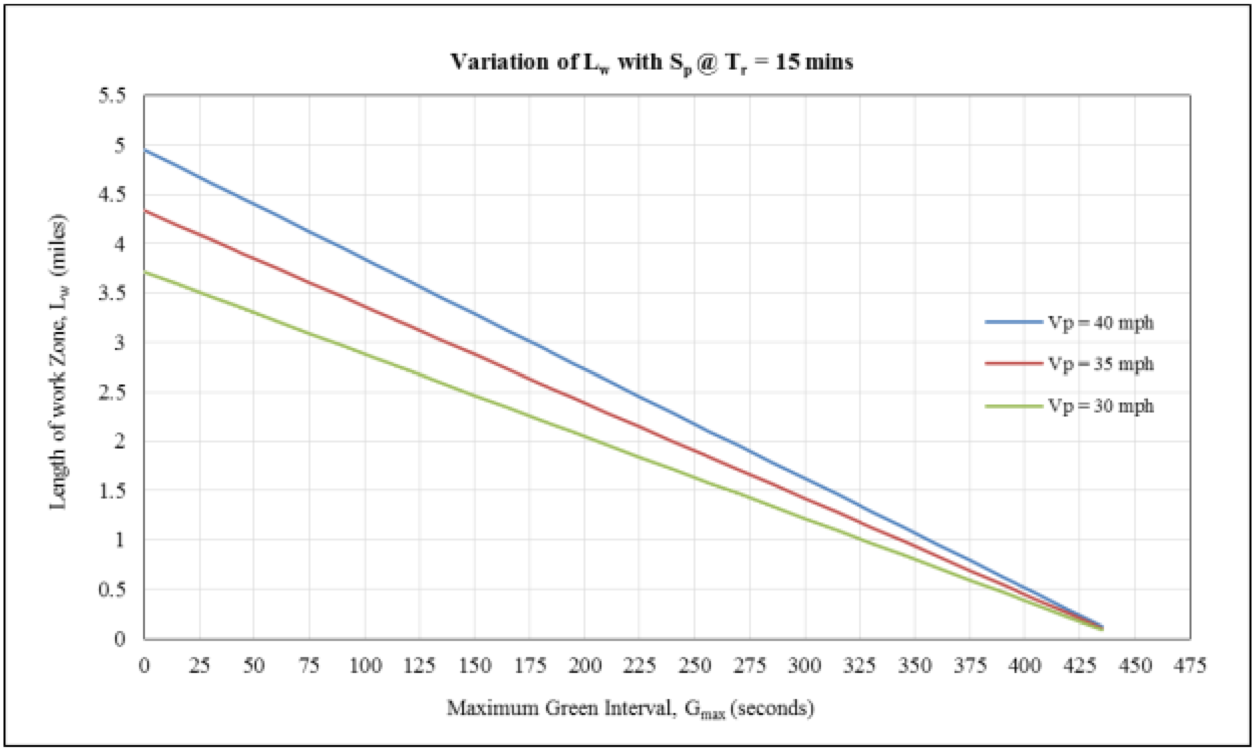

Figure G.4: Comparison of G_{max} against L_w for Different S_p

Appendix H: Additional Pictures

Figure H.1: Oversize Vehicle Following a Pilot Car

Appendix J: Additional Research Questions Regarding Project

(Appendix I not included to avoid confusion)

After the submission of the report, the vendor who supported this project, John Thomas, Inc., came up with a few questions regarding the project. These questions were analyzed by the research team and the findings were added in this Appendix as an extended study to the original report.

The questions the research team attempted to find the solutions were:

1. The four locations where the data were collected had a gap time which would be initiated if the signal detected a vehicle at the last second of the maximum green interval. This gap time was set to 5 seconds for the first three locations, and set to 12 seconds for the fourth location. Can there be a threshold value which can be used to set as a gap time instead of changing it to 5 or 12 seconds based on the location?
2. There are occasions where vehicles are still present in the queue when the signal's green interval maxed out. Original report discusses about a model which helps in arriving at the green time required for a location. Can we estimate the maximum green time needed for the peak queue to be served? Additionally, how much more would that maximum green number in magnitude be when compared with average green time required?
3. What is the time it took for a queue of vehicles to clear the signal within the green interval of a cycle?
4. What is the time it took for the same queue to exit at the other end of the work zone? Is there a difference in their queue clearance time? Is it affected by the queue size?

First Question

Introduction

As discussed in the original report, the green interval of the portable traffic signal (PTS) was set to extend by 5 or 12 seconds if the signal detected any vehicle arriving in the very last second of the maximum green interval. For the first three test locations, a gap or extension time of 5 seconds was set, and for the test location at US-50 the gap time was set to 12 seconds. For the fourth location at US-50, the 12 second gap time provided an arriving vehicle travelling at 40 mph to traverse a maximum distance of 720 ft before crossing the signal. Whereas for all other locations, the 5-second gap time provided the arriving vehicle travelling at 40 mph a maximum distance of 300 ft before arriving at the signal. A maximum distance of approximately 420 ft was provided to the arriving vehicle by increasing the gap time from 5 to 12 seconds. The research team observed red light running (RLR) data and the arrival times of the first vehicle after the onset of red to determine a threshold value that could be used instead of changing the gap times from 5 to 12 seconds.

Data Reduction

The research team observed all the cycles of the four test locations. After the end of green interval of each cycle, the time it took for the first vehicle to arrive at the signal was noted in seconds. The observed cycles contained two different test conditions, PTS with flagger present and PTS only. For each of these conditions, the arrival times of the first vehicle were noted. To understand the significance of changing the gap time from 5 to 12 seconds, the number of cycles when the first vehicle arrived within 5 seconds after the onset of red was noted separately from the number of cycles when the first vehicle arrived between 5 and 12 seconds. Tables J.1 and J.2 show the first vehicle arrival time data for the PTS with flagger condition and for the PTS only condition, respectively. In Tables J.1 and J.2, the first column shows the date. The second column shows the gap time set for that particular day. The third and fourth columns indicate the number of cycles during which the first vehicle arrived within 5 seconds, and the number of cycles during which the first vehicle arrived between 5 and 12 seconds. The fifth column shows the total number of cycles observed on that day which were set with that particular gap time.

Table J.1: First Vehicle Arrival Data for PTS with Flagger Condition

Dates Observed	Gap time (Seconds)	First vehicle arriving within 5 seconds	First vehicle arriving between 5 and 12 seconds	Total number of cycles during the day
5-Aug	5	0	1	26
12-Aug	5	0	0	9
19-Aug	5	0	2	61
20-Aug	5	0	2	36
26-Aug	12	0	3	12
27-Aug	12	6	9	75

Table J.2: First Vehicle Arrival Data for PTS Only Condition

Dates Observed	Gap time (Seconds)	First vehicle arriving within 5 seconds	First vehicle arriving between 5 and 12 seconds	Total number of cycles during the day
6-Aug	5	0	2	47
7-Aug	5	3	2	71
12-Aug	5	0	1	6
13-Aug	5	0	0	44
14-Aug	5	0	0	35
20-Aug	5	0	1	37
21-Aug	5	1	0	47
27-Aug	12	0	3	28

The RLR data were also observed. The number of RLR violations that occurred after the completion of maximum green interval cycles and the total number of RLR violations that occurred during a test day were noted. Similar to the procedure for determining the number of arriving vehicles, tables were created differentiating the two conditions, PTS with flagger and PTS only condition. Tables J.3 and J.4 show the gap time set for each day, the observed RLR violations for cycles with green time extended, and the total RLR violations observed for all cycles.

Table J.3: RLR Data for PTS with Flagger Condition

Dates Observed	Gap time (Seconds)	Observed RLR violations during green extended cycles	Total RLR violations occurred during all the cycles
5-Aug	5	0	4
12-Aug	5	0	0
19-Aug	5	20	65
20-Aug	5	0	17
26-Aug	12	0	2
27-Aug	12	2	4

Table J.4: RLR Data for PTS Only Condition

Dates Observed	Gap time (Seconds)	Observed RLR violations during green extended cycles	Total RLR violations occurred during all the cycles
6-Aug	5	0	7
7-Aug	5	11	27
12-Aug	5	0	0
13-Aug	5	0	16
14-Aug	5	0	3
20-Aug	5	2	8
21-Aug	5	6	33
27-Aug	12	0	1

From Table J.4 it can be seen that for August 7, there were a total of 11 RLR violations that occurred during green extended cycles out of 27 total RLR violations. From the video data, it was found that all the 11 RLR violations happened in two cycles. For one cycle, there was an unusual headway of 14 seconds between a car and a truck. Due to this the signal did not identify the truck, and the cycle ended with a minimum green time of 30 seconds even though the queue was not cleared in the green interval. This resulted in the remaining vehicles following the queue and running the red light. For the other cycle, the pilot car driver initiated the green time and observed a few vehicles coming from the opposite direction. The operator decided to wait for those vehicles to pass, where in the meantime there was a loss of 31 seconds in the green interval. If this lost green time were to be counted, the remaining vehicles which ran the red light would have been cleared in the green interval of the cycle.

Analysis and Findings

As discussed in the original report, due to its unusual location and the flaggers allowing the vehicles to pass even after the onset of red, the Location 3 data were not used in the analysis. Tables J.1 and J.2 were further summarized and shown in Tables J.5 and J.6 for analysis. Table J.5 represents the PTS with flagger condition and shows the number of times the first vehicle arrived within 5 seconds and between 5 and 12 seconds for all the study period. Column one represents the gap time set for all the observed cycles. Column two and three shows the number of vehicles arriving with the 5 second period and between 5 and 12 second period. Column four shows the total number of cycles observed during test period with gap time set to 5 and 12 seconds.

Table J.5: Summary of First Vehicle Arrival Data as per the Set Gap Time for PTS with Flagger Condition

PTS + Flagger			
Gap time (Seconds)	**First vehicle arriving within 5 seconds (5 included)**	**First vehicle arriving between 5 and 12 seconds (12 included)**	**Total number of cycles during days with green extension set to PTS**
5	0	1	35
12	6	12	87

Table J.6: Summary of First Vehicle Arrival Data as per the Set Gap Time for PTS Only Condition

PTS only			
Gap time (Seconds)	**First vehicle arriving within 5 seconds (5 included)**	**First vehicle arriving between 5 and 12 seconds (12 included)**	**Total number of cycles during days with green extension set to PTS**
5	3	5	203
12	0	3	28

Pie charts were created showing the proportion of cycles in which the first vehicle arrived within 5 seconds and in between 5 and 12 seconds compared to the total number of cycles observed. Figures J.1 and J.3 shows the proportion of cycles arriving at the PTS within 5 seconds after the end of previous cycle, between 5 to 12 seconds, and after 12 seconds when the gap time was set to 5 seconds. Similarly, Figures J.2 and J.4 show the proportion of cycles arriving at the PTS within 5 seconds, between 5 to 12 seconds, and after 12 seconds when the gap time was set to 12 seconds.

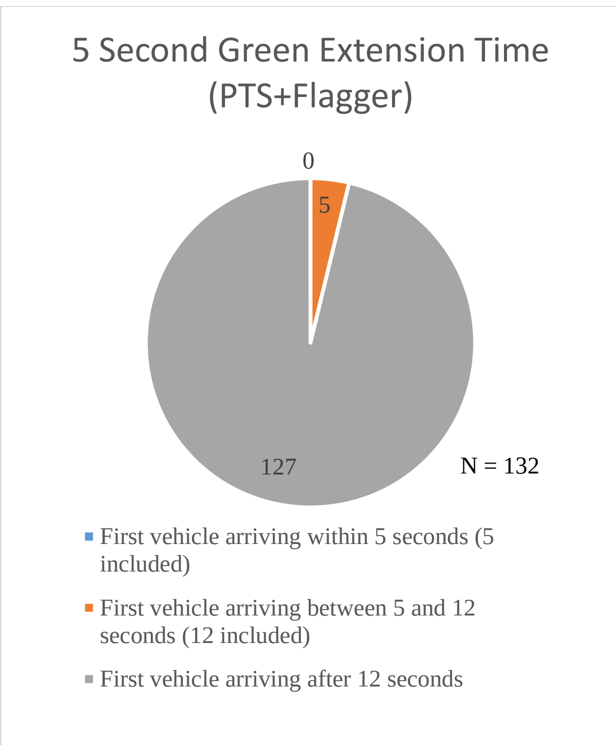

Figure J.1: 5-Second Gap Time with PTS and Flagger

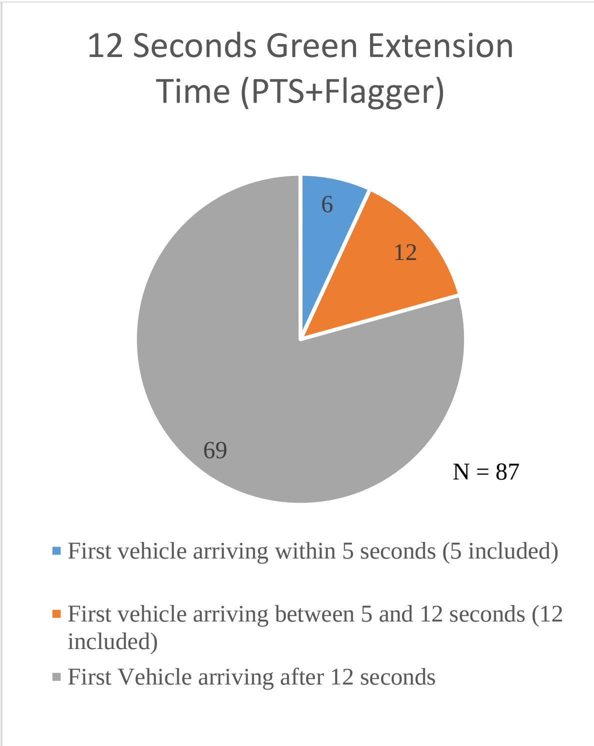

Figure J.2: 12-Second Gap Time with PTS and Flagger

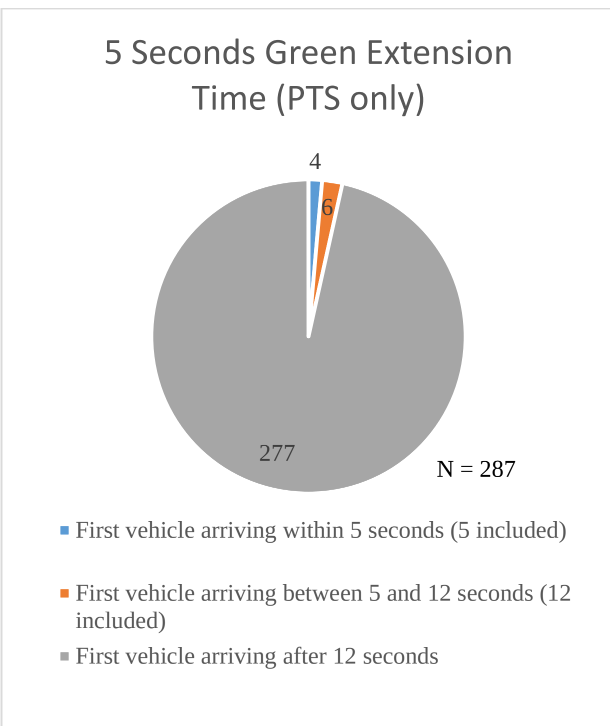

Figure J.3: 5-Second Gap Time with PTS Only

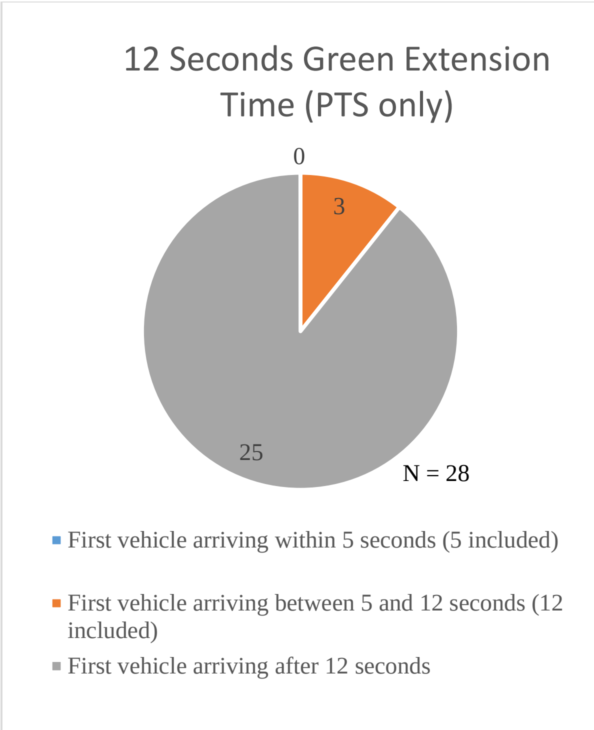

Figure J.4: 12-Second Gap Time with PTS Only

Tables J.3 and J.4 also were further summarized and shown in Tables J.7 and J.8 for analysis. Table J.7 represents the PTS with flagger condition, and shows the gap time in seconds, the observed RLR violations during those cycles where maximum green was reached, and the total number RLR violations that occurred during all the of cycles which were set to their respective gap time. On the other hand, Table J.8 represents the data for PTS only condition.

Table J.7: Summary of RLR Data as per the Set Gap Time for PTS Only

PTS +Flagger		
Gap time (Seconds)	**Observed RLR violations during green extended cycles**	**Total RLR violation occurred during all the cycles**
5	0	4
12	2	6

Table J.8: Summary of RLR Data as per the Set Gap Time for PTS with Flagger

PTS only		
Gap time (Seconds)	**Observed RLR violations during green extended cycles**	**Total RLR violation occurred during all the cycles**
5	11	53
12	0	1

Pie charts were also created for RLR data shown in Tables J.7 and J.8. Two pie charts for both PTS with flagger and flagger only condition were created. The pie charts show visually the amount of RLR violations observed for cycles with gap time initiated when compared to the total number of RLR violations observed for all the remaining cycles. Figures J.5 and J.6 represent the PTS with flagger condition. Figure J.5 shows the proportion of RLR incidents observed during green extended cycles to all the cycles that were set with a gap time of 5 seconds. Figure J.6 shows the proportion of RLR incidents observed during green extended cycles to all the remaining cycles that were set with a gap time of 12 seconds. Figures J.7 and J.8 represent the PTS only condition, where Figure J.7 shows the proportion of RLR incidents observed during green extended cycles to all the remaining cycles that were set with a gap time of 5 seconds, and Figure J.8 shows the proportion of RLR incidents observed during green extended cycles to all the remaining cycles that were set with a gap time of 12 seconds.

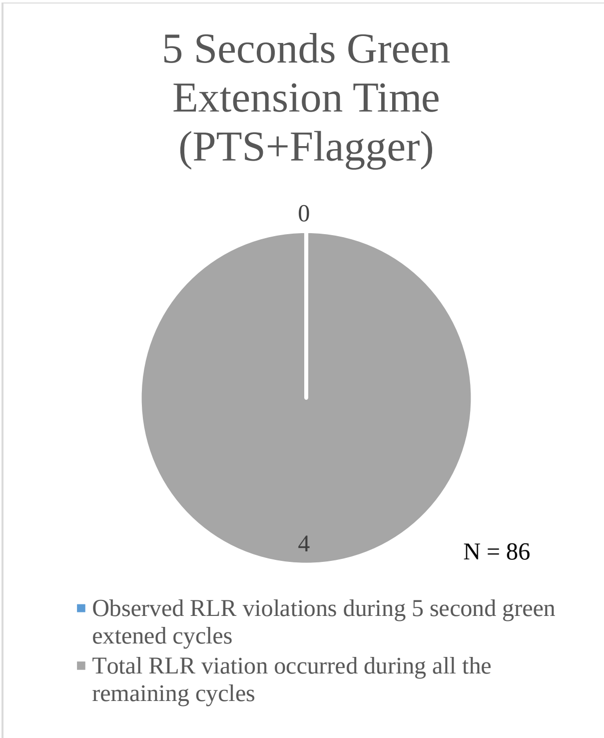

Figure J.5: 5-Second Gap Time RLR Data with PTS and Flagger

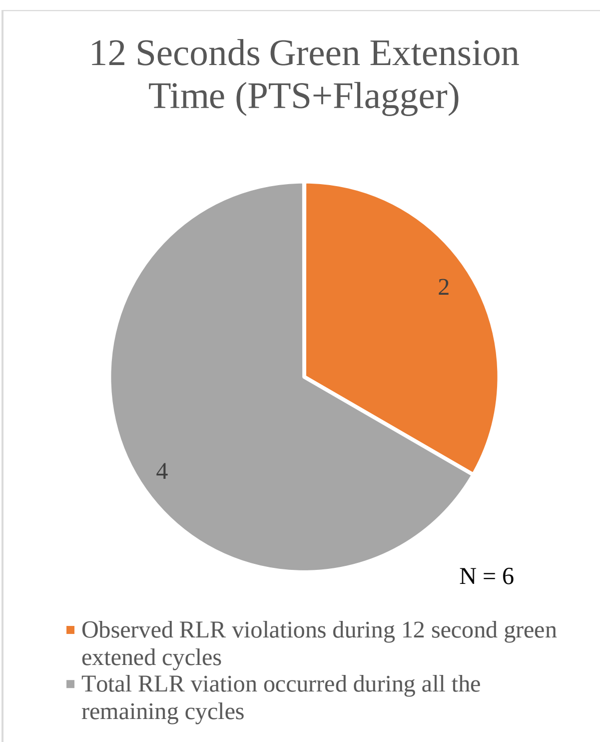

Figure J.6: 12-Second Gap Time RLR Data with PTS and Flagger

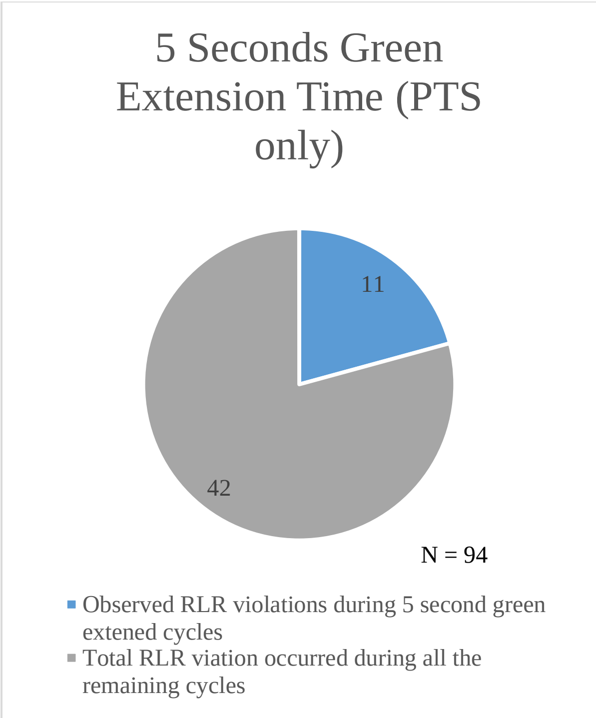

Figure J.7: 5-Second Gap Time RLR Data with PTS Only

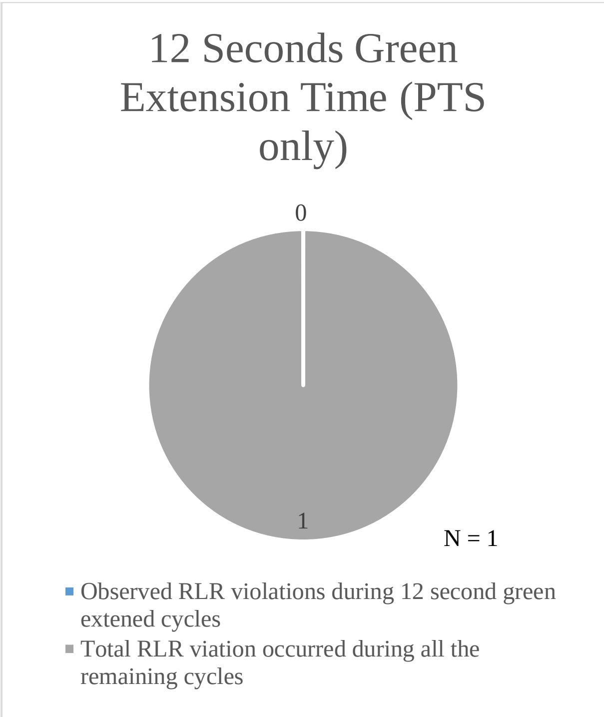

Figure J.8: 12-Second Gap Time RLR Data with PTS Only

From observing the Figures J.1 and J.3, when the gap time was set to 5 seconds it can be observed that there were a total of 11 cycles where the first vehicle arrived between 5 and 12 seconds after the onset of red out of total 419 cycles. This equals to 2.6 percent of cycles out of the total cycles where vehicles arrived between 5 and 12 seconds and were not served. From Figures J.5 and J.7, it can be seen that a total of 11 RLR violations occurred during the green extended cycles out of a total of 180 RLR violations, when the gap time was set to 5 seconds. As discussed in data reduction, these 11 violations occurred in two cycles due to unusual circumstances. If these 11 violations were not considered, there would be no RLR violations recorded for 5-second green extended cycles. That also implies that most of the vehicles from Figures J.1 and J.3 which were not served by the signal did not run a red light.

Second Question

Introduction

At the first three test locations, the maximum green time was set to 60 seconds with an additional 5-second gap time. So, depending on the arrival time of the last vehicle in the queue, the maximum green was perhaps 60 or 65 seconds. At the fourth location, the maximum green time was extended to 180 seconds for the first day, and then further extended to 240 seconds the next day, with an additional 12 seconds of gap time. Again depending on the arrival time of the last vehicle in the queue, the maximum green time was perhaps 240 or 252 seconds. But there were some queues observed in the test locations which exceeded the maximum green time and the additional gap time. Such queues have vehicles either following the queue and running the red light, or waiting at the stop line for the pilot car to arrive for the next cycle. Both the situations indicate a cycle failure scenario, whereas the first situation also included RLR violations. Therefore, all the cycles when the maximum green was reached were observed and were checked for any additional vehicles even after the end of the green interval. Any such cycles with vehicle queues still present after the end of the maximum green interval, and the number of remaining vehicles in those queues were noted. For analysis, these additional vehicles were then added to the number of vehicles that cleared the queue during the green interval. The research team analyzed the data for the maximum total queue that was observed out of all the cycles and proposed what would be the appropriate measures that can be taken to serve these additional vehicles. The analysis and findings included two different ways of serving these additional vehicles. One method was by using the saturation headway derived from the model presented in Chapter 5 and estimating the additional green time required. The other method was by estimating what would be the maximum expected queue for a location based on the AADT of the road.

Data Reduction

There were a total of 23 vehicles in all the queues combined that were not served. Table J.9 shows the number of vehicles which were still in the queue at the onset of red.

Table J.9: Number of Vehicles Not Served by the Maximum Green Interval

Date	Gap Time (seconds)	Number of vehicles cleared after the queue/ were still in queue after max. green				Total number of vehicles	AADT
		Cars	Trucks	Motorcycles	Total		
7-Aug	5	6	0	1	7[A]	23	1810
		1	0	0	1	25	
		3	0	0	3	29	
		1	0	0	1	25	
		2	0	0	2	26	
26-Aug	12	0	1	0	1	43	5770
27-Aug		8	0	0	8	84	5770

[A] - The pilot car waited for 32 seconds, for the arriving vehicles to pass after it initiated the green time, if the lost green time were to be counted, then all the vehicles in the queue would have been cleared.

Analysis and Findings

According to the model presented in Chapter 5, a queue starts to achieve a saturation headway of 3.31 seconds after the first eight vehicles. The queue with the maximum number of vehicles not served was used in multiplying the queue number with the saturation headway to come up with the new maximum green time for those locations.

For the location at US-56, on August 7 the maximum queue observed was 29 vehicles with three vehicles not served during the green interval. The additional green time needed would be (3*3.31) which would equal to 9.93, or approximately 10 seconds. Similarly, calculating the additional green time needed for the location at US-50 for the queue observed on August 27 with a total of eight additional vehicles would equal to approximately 27 seconds.

In addition to determining the additional green time needed, another method of estimating the maximum queue expected for a location was derived from the data. In this procedure, the total number of vehicles in the queues of the green extended cycles was calculated including the vehicles which were not served. The highest of these peak queues, the maximum total queue, was then compared with the AADT of the road. From Table J.9, the peak total queue of 29 vehicles on August 7 for Location 1 was compared with the AADT of the road. This maximum queue was 1.6 percent of the AADT. Similarly, calculating for the queue on August 27 for Location 4, the peak total queue was observed to be 1.46 percent of the total AADT. The value was 0.75 percent of the AADT for the peak total queue of 43 vehicles on Day 1 at Location 4. The maximum of these percentages, 1.6 percent of total AADT can be used in estimating the maximum peak queue that might be forming at a location.

These two procedures were based on a sample data of three days with a total of seven cycles. Out of these seven cycles, five occurred on August 7 and one instance each on August 26 and 27. In addition to the very few data values available for analysis, the assumptions made for the second procedure included a 50-50 directional split in the traffic. So, taking all these factors into consideration, the values obtained through this data should be used with caution. A much larger data set available for studying in a future research might help in arriving at a more accurate green time needed, and the number of vehicles that can be served by the PTS.

Third and Fourth Questions

Introduction

The research team evaluated whether the queue clearance times for vehicles approaching and exiting the work zone were different or not. The queue of vehicles which cleared the signal during the green interval was considered as a platoon and the time taken by that platoon was noted as queue clearance time. This queue clearance time was calculated for all the cycles. The time was calculated by observing the time it took from the start of the first vehicle at the onset of the green interval until the clearing of the last vehicle before the end of the green interval. For vehicles entering the work zone, the stop line or the start position of the first vehicle was used as a reference to calculate the time precisely. For vehicles exiting the work zone, an imaginary line parallel to the signal was assumed as reference to calculate the time it took for the platoon to clear. After calculating the queue clearance times for platoons on either side of the work zones, the difference in platoon clearance time was calculated by adjusting the video data of the entering time of the platoon at one end of the work zone with the exiting time of the platoon at the other end of the work zone. Table J.10 shows the entering and exiting time for platoons (queue of vehicles from a single cycle) for August 5 and their difference. The first column provides the number of platoons observed for that day. The second and third columns show the time it took for a platoon to clear the PTS at the entry and exit points of the work zone. The fourth column shows the time difference that occurred due to varying entering and exiting times of the same platoon of vehicles at the both ends of the work zones. See Appendix K for the tables containing the queue clearance times for the remaining days. From Table J.10, it can be seen that the number of vehicles entering and exiting the work zone and their times are not always equal.

Analysis

Statistical analysis of these differences in queue clearance times included a paired t-test. The test statistic consisted of:

H_o: $X_1 - X_2 = 0$

H_A: $X_1 - X_2 \neq 0$

X_1 and X_2 are the mean queue clearing times of the platoon while entering and exiting respectively.

Additionally:

Level of significance, $\alpha = 0.05$;

No. of observed cycles = n;

$s_{đ} = (sd / \surd n)$ = standard error;

d = differences between the pairs of data;

đ= Mean of the differences;

t-statistic: $t = đ / (s_d / \surd n)$

Table J.10: Entering and Exiting Times of the Platoons on August 5

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	9	10	31	29	2
2	8	9	27	30	-3
3	6	10	32	31	1
4	6	6	16	15	1
5	2	2	9	8	1
6	7	8	46	38	8
7	12	11	25	40	-15
8	8	4	31	20	11
9	11	11	37	30	7
10	8	8	33	27	6
11	6	5	18	13	5
12	6	6	20	19	1
13	5	5	15	20	-5
14	8	6	18	29	-11
15	9	12	28	35	-7
16	15	13	50	32	18
17	18	17	59	60	-1
18	12	10	37	45	-8
19	6	8	26	28	-2
20	8	6	25	14	11
21	6	5	28	13	15
22	9	8	35	26	9
23	6	6	32	23	9
24	5	5	23	11	12
25	7	6	24	14	10
26	9	9	17	14	3
27	8	8	22	22	0
28	8	7	29	19	10
29	10	9	35	19	16
30	8	8	23	46	-23
31	6	5	15	15	0
32	4	4	14	21	-7
33	5	6	14	19	-5
34	8	7	38	22	16
35	5	4	13	10	3
36	13	11	51	29	22
37	7	6	23	14	9
38	8	9	26	31	-5
	7.95	**7.63**	**27.50**	**24.50**	**3.00**

Table J.11 shows the t-test results for August 5. It can be observed that the p-value for these data was greater than 0.05, meaning the difference in mean times of the entering and exiting platoons was not statistically significant. Similar t-tests were performed for the remaining days and were shown in the tables presented in Appendix K. Table J.12 summarizes the statistical significance of the difference in the entrance and exit times of the platoons. It can be observed that for August 5, 7, 19, and 21, the difference in the average platoon entering and exiting times were not statistically significant, whereas for August 6, 12, 13, 14, 20, and 27, the differences in timing were statistically significant.

Table J.11: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 5th

	Entering Time	Exiting Time
Mean	27.5 sec	24.5 sec
Variance	127.6 sec^2	127 sec^2
Observations	38	38
Pearson Correlation	0.64	
df	37	
t Stat	1.94	
P(T<=t) two-tail	0.06	
t Critical two-tail	2.03	

From Table J.12, it can also be observed that the number of entering and exiting vehicles were not the same for all the test days. The difference in the number of entering and exiting vehicles ranged from 0.24 to 4.22 vehicles, whereas their timings ranged from 0.33 to 24.30 seconds. As per the model presented in Chapter 5, after the first eight vehicles in the queue, the average headway between vehicles evens out to approximately 3.31 seconds. Comparing this saturation headway number with the values in the sixth column of Table J.12, it can be seen that for days where there was a statistically significant difference in their timings, not more than a difference of 2 cars of headway was exceeded (2 * 3.31 = 6.62 seconds). So, the difference in the number of vehicles slightly affects the difference in timings, but no particular pattern in the differences was observed and none of these differences were large relative to the overall cycle length.

Table J.12: Average Number of Vehicles in a Queue and Their Time Taken for Entering and Exiting in Statistical Terms for Test Days

Date	Average number of entering vehicles	Average number of exiting vehicles	Difference in number of vehicles	Average time taken for entering vehicles	Average time taken for existing vehicles	Difference of average time	Statistical significance
5-Aug	7.95	7.63	0.32	27.50	24.50	3.00	Statistically Not significant
6-Aug	6.59	6.18	0.41	22.43	19.37	3.06	Statistically significant
7-Aug	9.29	8.17	1.12	33.54	30.61	2.93	Statistically Not significant
12-Aug	1.82	1.59	0.24	9.35	4.41	4.94	Statistically significant
13-Aug	2.05	2.84	-0.78	8.29	4.04	4.25	Statistically significant
14-Aug	1.72	1.44	0.28	9.81	3.81	6.00	Statistically significant
19-Aug	9.49	8.83	0.67	38.92	38.59	0.33	Statistically Not significant
20-Aug	10.26	8.32	1.93	32.81	38.26	-5.45	Statistically significant
21-Aug	9.73	7.64	2.09	39.91	33.00	6.91	Statistically Not significant
26-Aug	NA [B]						
27-Aug	29.71	25.48	4.22	125.56	101.25	24.30	Statistically significant

[B] – Data were collected on only one end of the work zone. Hence, the queue of vehicles on the other end was not available for calculating the platoon entering and exiting times.

Appendix K: Platoon Entrance and Exit Times

This appendix shows the tables containing platoon entrance and exit times at either end of the work zones for all the observed cycles. Additionally, the statistical t-tests performed and their values were also shown in the tables located after the tables related to the platoon timings for their respective test dates.

Table K.1: Entering and Exiting Times of the Platoons on August 6

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	3	2	8	3	5
2	3	3	6	5	1
3	4	3	36	8	28
4	4	4	10	6	4
5	7	7	18	23	-5
6	4	4	12	9	3
7	2	3	4	8	-4
8	9	9	39	31	8
9	10	10	30	26	4
10	7	7	22	17	5
11	2	5	4	13	-9
12	1	1	1	1	0
13	9	9	24	30	-6
14	7	7	19	11	8
15	11	10	39	31	8
16	9	9	28	35	-7
17	5	6	17	11	6
18	6	5	24	15	9
19	8	8	34	15	19
20	7	8	25	21	4
21	12	12	36	28	8
22	9	9	38	30	8
23	7	7	25	20	5
24	6	7	19	18	1
25	7	8	16	17	-1
26	3	3	9	9	0
27	4	3	9	4	5
28	9	9	33	26	7

29	12	10	36	22	14
30	11	11	39	40	-1
31	9	9	24	20	4
32	8	5	26	29	-3
33	5	5	24	11	13
34	10	8	60	29	31
35	5	4	25	7	18
36	6	6	27	18	9
37	8	8	38	43	-5
38	5	4	13	8	5
39	3	3	6	7	-1
40	3	3	12	5	7
41	10	7	30	63	-33
42	4	3	18	14	4
43	4	4	13	8	5
44	7	4	22	17	5
45	9	8	22	34	-12
46	3	4	6	7	-1
47	9	6	26	16	10
48	6	6	14	11	3
49	9	6	40	64	-24
50	8	8	20	35	-15
51	7	5	18	9	9
	6.59	**6.18**	**22.43**	**19.37**	**3.06**

Table K.2: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 6

	Entering Time	**Exiting Time**
Mean	22.43 sec	19.4 sec
Variance	146.93 sec^2	192.04 sec^2
Observations	51	51
Pearson Correlation	0.67	
df	50	
t Stat	2.052	
P(T<=t) two-tail	0.046	
t Critical two-tail	2.008	

Table K.3: Entering and Exiting Times of the Platoons on August 7

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	5	3	17	9	8
2	6	6	27	22	5
3	4	2	22	5	17
4	4	4	13	8	5
5	1	1	1	1	5
6	4	4	19	12	7
7	4	2	21	19	2
8	7	5	22	12	10
9	2	2	11	3	8
10	2	2	11	4	7
11	2	3	9	8	1
12	7	7	23	26	-3
13	18	11	61	69	-8
14	8	6	61	18	43
15	10	7	31	32	-1
16	15	11	50	41	9
17	7	4	42	23	19
18	11	7	60	21	39
19	3	2	17	9	8
20	19	18	61	80	-19
21	14	13	42	43	-1
22	9	13	32	88	-56
23	22	14	62	57	5
24	23	19	63	67	-4
25	16	13	45	47	-2
26	24	14	64	63	1
27	20	16	63	64	-1
28	21	19	63	66	-3
29	24	22	62	63	-1
30	24	16	62	74	-12
31	3	3	7	9	-2
32	10	10	38	28	10
33	4	3	39	15	24
34	3	3	16	13	3
35	5	4	29	11	18
36	4	4	31	16	15
37	9	8	33	27	6

38	9	9	36	51	-15
39	5	5	13	16	-3
40	13	9	48	61	-13
41	1	1	4	2	3
42	5	5	30	32	-2
43	11	13	36	31	5
44	7	7	41	19	22
45	9	6	34	24	10
46	6	9	19	33	-14
47	8	11	28	38	-10
48	7	9	23	24	-1
49	7	8	30	33	-3
50	13	12	37	26	11
51	12	10	47	30	17
52	10	15	37	77	-40
53	4	5	15	11	4
54	4	4	22	13	9
55	10	10	32	27	5
56	10	12	37	33	4
57	9	9	31	24	7
58	4	4	18	10	8
59	10	8	31	18	13
	9.29	**8.17**	**33.54**	**30.61**	**3.03**

Table K.4: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 7

	Entering Time	**Exiting Time**
Mean	33.54 sec	30.61 sec
Variance	308.67 sec^2	519.21 sec^2
Observations	59	59
Pearson Correlation	0.76	
df	58	
t Stat	1.51	
P(T<=t) two-tail	0.136	
t Critical two-tail	2.001	

Table K.5: Entering and Exiting Times of the Platoons on August 12

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	3	3	13	7	6
2	2	2	16	9	7
3	2	1	8	3	5
4	2	1	15	4	11
5	1	2	2	3	-1
6	2	2	12	3	9
7	2	3	14	9	5
8	1	0	3	0	3
9	0	0	0	0	0
10	2	1	12	3	9
11	1	1	3	2	1
12	1	1	3	3	0
13	4	3	22	8	14
14	1	1	2	3	-1
15	2	2	18	7	11
16	5	4	16	11	5
17	0	0	0	0	0
	1.82	**1.59**	**9.35**	**4.41**	**4.94**

Table K.6: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 12

	Entering Time	Exiting Time
Mean	9.3 sec	4.4 sec
Variance	50.62 sec^2	11.76 sec^2
Observations	17	17
Pearson Correlation	0.82	
df	16	
t Stat	4.31	
P(T<=t) two-tail	0.0005	
t Critical two-tail	2.12	

Table K.7: Entering and Exiting Times of the Platoons on August 13

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	3	2	20	3	17
2	6	6	26	15	11
3	2	3	5	15	-10
4	5	5	20	20	0
5	0	1	0	1	-1
6	2	2	14	6	8
7	0	0	0	0	0
8	0	1	0	1	-1
9	0	0	0	0	0
10	1	1	2	1	1
11	0	0	0	0	0
12	0	2	0	5	-5
13	2	2	12	4	8
14	2	2	25	3	22
15	1	1	3	1	2
16	3	3	14	5	9
17	0	0	0	0	0
18	1	3	0	10	-10
19	0	1	0	1	-1
20	2	2	6	2	4
21	1	3	3	7	-4
22	1	2	2	2	0
23	1	2	2	7	-5
24	0	0	0	0	0
25	1	1	3	2	1
26	1	3	1	5	-4
27	1	3	2	8	-6
28	1	2	1	10	-9
29	1	0	2	0	2
30	0	1	0	1	-1
31	2	4	7	9	-2
32	0	6	0	36	-36
33	3	4	9	13	-4
34	0	1	0	1	-1
35	1	2	1	13	-12
36	1	3	2	14	-12
37	0	2	0	4	-4

38	1	0	3	0	3
39	2	2	9	16	-7
40	3	4	14	10	4
41	5	1	22	2	20
42	1	1	3	1	2
43	2	2	8	2	6
44	1	1	1	1	0
45	3	1	28	1	27
46	2	0	15	0	15
47	0	0	0	0	0
48	1	1	2	1	1
49	3	1	26	2	24
50	4	1	24	1	23
51	6	2	27	2	25
52	1	2	2	3	-1
53	2	1	9	1	8
54	4	1	28	1	27
55	3	1	18	1	17
56	3	2	11	8	3
57	4	1	19	2	17
58	3	1	16	1	15
59	2	1	7	1	6
60	0	0	0	0	0
61	0	0	0	0	0
62	0	0	0	0	0
63	0	0	0	0	0
64	3	2	23	11	12
65	2	0	39	0	39
66	4	1	13	1	12
67	0	0	0	0	0
68	0	0	0	0	0
69	2	1	6	1	5
70	5	0	15	0	15
71	4	2	15	3	12
72	6	1	20	1	19
73	0	0	0	0	0
74	0	0	0	0	0
	1.72	**1.49**	**8.18**	**4.04**	**4.14**

Table K.8: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 13

	Entering Time	Exiting Time
Mean	8.17 sec	4.04 sec
Variance	93.96 sec^2	36.81 sec^2
Observations	74	74
Pearson Correlation	0.029461327	
Hypothesized Mean Difference	0	
df	73	
t Stat	3.152805926	
P(T<=t) one-tail	0.001173455	

Table K.9: Entering and Exiting Times of the Platoons on August 14

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	3	1	8	1	7
2	4	2	18	7	11
3	3	0	20	0	20
4	4	1	14	1	13
5	0	0	0	0	0
6	4	1	34	1	33
7	2	1	15	2	13
8	0	0	0	0	0
9	4	1	28	2	26
10	2	0	20	0	20
11	4	2	15	9	6
12	2	0	48	0	48
13	1	0	1	0	1
14	1	1	1	2	-1
15	2	1	7	1	6
16	0	0	0	0	0
17	2	2	18	2	16
18	4	1	33	1	32
19	1	1	1	1	0
20	3	2	14	11	3
21	2	1	8	1	7

22	2	3	10	18	-8
23	0	1	0	1	-1
24	0	1	0	2	-2
25	0	3	0	4	-4
26	2	3	9	10	-1
27	1	2	1	3	-2
28	1	3	1	3	-2
29	3	4	21	7	14
30	0	0	0	0	0
31	3	2	13	5	8
32	1	0	2	0	2
33	3	3	9	11	-2
34	0	1	0	1	-1
35	2	3	11	11	0
36	3	2	15	3	12
37	0	1	0	2	-2
38	2	2	11	3	8
39	2	3	9	6	3
40	0	0	0	0	0
41	0	1	0	2	-2
42	0	2	0	4	-4
43	1	4	7	26	-19
	1.72	**1.44**	**9.81**	**3.81**	**6.00**

Table K.10: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 14

	Entering Time	Exiting Time
Mean	9.8 sec	3.8 sec
Variance	122.3 sec^2	28.12 sec^2
Observations	43	43
Pearson Correlation	0.023	
df	42	
t Stat	3.24	
P(T<=t) two-tail	0.002	
t Critical two-tail	2.02	

Table K.11: Entering and Exiting Times of the Platoons on August 19

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	4	7	42	35	7
2	13	11	58	42	16
3	6	8	30	24	6
4	9	9	46	26	20
5	11	6	36	29	7
6	3	3	22	8	14
7	6	6	32	31	1
8	4	3	15	17	-2
9	10	7	58	34	24
10	12	2	46	7	39
11	6	8	20	23	-3
12	8	8	28	29	-1
13	8	9	39	22	17
14	3	6	12	23	-11
15	7	8	35	26	9
16	9	10	29	39	-10
17	13	12	59	43	16
18	6	4	26	19	7
19	10	9	45	31	14
20	4	12	34	68	-34
21	7	7	32	23	9
22	12	9	44	42	2
23	8	13	28	44	-16
24	17	15	29	48	-19
25	1	16	2	60	-58
26	2	7	6	28	-22
27	15	13	37	171	-134
28	19	23	52	98	-46
29	3	3	39	8	31
30	6	4	46	15	31
31	9	13	25	43	-18
32	10	8	47	37	10
33	5	4	23	10	13
34	15	14	60	58	2
35	9	7	63	29	34
36	12	11	58	43	15
37	13	12	62	57	5

38	10	7	47	25	22
39	12	9	53	56	-3
40	19	16	58	65	-7
41	11	11	60	49	11
42	15	8	46	31	15
43	6	8	30	48	-18
44	11	9	49	51	-2
45	14	9	44	42	2
46	9	5	39	29	10
47	7	5	32	16	16
48	9	8	30	26	4
49	6	3	13	20	-7
50	10	8	44	50	-6
51	11	6	47	31	16
52	7	6	25	27	-2
53	7	4	30	11	19
54	5	4	22	13	9
55	10	6	37	21	16
56	12	15	54	60	-6
57	9	7	44	34	10
58	20	31	35	153	-118
59	16	5	60	16	44
60	13	9	42	34	8
61	7	9	35	39	-4
62	12	4	55	13	42
63	15	17	56	81	-25
	9.49	**8.83**	**38.92**	**38.59**	**0.33**

Table K.12: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 19

	Entering Time	Exiting Time
Mean	38.9 sec	38.6 sec
Variance	213.65 sec^2	835.18 sec^2
Observations	63	63
Pearson Correlation	0.192	
df	0	
t Stat	0.089	
P(T<=t) two-tail	0.93	
t Critical two-tail	1.99	

Table K.13: Entering and Exiting Times of the Platoons on August 20

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	7	8	31	47	-16
2	5	5	19	22	-3
3	4	8	25	61	-36
4	11	14	55	78	-23
5	8	5	41	16	25
6	4	4	25	17	8
7	10	15	38	89	-51
8	12	16	60	69	-9
9	7	5	28	37	-9
10	10	13	51	68	-17
11	10	11	57	50	7
12	9	7	40	24	16
13	4	7	13	19	-6
14	9	8	43	32	11
15	6	5	29	29	0
16	12	8	54	54	0
17	7	7	44	57	-13
18	10	11	38	67	-29
19	4	5	16	24	-8
20	12	11	57	88	-31
21	9	12	40	37	3
22	5	4	19	52	-33
23	5	10	32	38	-6
24	9	10	53	55	-2
25	9	8	25	20	5
26	8	10	47	44	3
27	13	13	57	70	-13
28	9	5	35	13	22
29	4	5	11	13	-2
30	7	7	21	25	-4
31	4	7	16	38	-22
32	8	12	25	53	-28
33	6	8	25	35	-10
34	7	11	28	44	-16
35	11	8	31	43	-12
36	10	16	35	70	-35
37	5	4	21	39	-18
38	14	7	58	47	11

39	14	11	30	49	-19
40	7	1	24	1	23
41	9	7	41	36	5
42	18	13	58	59	-1
43	8	5	15	29	-14
44	14	11	56	43	13
45	8	5	23	17	6
46	7	8	30	43	-13
47	7	2	22	3	19
48	12	10	38	41	-3
49	13	9	40	30	10
50	9	6	36	33	3
51	16	5	28	13	15
52	26	10	45	27	18
53	6	4	8	15	-7
54	9	2	13	4	9
55	29	11	59	45	14
56	15	8	31	50	-19
57	15	10	27	46	-19
58	23	12	52	55	-3
59	16	9	24	48	-24
60	5	6	18	14	4
61	10	11	28	46	-18
62	9	10	36	39	-3
63	9	7	25	26	-1
64	10	8	20	25	-5
65	13	12	19	42	-23
66	14	6	31	20	11
67	7	3	17	8	9
68	6	5	11	14	-3
69	13	9	33	42	-9
70	14	4	13	23	-10
71	17	8	28	29	-1
72	14	11	18	35	-17
73	6	13	27	45	-18
74	27	14	61	52	9
	10.26	**8.32**	**32.81**	**38.26**	**-5.45**

Table K.14: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 20

	Entering Time	Exiting Time
Mean	32.8 sec	38.3 sec
Variance	206.87 sec^2	380.3 sec^2
Observations	74	74
Pearson Correlation	0.62	
df	73	
t Stat	-3.02	
P(T<=t) two-tail	0.003	
t Critical two-tail	1.99	

Table K.15: Entering and Exiting Times of the Platoons on August 21

Platoon	Entering vehicles	Exiting vehicles	Entering Time (seconds)	Exiting Time (seconds)	Difference (seconds)
1	4	2	26	2	24
2	7	8	38	27	11
3	11	14	50	84	-34
4	11	3	53	10	43
5	8	10	24	37	-13
6	10	11	61	103	-42
7	9	8	29	23	6
8	4	4	21	27	-6
9	6	6	34	16	18
10	8	5	46	19	27
11	9	7	43	46	-3
12	6	12	19	38	-19
13	8	6	37	13	24
14	13	12	62	46	16
15	14	12	62	35	27
16	18	12	62	100	-38
17	6	2	20	2	18
18	12	8	37	23	14
19	12	3	41	7	34
20	12	4	58	10	48
21	17	13	60	40	20
22	14	10	61	35	26

23	9	6	39	21	18
24	12	9	43	26	17
25	9	7	35	23	12
26	9	4	36	20	16
27	2	5	8	37	-29
28	12	10	52	37	15
29	13	10	48	46	2
30	10	5	35	15	20
31	11	5	29	18	11
32	4	7	12	33	-21
33	11	12	36	70	-34
	9.73	**7.64**	**39.91**	**33.00**	**6.91**

Table K.16: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 21

	Entering Time	**Exiting Time**
Mean	39.9 sec	33 sec
Variance	232.3 sec^2	619.4 sec^2
Observations	33	33
Pearson Correlation	0.39	
df	32	
t Stat	1.68	
P(T<=t) two-tail	0.10	
t Critical two-tail	2.03	

Table K.17: Entering and Exiting Times of the Platoons on August 27

Platoon	Entering vehicles	Exiting vehicles	Entering Time	Exiting Time	Difference
1	18	16	77	59	18
2	28	26	103	70	33
3	32	35	143	116	27
4	30	28	119	94	25
5	18	20	89	87	2
6	27	28	143	98	45
7	20	21	119	86	33
8	14	12	104	33	71
9	34	9	140	26	114
10	10	11	67	37	30
11	20	22	71	63	8
12	22	25	110	91	19
13	23	29	97	113	-16
14	13	14	57	36	21
15	25	30	162	137	25
16	22	23	119	73	46
17	22	21	98	64	34
18	21	22	101	89	12
19	29	28	170	108	62
20	22	17	90	61	29
21	19	26	80	93	-13
22	25	23	121	104	17
23	22	16	104	39	65
24	20	22	74	64	10
25	26	25	124	101	23
26	9	12	39	34	5
27	25	28	112	121	-9
28	29	34	128	98	30
29	22	23	118	87	31
30	29	29	119	114	5
31	28	33	139	131	8
32	28	31	119	105	14
33	15	17	70	81	-11
34	43	46	192	155	37
35	30	34	161	106	55
36	35	36	144	121	23
37	26	32	117	131	-14

38	42	53	168	147	21
39	25	27	127	96	31
40	42	41	202	171	31
41	32	32	147	104	43
42	36	34	155	119	36
43	20	22	91	73	18
44	38	46	138	130	8
45	23	21	124	86	38
46	31	41	121	109	12
47	34	31	140	131	9
48	37	37	119	85	34
49	24	28	93	79	14
50	23	23	102	80	22
51	10	7	64	32	-32
52	23	19	95	60	-35
53	27	21	125	64	-61
54	39	32	207	141	-66
55	24	18	111	96	-15
56	21	15	101	64	-37
57	27	22	127	105	-22
58	24	13	115	76	-39
59	24	18	105	73	-32
60	21	16	99	68	-31
61	19	17	109	112	3
62	29	24	114	87	-27
63	28	19	127	107	-20
64	29	22	128	101	-27
65	21	11	90	57	-33
66	22	15	84	42	-42
67	28	21	131	74	-57
68	32	24	131	114	-17
69	31	21	102	131	29
70	28	21	98	67	-31
71	25	18	109	87	-22
72	21	18	108	84	-24
73	31	28	128	141	13
74	34	26	142	115	-27
75	22	19	95	54	-41
76	21	16	97	51	-46
77	28	21	112	93	-19

78	21	22	102	72	-30
79	48	34	187	162	-25
80	26	21	90	81	-9
81	25	24	153	99	-54
82	24	15	81	59	-22
83	28	20	95	67	-28
84	34	26	137	102	-35
85	42	32	171	159	-12
86	40	29	165	139	-26
87	54	34	210	207	-3
88	57	35	202	173	-29
89	46	27	167	132	-35
90	47	29	148	164	16
91	51	35	168	116	-52
92	42	31	182	149	-33
93	35	23	153	149	-4
94	30	18	99	69	-30
95	76	44	251	223	-28
96	70	47	214	207	-7
97	65	42	201	272	71
98	44	33	156	129	-27
99	59	40	177	162	-15
	29.71	**25.48**	**125.56**	**101.25**	**0.57**

Table K.18: Paired t-test Results for Means of Entering and Exiting Times of the Platoons on August 27

	Entering Time	**Exiting Time**
Mean	125.6 sec	101.2 sec
Variance	1497.8 sec^2	1890.4 sec^2
Observations	99	99
Pearson Correlation	0.85	
df	98	
t Stat	10.47	
P(T<=t) two-tail	<0.001	
t Critical two-tail	1.98	


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