EVALUATION OF DAYTIME VS. NIGHTTIME RED LIGHT RUNNING USING AN ADVANCED WARNING FOR END OF GREEN PHASE SYSTEM

A Thesis

by

KWAKU ODURO OBENG-BOAMPONG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Civil Engineering

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Approved as to style and content by:

Carroll J. Messer (Chair of Committee)	Conrad L. Dudek (Member)
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ABSTRACT

Evaluation of Daytime vs. Nighttime Red Light Running
Using an Advanced Warning for End of Green Phase System.
(August 2004)

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Chair of Advisory Committee: Dr. Carroll J. Messer

The problem of dilemma zone protection and red-light-running is especially important in certain rural intersections due to the higher speeds at these intersections and their isolated nature. In addition, the presence of a larger percentage of trucks mean that adequate warning and help need to be given to these truck drivers in order to enable them to stop safely, or proceed through the intersection before the onset of red.

To curb any potential danger at such intersections, a Texas Department of Transportation (TxDOT) research project on Advanced Warning for End of Green Phase (AWEGS) at high speed intersections deployed AWEGS at two rural intersection sites – Tx 6 @ FM 185 near Waco and US 290 @ FM 577 in Brenham. The deployment of AWEGS involved a Level 1 and a later upgrade to a more efficient Level 2 in Waco. Initial results on red-light-running, even though promising, were expressed as observed red-light-running events per day. These resulting rates did not reflect exposure, and the results also raised some concerns with regards to some increase in red-light-running from Level 1 to Level 2.

A more detailed analysis of the red-light-running issue at these two sites is provided in this thesis. The main areas of red-light-running analyses presented here are with respect to the reductions in red-light-running rates for the exposure factors of number of cycles and vehicular volumes, the comparison of day and night RLR rates and the nature of speeds of vehicles running the red light at the intersection in Waco.

AWEGS was found to reduce the total red-light-running per exposure factor after its deployment. Both Level 1 and Level 2 AWEGS operations were found to reduce red-light-running by up to 60%. Generally, total red-light-running per exposure factor between Level 1 and Level 2 was found to be about the same. Level 2 had lower daytime red-light-running rates and higher nighttime rates than Level 1. Generally, day rates were found to be higher than night rates for all levels of AWEGS deployment.

It is recommended that, to better understand the operational aspects of AWEGS and to improve its operations, more implementation of AWEGS and further tests be done. An automated method to collect and analyze data needs to be developed as well as a means of automatically recording video data for calibration and verification It is also recommended that Level 1 technology be implemented in areas where the Level 2 technology may be either too complex or too expensive.

ACKNOWLEDGMENTS

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CHAPTER I

INTRODUCTION

Each year in the United States more than 1 million motor vehicle collisions occur at traffic signals, resulting in more than 500,000 injuries and several thousand fatalities; the number of fatal crashes occurring at traffic signals increased by 19% between 1992 and 1996 (*1*). A 1998 survey of Texas drivers by the FHWA and reported by Bonneson *et al* (*2*) found that two of every three Texans witness red-light-running everyday.

The rapid rate of population growth has resulted in traffic signals being installed more frequently at high-speed and high-growth rural intersections because of higher traffic volumes due to urban-rural migration. Most of these intersections have posted speed limits above 50 mph and in some instances 70 mph. One of the major hazards with traffic signal operation on such high-speed approaches occurs when the motorist faces a dilemma approaching a signal when it turns yellow. A situation arises when the motorist is caught between either proceeding through, or stopping at, an intersection. Subsequent crashes resulting at such intersections are typically serious and involve high property damage and personal injuries due to the high speeds involved.

High-speed intersections are usually isolated and this means they are typically encountered after the motorist has driven long distances without encountering any intersection. Thus, the motorist is usually not expecting a signal and may be speeding. The element of surprise needs to be eliminated with advanced warning devices to help minimize or remove the dilemma zone in such cases as the potential for hazards are increased at such intersections.

This thesis follows the style and format of the *Transportation Research Record*.

OVERVIEW OF RESEARCH PROJECT 0-4260

The Advanced Warning for End of Green Phase System (AWEGS) at high-speed rural intersections is a Texas Department of Transportation (TxDOT) sponsored research project in association with the Texas Transportation Institute (TTI). The project was geared at improving safety at these high-speed intersections that are especially dangerous with the presence of a high proportion of trucks. The steady increase in rural to urban migration has caused an increasing number of rural intersections to experience a relatively high proportion of vehicular activity. Consequently, warranted traffic signals are being installed more frequently at such high-speed and rural intersections. Most of these intersections have posted speed limits above 50 mph and in some instances 70 mph.

The sudden nature of these intersections means adequate warning needs to be provided motorists of the traffic signal ahead through active warning signs as well as providing some protection for very high-speed vehicles who may not be able to stop comfortably within the time frame given them by these advanced warning devices. Truck drivers find advance warning flashers to be particularly beneficial mainly due to the considerable mass and momentum of their vehicles and the unique braking challenges this poses to them. The goal of AWEGS is to provide extra protection for high-speed vehicles approaching the intersection. AWEGS was deployed in two stages involving Level 1 and Level 2 technologies with the latter more adaptive to traffic speeds and type of vehicles.

SITE SELECTION

Two high-speed intersections in Texas were used as initial deployment sites for the AWEGS system. The two intersections were selected based on their crash history and the higher speeds that existed at both intersections. The two sites were the intersections of FM 518 with SH 6 in Waco and FM 577 with US 290 in Brenham. The intersection at Waco is slightly skewed and has a single lane approach, while the intersection at Brenham is almost like a diamond interchange with a dual lane approach. Figure 1.1 shows a picture of the Westbound approach at Waco before the deployment of AWEGS.

Figure 1.1 Westbound TX 6 Approach at Waco before AWEGS

PROBLEM STATEMENT

The results obtained from the deployment of AWEGS, however encouraging, had a few uncertainties. The initial rates were expressed as red-light-running per day with no idea of the effects of traffic volume and frequency of signal changes. Thus a more informative rate will be needed to properly understand the rate per exposure observed at these intersections. As noted in earlier research (*2*,*3*,*4*), factors affecting red-light running include the number of approaching vehicles to the intersection, frequency of signal cycles, type of signal control, vehicle approach speed, duration of yellow interval, approach grade and signal visibility. The goal is thus to express the rates obtained in a per cycle, per vehicle or per vehicle-cycles to capture the effect of number of approach vehicles and frequency of signal cycles observed at the two sites.

Current research has suggested using rates of per 100 cycles, per 1,000 vehicles and per 10,000 vehicle-cycles. (*5*)

Also, while Level 2 technology deployment saw decreased rates of red-light-running in the real red, it also led to a slight increase in red-light-running as compared to Level 1. To determine the overall performance of Level 1 compared with Level 2, the red-light-running per exposure factors should provide some insight as to the relative performance of these two Levels.

Nighttime traffic has the distinction of lighter volumes and the threat of more red-light running due to glare, fatigue, as well as less threat of citation. However, the goal of this research is not to determine the effects of these factors, but to determine if there was any reduction or otherwise change in performance of AWEGS during this time as opposed to daytime red-light running. Evaluating nighttime vs. day time rates gives an idea of the performance of AWEGS during lighter traffic volumes and may help eliminate some lingering questions as to the reasons for the results obtained in the initial evaluation.

It is also desirable to know the nature of speeds of vehicles crossing the stop line during both red clearance and real red. It is desirable to determine if AWEGS had an effect on speeds of vehicles that run the red light.

RESEARCH OBJECTIVES

The research objective of this paper was to evaluate the effects of an advanced warning for end of green phase on red-light-running. This objective will be met by specifically achieving the following tasks:

- Perform literature review of factors affecting red-light running;
- Perform literature review of time of day red light running;
- Determine the effects of AWEGS on red-light-running rates per time of day;
- Evaluate proposed Measures of Effectiveness (MOEs) and correlate the red-light-running rates with the volume of traffic and frequency of signal changes observed on approaches (i.e. per 10,000 vehicle-cycles);

- Determine the effect of AWEGS on speeds of vehicles running the red lights; and
- Identify possible reasons for results and recommend some means of addressing these reasons.

SCOPE OF RESEARCH

This research deals mainly with high speed intersections. The analysis done was with respect to data collected at the two intersection sites where the AWEGS system was deployed in Texas. Though the literature covers a broad range of red light running issues having significance for urbanized as well as rural intersections, the subsequent analysis of results obtained and presented in this research will be based solely on the deployment of the AWEGS system at the two rural high-speed intersections.

CHAPTER II

LITERATURE REVIEW

This chapter looks at the process of running the red light and some countermeasures described in the literature as potential tools for reducing red light running. The dilemma zone concept is initially discussed as one main contributing situation that drivers encounter as they approach a signalized intersection. Also, factors that have significant influence on a driver's propensity to run the red light and countermeasures in the literature will be discussed. Retting *et al* (*6*) report that approximately 1 million collisions occur at signalized intersections in the United States each year.

Research shows that motorists are more likely to be injured in crashes involving red-light running than in other types of crashes. Occupant injuries occurred in 45 percent of the red-light running crashes studied compared with 30 percent for other crash types. One reason for high injury rates in this type of crash is that these collisions often involve side impacts with other vehicles at relatively high speeds, which can result in passenger compartment intrusion. Injury severity increases with the severity of vehicle intrusion, and ejection is also a risk in side-impact crashes (*7*).

DILEMMA-ZONE CONCEPT

The dilemma zone, also known as the zone of indecision, is that section of the approach roadway to the intersection within which drivers show a difference in desire (or ability) to stop when presented the yellow signal indication (*8*). A driver approaching a signalized intersection at the onset of yellow must decide whether to cross the intersection or to stop before reaching the stop line. The choice is usually quite definite if the driver is near enough to the stop-line that proceeding through the intersection is necessary, safe and possible. The choice again is clear if the driver is far enough away from the stop-line that braking is necessary and possible.

The decision becomes conflicting, however, if the driver is positioned in the option zone, where both choices are possible, or in the dilemma zone where it is neither possible to proceed straight through at constant speed to clear the stop line before the onset of red nor possible to brake safely and comfortably. Figure 2.1 shows the various aspects of a typical dilemma zone situation.

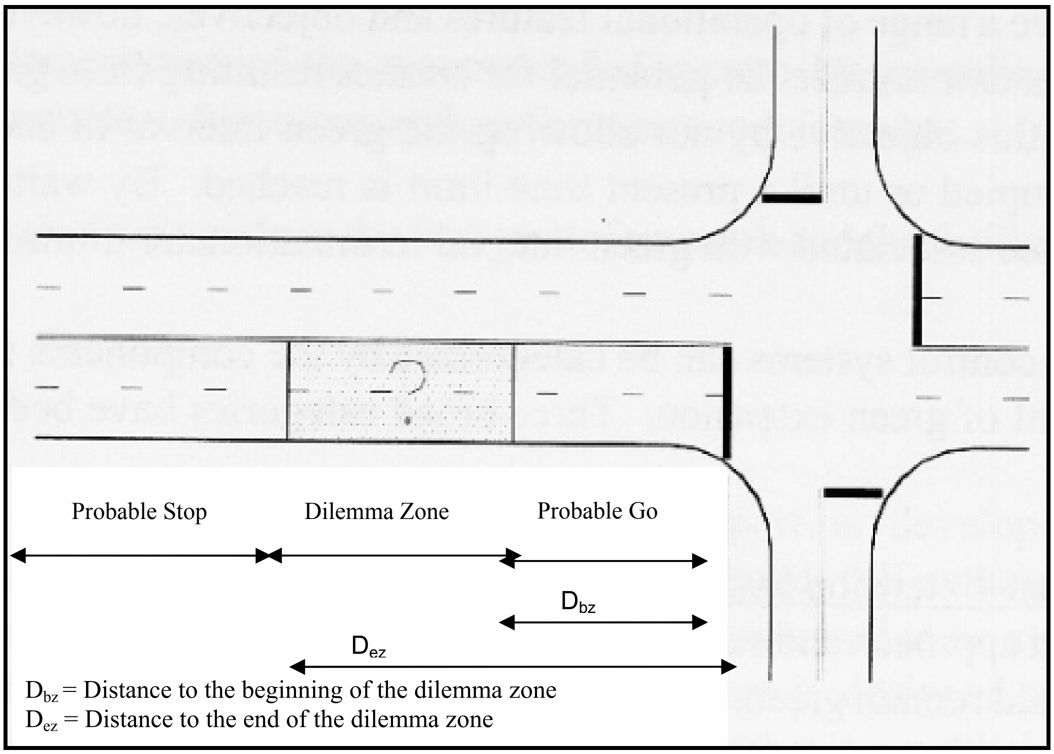

Figure 2.1 Dilemma-Zone Boundaries on a Typical Intersection Approach

This decision process encountered by motorists, as the signal turns yellow often leads to red-light-running (RLR) events. A number of countermeasures are available for addressing the red-light-running problem. These include engineering measures, which provide more durable and physical solutions, and enforcement techniques which attempt to deter unsafe driver behavior.

FACTORS AFFECTING FREQUENCY OF RED-LIGHT-RUNNING

Various factors (exposure factors) affect the rate of running the red light. These are outlined in the section below and categorized into Exposure and Other Factors.

Exposure Factors

These factors have to do with certain conditions that, when present, expose drivers to conditions that may promote red-light-running.

Flow Rate

The flow rate on any approach is an important factor influencing the rate of red-light running. The number of drivers running the red light each signal cycle will likely increase as the flow rate increases (*2*). Mohammed et al. (*3*), using crash data from 1,756 urban intersections in California, found that approach crash frequency increased from 0.25 crash/yr at a two-way volume of 8,000 veh/day to 0.5 crash/yr at 50,000 veh/day.

Number of Signal Cycles

Generally, an increase in the cycle length from 60 to 120 seconds may reduce the number of times the yellow light is presented by about 50%. This may lead to a reduction of red-light-running (theoretically) by a similar amount (*2*).

Phase Termination by Max-Out

Typically, green–extension systems use one or more detectors located upstream of the intersection to hold a phase in green for as long as is needed. However, in the event that the green is held to its limit, the phase "maxes-out" and ends regardless of whether a vehicle is approaching the intersection or not. An actuated system that maxes out has a propensity to expose drivers to a red-light-running situation.

Zeeger and Dan (*9*) examined the effect of green-extension systems on the frequency of red-light-running using two rural intersections as case studies. They found out that a 65% reduction in red-running frequency was achieved due to the use of green-extension systems.

Other Factors

Other factors that may serve as contributing to the event of red-light-running have to do with driver behavior, likely consequences of not stopping, or that of stopping. The main aspects of driver behavior that have been mentioned by several researchers to affect motorists decision to run the red light or not include (*10*,*11*,*12*):

- Travel time to the stop line;
- Approach speed of vehicle;
- Signal coordination;
- Yellow interval duration;
- Approach grade; and
- Headways.

Probable consequences of not stopping that may influence driver decision to stop or proceed through a red light include the threat of right-angle crashes and possible citation (*13*, *14*) Probable consequences of stopping that might affect a driver's decision may include the threat of a rear-end crash and the expected delay to be encountered at the red light (9).

COUNTERMEASURES TO RLR – ENFORCEMENT TECHNIQUES

Freedman and Paek note that resources to enforce traffic laws, including signal violations are generally inadequate and have diminished in relation to the number of vehicles on the road (*15*).

Traditional Enforcement

Traditional enforcement of obeying traffic signals, when employed, requires an officer to observe a red-light violation and then chase, stop, and cite the violator. This process can be hazardous to motorists, pedestrians, and officers because in many of these cases, the officer would have to run the red light after the violator. Such safety issues plus the frequency of red-light-running events especially in urban environments mean police officers cannot sufficiently enforce against red-light-running (*1*).

Red-Light Cameras

This method involves a red-light camera being connected to the traffic signal and to sensors buried in the pavement at the crosswalk or stop line. These cameras automatically photograph the license plates of vehicles whose drivers run red lights as well as a photograph of the violator. The system continuously monitors the traffic signal, and the camera is triggered by any vehicle passing over the sensors above a preset minimum speed and a specified time after the signal has turned red.

Red-light camera technology has been used in foreign countries. Retting *et al* (*1*) reports of study results conducted in Victoria, Australia showing a 32 percent decrease in right-angle collisions and a *1*0 percent reduction in injuries after the cameras were installed (*16*). An added benefit of red-light cameras is that driver compliance is usually increased at other sites within a region that are not even camera-equipped (*17*).

However, critics of the red-light camera system cite cases of violators not necessarily being owners of the vehicles and also the "big brother" issue. A survey conducted in Arlington, Virginia showed that 72 percent of violators were registered as vehicle owners and nine percent had matching addresses (*1*). Thus, on the basis of these results, it is likely that sanctions against vehicle owners for red-light-running could be expected to deter many potential violations. Even though some surveys have revealed wide acceptance and support for red-light camera use, it is in no way a done deal, and a significant proportion of motorists have reservations with regards to its use (*1*).

COUNTERMEASURES TO RLR – ENGINEERING MEASURES

Removal of Unwarranted Traffic Signals

Traffic signals maintained at locations with very low traffic volumes may contribute to red-light-running and intersection crashes. Retting *et al* (*1*), report studies of low volume intersections that were converted from signal control to stop sign control recording significant reductions in crashes and injuries (*18*,*19*).

Improved Signal Timing

Another factor shown to influence the risk of red-light violations and potential intersection conflicts is the length of the clearance interval. Inadequate signal change interval has been reported to be associated with increased crash rates (*20*). Studies have indicated that increases in the length of the yellow signal toward values associated with the ITE - proposed recommended practice significantly decreased the chance of red-light running (*21*). Table 2.1 shows typical yellow (change) interval times for varying speeds used by various jurisdictions.

Table 2.1 Change Intervals Used by Various Jurisdictions (*22*)

Region	Speed kmph (mph)	Yellow Time (sec)
New York State	89(55)	5.0
	97(60)	5.4
Iowa DOT	> 64 (40)	5
Montgomery County, Maryland	> 72 (45)	5
Lakewood, Colorado	89 (55)	5.5

Installation of Advanced Warning Flashers

The most common advanced warning flasher being used currently is the basic advance warning sign which serves to forewarn drivers of a signalized intersection ahead. This yellow sign typically uses the "Signal Ahead" symbolic message and is often accompanied by continuously-flashing beacons to aid drivers detect and interpret the sign's meaning.

Another method currently being utilized sporadically throughout the United States and Canada involves the installation of advance flashing beacons and/or other methods to provide advance warning to motorists of the end of the green signal phase and thus reduce or eliminate the dilemma faced by vehicles. Sayed *et al* noted that effective advance warning flasher implementation has the potential to minimize the number of vehicles in the "dilemma zone" and lead to an increased safety in this zone, thus reducing accident frequency (*23*).

Common AWF signs used include the following (*23*):

- Prepare to Stop When Flashing (PTSWF): The PTSWF sign is basically a warning sign with the text Prepare To Stop When Flashing complemented by two amber flashers that begin to flash a few seconds before the onset of the yellow interval at a downstream signalized intersection) and that continue to flash until the end of the red interval.
- Flashing Symbolic Signal Ahead (FSSA): This is similar to the PTSWF but with the words replaced by a schematic traffic signal composed of a rectangle with solid red, yellow, and green circles. The flashers operate just as in the PTSWF sign.
- Continuously Flashing Symbolic Signal Ahead (CFSSA): This device is identical to the FSSA sign but the flashers attached to it, flash all the time as they are not connected to a traffic signal controller.
- Passive Symbolic Signal Ahead (PSSA): This is only the Signal Ahead sign and no flashers are used (*24*).

In a study conducted by Pant and Huang in Ohio, it was detected that in general, the use of active advance warning signs such as the PTSWF or FSSA signs encouraged high speed under some flasher and signal conditions. This was particularly the case when the flasher was inactive and the signal indication was either green or yellow. They found that the use of the signs should be discouraged at high-speed signalized intersections with a tangent approach (*24*).

DILEMMA ZONE PROTECTION

Bonneson *et al* (*25*,*26*) noted that there was a trend towards increased dilemma zone lengths and this increase was suggested to be due to decreasing driver respect for the change interval. Middleton et al (*22*) noted that a later study by Zeeger (*9*) revealed dilemma zones that were 28 to 38 percent longer than those measured earlier by Parson et al (*27*), for speeds of 72 to 80 kmph (45 to 50 mph).

Basic Green Extension Systems

A study by Agent and Pigman (*28*) found that a large number of traffic crashes at signalized intersections on high-speed roadways occur during or just after the change interval. The green extension system and an advanced warning flasher system were both evaluated, and ways in which to use them to diminish dilemma zone problems at high-speed intersections were suggested.

Application and evaluations of basic green-extension systems have been documented since the mid-1970s. These systems have been proven to offer safety benefits and have found their greatest use at rural intersections due to the higher speeds and isolated conditions at these intersections (*8*).

The typical basic green-extension system utilizes multiple advance detectors located along an intersection’s approach, with the first detector located just in advance of the dilemma zone. Two or three additional detectors are then located between the first detector and the stop line. The location of these intermediate detectors is determined through a consideration of the speeds of vehicles and controller passage-time setting (*8*).

The objective of this design is to ensure that all but the slowest vehicles (15th percentile) progress through their respective dilemma zones before allowing the phase to end. Figure 2.2 shows a typical layout of the basic green extension system.

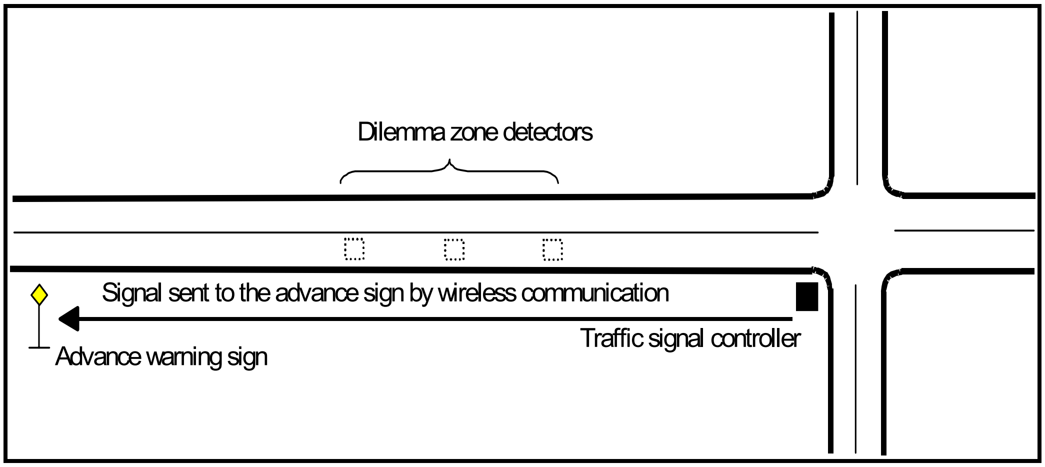

Figure 2.2 Typical Layout of the Basic Green Extension System

In operation, the controller extends the green interval until it determines that the clearance zone is clear of vehicles or until a preset maximum green limit is reached. Bonneson and McCoy (*29*) provide an in-depth look at basic green-extension systems. Wu *et al* (*30*) reported a reduction in crash rate of 35 percent for intersections with approach speeds of 55 mph after the adoption of the basic green-extension system. Zeeger and Deen, also found crash frequency was reduced by 54 percent due to the use of a green-extension system, based on three years prior and one year after data at three sites (*31*).

This system is likely to cause delay to vehicles waiting on conflicting phases since the multiple detectors increase the size of the maximum allowable headway. Bonneson *et al* (*8*), report that the difference in average waiting time for a conflicting phase between stop-line-only detection and multiple advance detection is about 15 seconds or less depending on the flow rate. However, Wu *et al* (*30*) noted that overall intersection delay does not increase significantly when multiple advance detection is used. This indicates that any delay increase to the minor movements is offset by a delay reduction to the major movement. An example of a multiple advance detector design specifications for various design speeds is shown in Table 2.2.

Table 2.2 Multiple Advance Detector Design Specifications (*8*)

85% Approach Speed (mph)	Distance to 3rd Loop (feet)	Distance to 2nd Loop (feet)	Distance to 1st Loop (feet)	Passage Time (sec)	Maximum Allowable Headway (sec)
45	210	330		2.0	4.5
50	220	350		2.0	4.4
55	225	320	415	1.2	4.2
60	275	375	475	1.4	4.3
65	320	430	540	1.2	4.1
70	350	475	600	1.2	4.2

Enhanced Green-Extension Systems

These systems operate much like the basic green-extension system, but also have the ability to hold the major-road through green interval past the maximum green setting thus helping reduce the problem of the green phases *maxing out*. The TTI Truck Priority system and the Swedish LHOVRA systems are such examples (*32*). The former is briefly discussed below.

TTI Truck Priority System

The TTI Truck Priority system was designed specifically to reduce the number of trucks stopping on high-speed rural intersection approaches (*32*). This is so because trucks typically require longer braking distances and hence have strikingly differing dilemma zones than other vehicles. The truck priority system includes the following four components:

- One detector speed trap (i.e. two detectors spaced 18 ft apart in the lane) in each approach lane located about 7.0 seconds upstream of the intersection;
- A vehicle classifier that determines vehicle speed and classification from the detector trap;
- A microcomputer that analyzes the speed and classification data to determine when a green extension is appropriate; and
- A basic green-extension system (as described previously).

This system mainly seeks to hold the green interval whenever a truck is within the "clearance zone" (i.e. within about 500 ft of the stop line) and hence minimizes the frequency of truck stops on the major-road approaches. A typical design is shown in Figure 2.3 for an 85th percentile approach speed of 55mph.

In an evaluation of the truck priority system at one intersection in Texas, Sunkari and Middleton (*33*), found that about 4 percent of trucks benefit by not having to stop as a result of active green extension. This was due primarily to the small number of trucks that arrive during the end of the green interval. And the system was actually found to extend the green for all trucks that were in need of clearance zone protection. Benefits of this system include reduced frequency of stops (and resulting pavement damage) and reduced delay to trucks (*8)*.

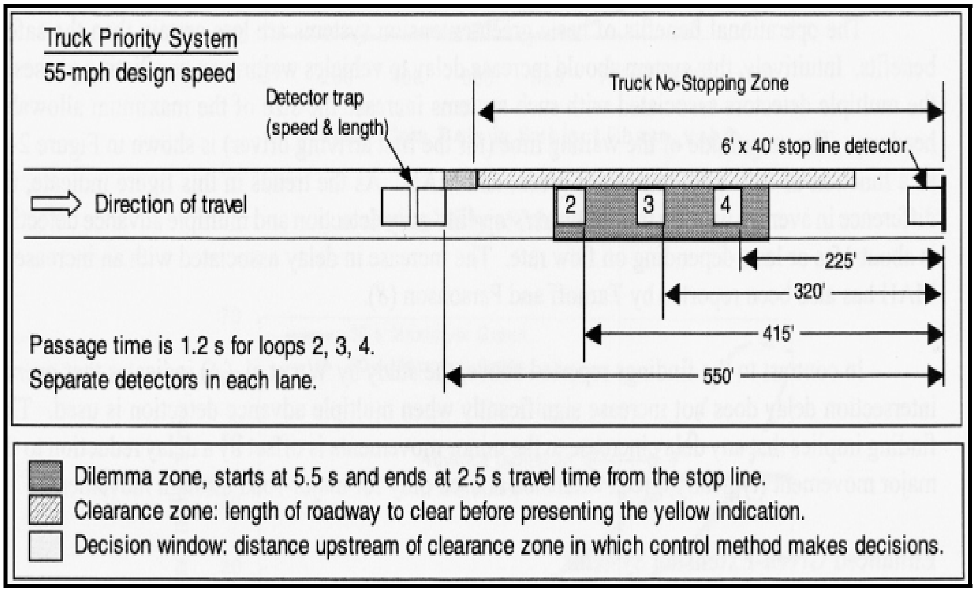

Figure 2.3 Truck Priority System (*8*)

Green Termination System

Other systems that have been used include the green termination system, which unlike the green-extension system, determines the best time to end a green phase. Bonneson *et al* (*8*) cite an example of the green termination system as the Self Optimizing Signal (SOS) system developed by the Transport Research Institute for the Swedish National Administration. The objective of the SOS system is to determine the optimal time to end a phase based on considerations of safety to vehicles served by the major-road through phases and delay to vehicles served by conflicting phases. The system includes the following components (*8*):

- A detection design that is similar to the one shown in Figure 2.4;
- A micro computer that monitors the location and lane (i.e. inside or outside lane) of each vehicle on the approach; and
- A full-actuated controller with stop-line presence detection.

Unlike the basic green-extension system, the SOS system does not necessarily wait until the dilemma zone is fully clear or gaps out, to permit green interval termination. Rather, the system identifies a "best" time to end the green within reasonable time limits. This supposedly "best" time is dependent on how many vehicles will be in the dilemma zone and how much delay will be incurred by waiting motorists at each 0.5-second time interval in the next 20 seconds (*8)*.

Bonneson *et al* (*8*) proposed a new concept for vehicle detection and control at rural signalized intersections. The concept detection-control system is similar to a green-termination system because it uses vehicle speed and length to predict the "best" time to end the phase.

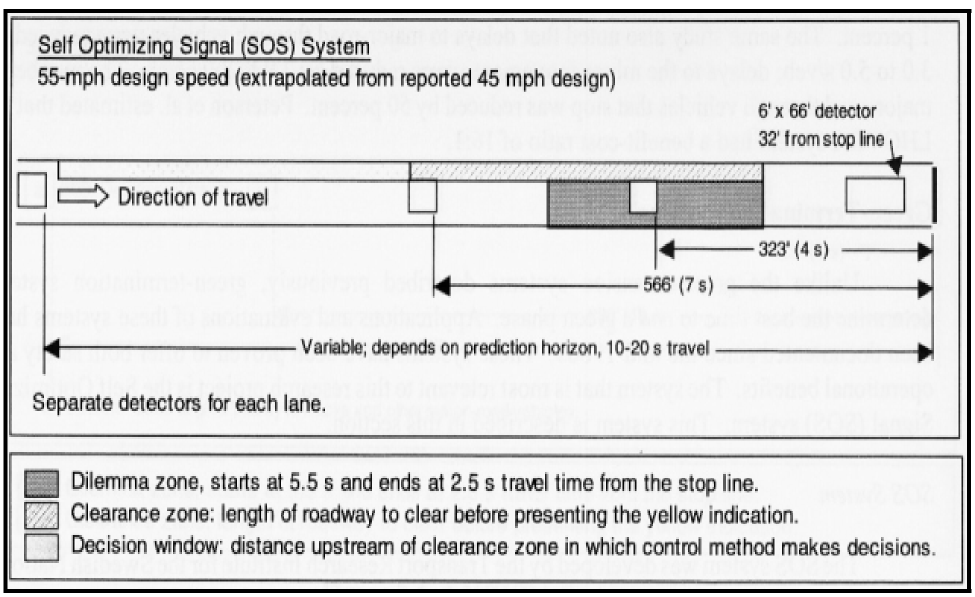

Figure 2.4 SOS System for 55–mph Design Speed (*8*)

The objective of the system is to identify the best time to end the major-road through phase based on consideration of the number of vehicles in the dilemma zone, the number of trucks in the dilemma zone, and the waiting time of vehicles in conflicting phases.

ADVANCED WARNING AT HIGH SPEED INTERSECTIONS

Two studies on advanced warning systems at high speed intersections are documented here. The first involves a system deployed and used by the Metro Division of the Minnesota Department of Transportation (MnDOT) and the second is the Advanced Warning for End of Green Phase System (AWEGS), at high speed intersections deployed in Texas and on which this research is based.

Study on Advanced Warning Flashers in Minnesota

The system involved the use of advanced warning flashers as an additional dynamic signing tool available for specific signalized intersections with a combination of documented accident, sight line, isolated and problematic operation. This study used Motion Imaging Recording System (MIRS) technology to collect data on the number, vehicle speed, vehicle type (cars or trucks), elapsed time into the red period, and time of day vehicles ran the red period of the southbound approach of the trunk highway signal system at United States Trunk Highway (USTH) 169 and County State Aid Highway 1/Pioneer Trail in Bloomington, Minnesota (*34*). The study was conducted both before and after the installation of the advanced warning flashers at this location a period between October and December of 1998.

The MIRS system was used to monitor and photograph red light running vehicles in the two southbound through lanes of traffic at this site. It consisted of a 12 foot high camera pole with an enclosed housing for the camera/flash unit, a model 36mST-MC red light camera and flash unit shown in Figures 2.5 and 2.6 below, and three turn saw cut inductance loop detectors. The camera, loop detectors and in-place signal controller were interconnected to allow the camera to know precisely when the red phase for the signal began (*34*).

Figure 2.5 MIRS Pole and Camera Box

Figure 2.6 Interior of MIRS Camera Box

The system monitors a set of two inductance loop detectors buried in the pavement of the approaches. The first loop was located approximately one foot past the intersection 24 inch wide stop line and the second loop placed about four feet past the first loop closer to the center of the intersection. The pole, camera housing and camera were located 103 feet from the stop line of the southbound approach. The camera was positioned and aimed manually to point towards the center of the intersection to take a photo of vehicles running the red light. The camera computer was programmed with a threshold speed and delay time which was used to try and prevent the system from triggering and taking pictures of stopped vehicles on the loop moving sometime during the red period. Vehicles photographed above the threshold speed are assumed to be running the red light while those below this speed are assumed otherwise. The system utilized the “BE PREPARED TO STOP” and “WHEN FLASHING” sign with accompanying dual eight inch flashing yellow beacons shown in Figure 2.7 below.

Figure 2.7 Advanced Warning Flashers on Trunk Highway 169 (34)

The study results showed that there was a 29% overall reduction in red-light-running, 63% in truck red-light-running and an 18.2% reduction in speed of violating trucks. However, one area of concern found from the study was the still relatively high number of drivers running the red light even with the advanced warning at speeds well over the speed limit, thereby posing a danger to opposing traffic movements (*34*). An estimated 23% increase was observed in the number of vehicles running the red light 3.6 or more seconds after the start of the red period. They also found that the time of day with the most frequent car red light running violations coincided with the evening "rush hour".

AWEGS System in Waco, TX

The Advanced Warning for End of Green Phase system was deployed at high-speed rural intersections with speeds typically over 50 mph. In Waco, the system was deployed in two levels, with Level-2 technology being the one proposed to be implemented. The purpose of the system is to provide an advanced indicator for high-speed vehicles of the end of their green time as well as providing protection for those vehicles that are traveling at speeds too high to stop safely before the start of red. This is done by the installation of advanced detectors upstream of the intersection that determine the presence, speeds and hence travel time of approaching vehicles. The following sections discuss the different levels of technologies as well as some advantages of the AWEGS system.

Level 1 Technology

Some existing traffic signal controllers have incorporated Advance Warning (AW) logic *(16)*. However, none of the signal controllers used in Texas meeting the TxDOT specifications have the AW logic built in explicitly. Level one deployment uses existing controllers with minimal external logic built to deploy the state of the practice of advance warning systems. A review of the capabilities of the controllers that meet the TxDOT specifications reveal that it is possible to implement an advance warning system by making some changes in the controller cabinet and/or by using some of the existing features in the controllers. The current version of the Eagle controller software has a feature called "trailing overlaps" that can potentially be used to implement advance warning logic where, after the subject phase terminates, its green indication continues to be displayed for a user specified duration (*35*).

In Level 1 technology, only one advanced detector is activated and this allows the determination of the presence of a vehicle upstream of the intersection. If the controller is about to gap out, and a vehicle arrives at the advanced detector ADA, a fixed hold is placed on the phase, irrespective of the speed or type of the vehicle. This fixed hold is usually given as 5 seconds. This allows the vehicle to get onto the dilemma zone detectors where the controller recognizes it and gives it ample time to cross the intersection before the onset of red.

This system, even though reliable in ensuring a vehicle passes safely through the intersection creates inefficiency as vehicles requiring less than five seconds hold time in order to cross the intersection safely still have five seconds. A result of this is that within those five seconds, other vehicles may arrive on the advanced detector with a continuing holding of the green phase until a "max out" occurs, with side street traffic being unnecessarily delayed. Thus the number of holds is likely to be high.

Level 2 Technology

The main feature of Level 2 technology is the measurement of individual vehicle speeds, and hence travel time, across the upstream, ADA and BDA detectors.

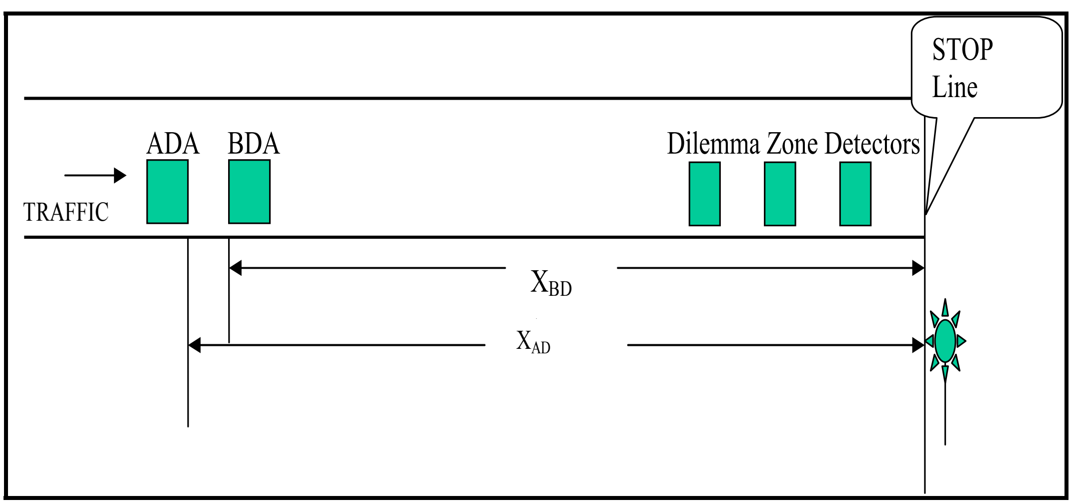

Figure 2.8 Determining Speeds of Individual Vehicles in AWEGS

Figure 2.8 shows a typical layout of the upstream ADA and BDA detectors. The speeds of individual vehicles can be calculated from:

$$v_i(t) = \frac{X_{AD} - X_{BD}}{ttAB_i}$$

where:

$v_i(t)$ = speed of vehicle *i*;
X_{AD} = Distance of upstream ADA detector from stop line;
X_{BD} = Distance of upstream BDA detector from stop line; and
$ttAB_i$ = Travel time of vehicle *i* from ADA to BDA detector.

In Level 2, a variable hold is placed on the phase to accommodate a vehicle between the BDA detector and the first dilemma zone detector if and when necessary. This variable hold is calculated for each vehicle based on the vehicle's speed (or travel time) and estimated dilemma zone. The placement of the advanced detectors ADA and BDA ensure that trucks are identified and their special dilemma zone properties accounted for. Recommended head-to-head spacing between the ADA and BDA inductive loop detectors is 30 feet as shown in given in Figure 2.9. This should be long enough to provide accurate travel time measurement. The gap spacing between the detectors should be able to differentiate between a large car and a small truck. The recommended spacing between the detectors is 24 feet, which also accommodates the computer's scanning process.

The AWEGS system needs an accurate estimation of the time gap between arriving vehicles as well as the signal controller's effective critical gap for the given dilemma zone detector arrangement and passage gap set in the controller for the phase. The problem of predicting if and when the downstream traffic actuated signal controller may gap out an existing green phase between arriving vehicles involves firstly being able to forecast the likely critical passage gap and then predicting the actual gap once the next arriving vehicle is detected.

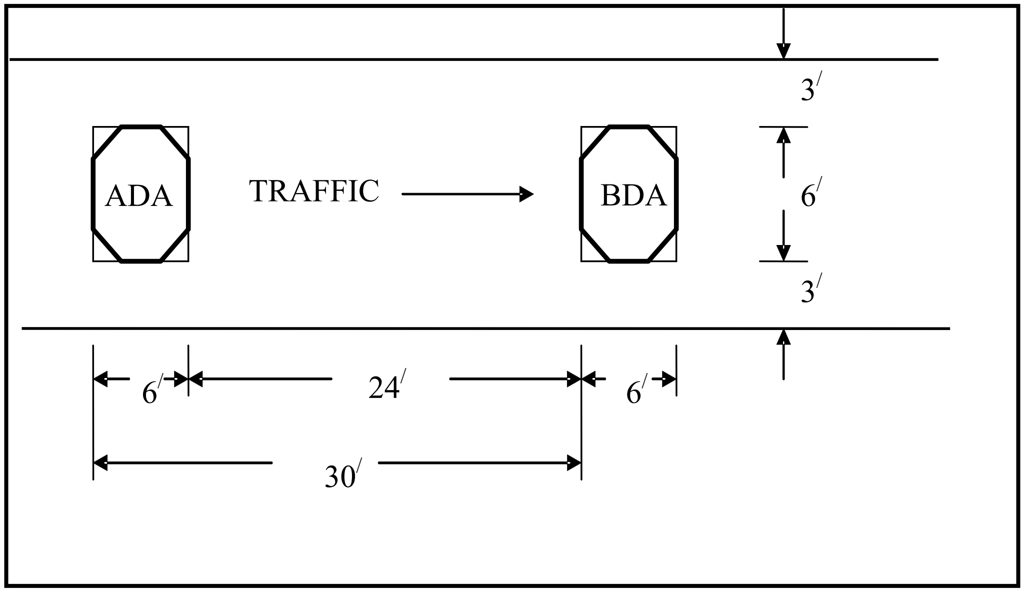

Figure 2.9 Proposed AWEGS Advanced Detector Spacing and Dimensions

Layout

A detailed layout of the AWEGS system is shown in Figures 2.10 and 2.11 for Brenham and Figure 2.12 for the installation in Waco. These show the positioning of advanced detector loops and dilemma zone detectors.

Significance of AWEGS over Previous Applications

The notable advantage of the AWEGS system lies in its ability to determine the individual dilemma zones of vehicles. This helps eliminate unnecessary holds occurring in the fixed hold state of the Level one deployment, displayed for a user specified duration. A description of this proposed Level 2 technology follows.

The safety benefit of green extension can be removed if the phase is extended to its maximum green setting (i.e. max out). The probability of this type of green interval termination is dependent on flow rate in the subject phase and the Maximum Allowable Headway (MAH). The MAH is the largest headway in the traffic stream that can occur and still sustain a continuous extension of the green interval.

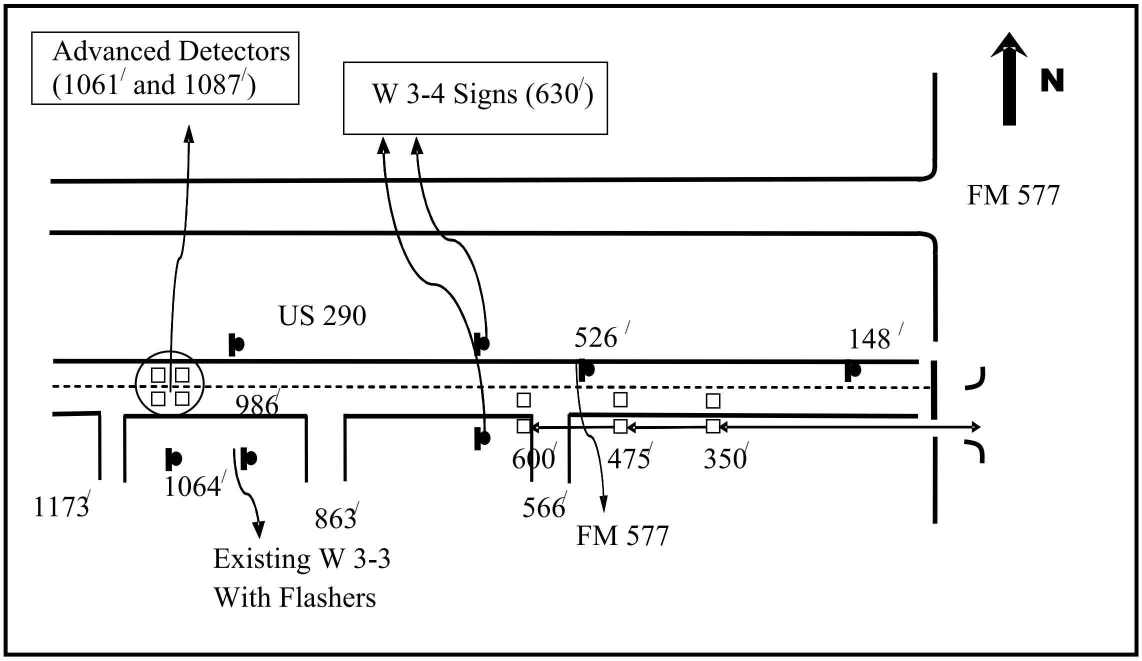

Figure 2.10 Layout of Eastbound Approach at Brenham

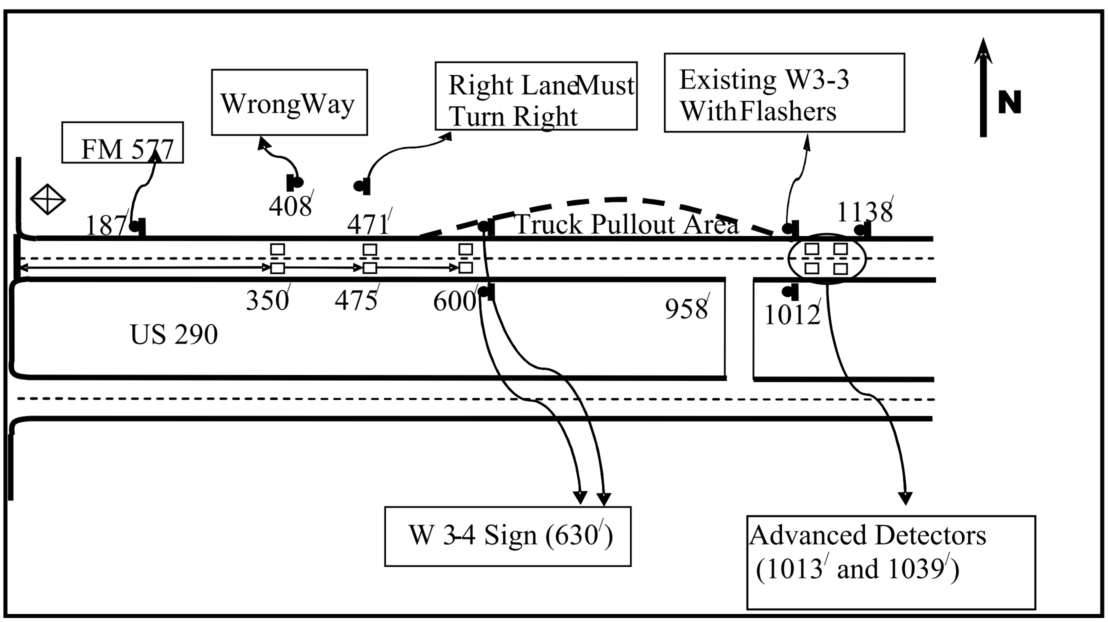

Figure 2.11 Layout of Westbound Approach at Brenham

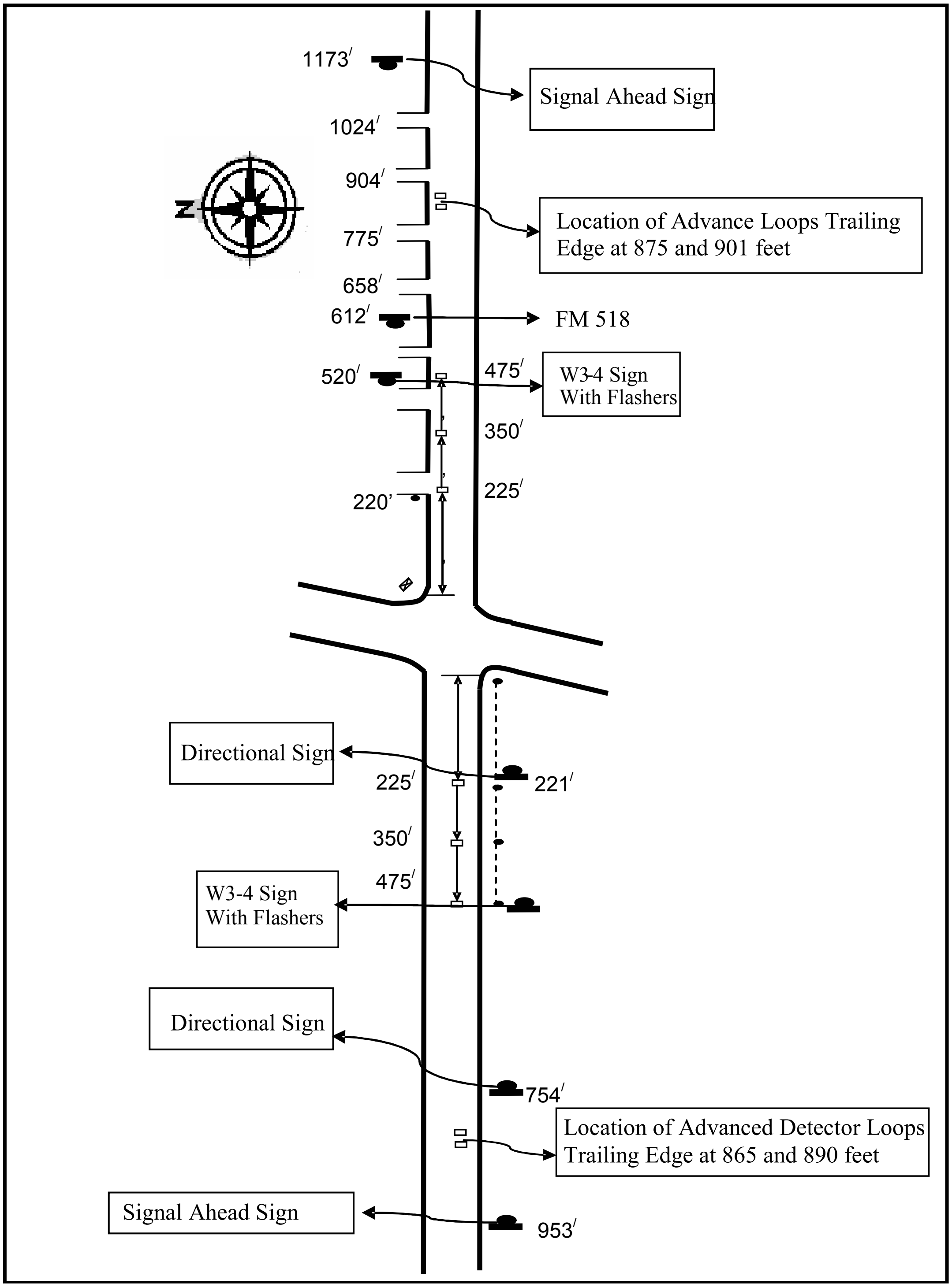

Figure 2.12 Layout of Approaches at Waco

Data Collection in AWEGS

This was done by means a computer program that logged in actuations of detectors in the field. The AWEGS system collects some of the events it monitors and also the decisions it makes, based on these events, into log files for system verification and evaluation. The collected data is written into two log files named with file extension formats of either *.vda* or *.ada*. The *.vda* file collects events and data necessary for evaluating the phenomenon of red-light-running at the intersection during the period before and after system installation. On the other hand, the *.ada* log file documents the decisions made by the system and most of the intersection and controllers events the AWEGS system monitors. Thus the passage of vehicles was identifiable in such files, which were converted into Microsoft Excel files. In addition to this, the current status of the advanced warning flashers and the traffic signal itself were logged into these files as well.

The red light running problem before the installation of the AWEGS system was measured by means of surrogate methods at TX HWY 6 / FM 185 intersection in Waco. Events logged into these *.vda* files included timestamps for actuations of the loops provided by the video imaging system installed at the site. Each main-street monitored approach has two video loops. The first video loop is located just downstream of the stop-bar (~ 5-10 ft) while the second video loop is located further downstream of the stop-bar (~ 30 – 50 ft). Each pair of video loops associated with a main-street approach is used to detect red-light-runners.

The *.vda* file also contained time actuations for the beginning of the green, yellow, all-red, and red intervals of main-street phases. Also contained in this *.vda* file are counts of vehicles detected by the first of the video loops pair, associated with the approach, during the green, yellow, all-red, and red intervals of the main-street phases. A Video Imaging Vehicle Detection System (VIVDS) located at the intersection was used. An example of this is shown in Figure 2.13 for Waco. Figures 2.14 and 2.15 show the layout of the video detection zones in Waco and Brenham, respectively.

Figure 2.13 Video Imaging Vehicle Detection System at Waco

Before and After Study Results on Red-Light-Running

Waco

The study period before AWEGS was conducted from October 19, 2002 to November 2, 2002. After the deployment of Level one technology, three different periods of After studies were done in the months of December and March/April. These periods were specifically from December 4 - 17, 2003; December 18 – 31; 2002; and March 26 to April 3, 2003. Thus, for a total of 35 days after the installation of the AWEGS system, data were collected to analyze the impact of the Level 1 system on RLR. After Level two technology deployment, data was collected for the period between July 16, 2003 and August 9, 2003 for a total of 21 days.

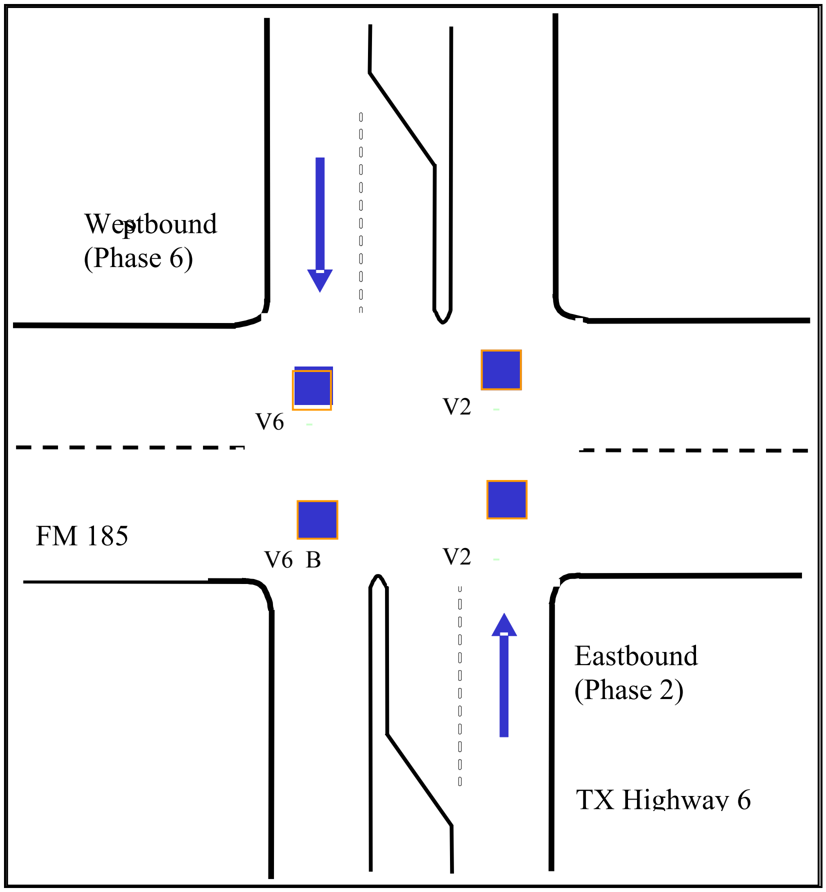

Figure 2.14 Video Detection Zones at Waco Intersection

Initial analysis of red-light-running data showed significant reductions in red-light-running events as showed in Table 2.3 below. (*36*). There was a rate of 8.62 red–light-runners per day for the period of study before the installation of AWEGS. After the first installation of AWEGS, 4.69 runners per day were recorded during Level 1. This is a statistically significant 45 percent reduction in RLR. The Level 2 deployment also was very effective, producing only 5.24 RLR per day, or nearly a 40 percent reduction.

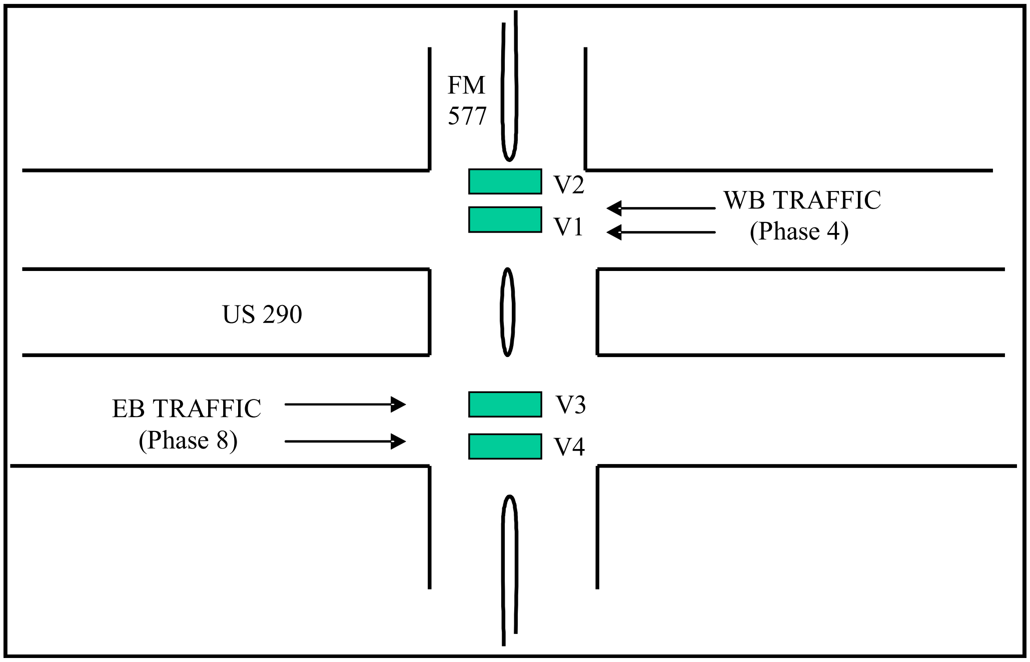

Figure 2.15 Video Detection Zones at Brenham Intersection

Table 2.3 Results of Red-Light Running in Waco (*36*)

		Time Period		Actual Count			Rate/day		
Study Period	**No. of Days**	**From**	**To**	**Red Clear.**	**Real Red**	**Total**	**Red Clear.**	**Real Red**	**Total**
Before	13	10/19/02	11/2/02	93	19	112	7.15	1.46	8.62
Level 1	35	12/4/02	4/3/03	135	29	164	3.86	0.83	4.69
Level 2	21	7/19/03	8/8/03	96	14	110	4.57	0.67	5.24

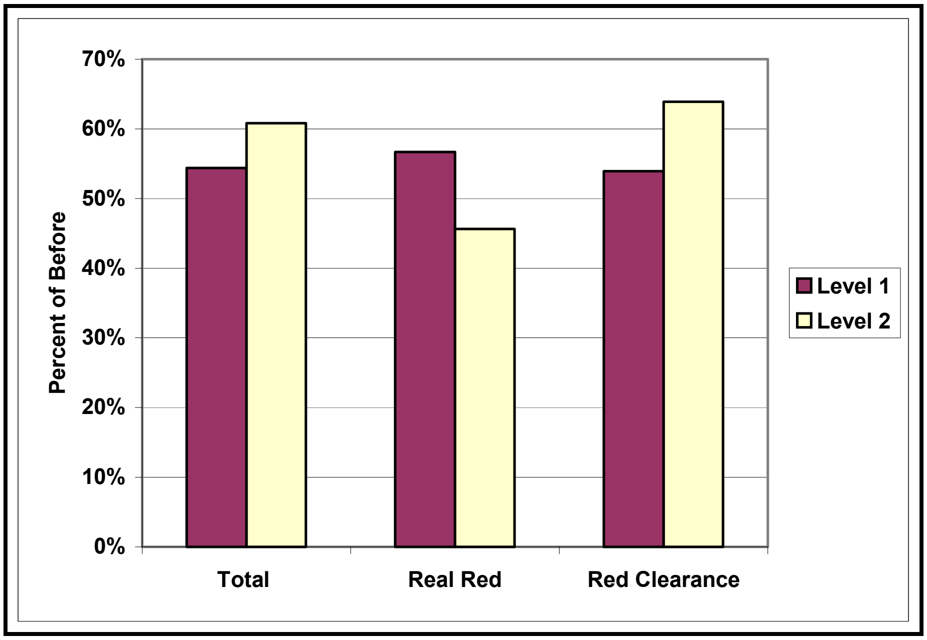

Figure 2.16 Reduction in Red-Light-Running in Waco

Figure 2.16 provides a summary of reductions in red-light-running and shows that the Waco site experienced significant reductions in RLR of 45 and 40 percent for the Level 1 and Level 2 study cases, respectively, as compared to the Before condition without AWEGS. A look into the nature of these reductions shows that the Level 2 reductions of RLR in real red (i.e. for 3.5 seconds into the real red) was 45 percent, or about 10 percent higher than in Level 1. On the other hand, the reduction in RLR during red clearance (with duration of 1.5 seconds) was about 10 percent higher in Level 1 deployment than in Level 2. Since there were overall reductions in RLR, one can presume that more traffic was diverted out of the real red zone to stop, than out of the red clearance.

Brenham

The red-light-running (RLR) phenomenon at the intersection of FM 577 and US 290 in Brenham was conducted over a two-month period. Twenty-one days prior to the installation of the AWEGS system (in May 2003), data were collected to determine the level of RLR at the intersection. Approximately one month after the installation of the system (during July and August 2003 near the end of the research project), data were collected and analyzed for 21 days to determine the effect of the AWEGS system on the red-light-running events. Table 2.4 contains a summary of the results for both periods of data collection.

Table 2.4 Summary of Red-Light Running in Brenham (*36)*

Study Period	No. of Days	Time Period		Actual Count			Rate/day		
		From	To	Red Clear	Real Red	Total	Red Clear	Real Red	Total
Before	**21**	5/3/2003	5/30/2003	1475	404	1,879	70.24	19.24	89.48
After	**21**	7/17/2003	8/12/2003	859	200	1,059	40.90	9.52	50.43

Figure 2.17 shows the percent reduction in red-light-running obtained after the deployment of Level 2 AWEGS technology in Brenham. It showed an almost 45% reduction in total red-light-running with a reduction of 50% in vehicles running the light during the real red period (3.5 seconds after the end of all red period).

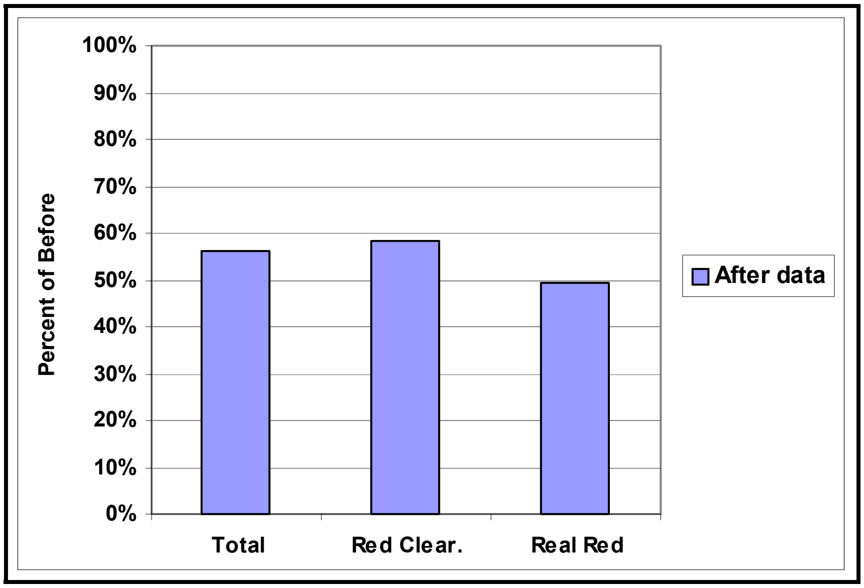

Figure 2.17 Reduction in Red-Light Running in Brenham

CHAPTER III

STUDY METHODOLOGY

STUDY SITE SELECTION

As discussed earlier, the sites used to conduct this research were located in Texas. One was the intersection of Texas 6 and FM 185 about six miles west of Waco. Existing dilemma zone detection here was a more widely but uniformly spaced version of Nader's Guide for 60 mph. One advance warning AWEGS sign was provided for each high-speed approach of Texas 6.

The second study site was at the signalized intersection of US 290 and FM 577 along the US 290 bypass in southeast Brenham. This is a four-lane divided road. Two advance warning signs, one on each side of the roadway, were placed for each approach of US 290, as shown in Figure 3.1 below.

Figure 3.1 Westbound US 290 Approach in Brenham After AWEGS Installed

DATA COLLECTION

The data used for this research was the same data collected during the initial analysis of AWEGS. The only addition being the site measurement of distances between the VIVDS detection zones at the stop lines of approaches in Waco. This helped determine the speeds of vehicles as they crossed the intersection. Figure 3.2 below shows the measurements that were taken and the respective distances. Two measurements of each distance were made and an average taken. The distance from A6 to B6 detection zones for phase 6 (Westbound) was measured as 74.1 feet and that from A2 to B2 for phase 2 (Eastbound) was determined to be 59.4 feet.

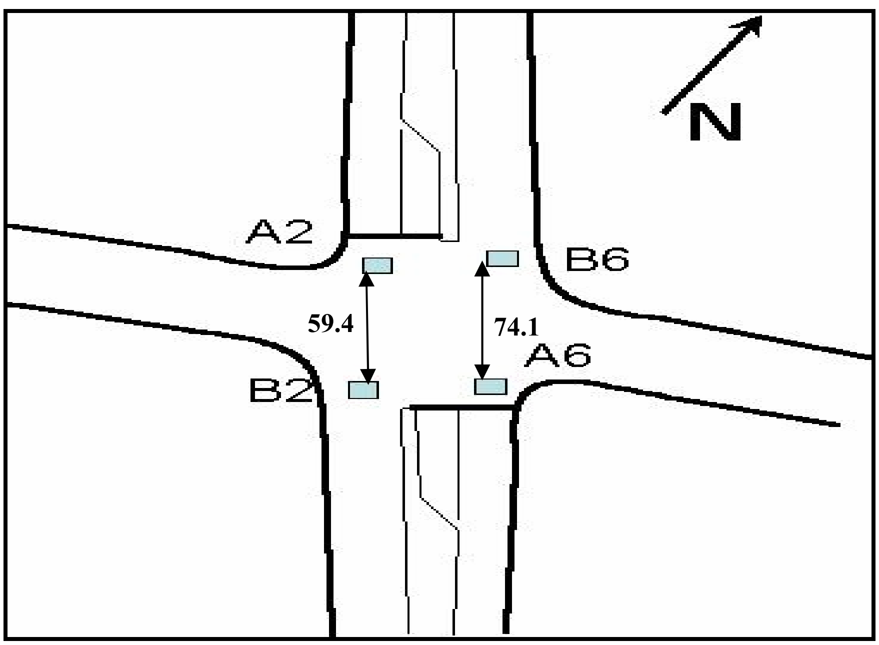

Figure 3.2 Distances Between VIVDS Detection Zones at Waco

A similar analysis was not done for Brenham due to the nature of video detection/monitoring used in Brenham did not allow for a feasible determination of distances between the detection zones and hence determination of speeds. While Waco had two distinct detection zones per approach, Brenham used one detection zone per approach, and without knowledge of the length of approaching vehicles it was virtually impossible to determine speeds of vehicles as they crossed the intersection during the red phase.

DATA ANALYSIS

The first analysis on nighttime vs. daytime was done for both AWEGS deployment sites; however, speeds determination was focused solely on the deployment in Waco. This was because the nature of video detection/monitoring used in Brenham did not allow for a feasible determination of speeds, as discussed previously.

Since the system relied on data logged into the computer system with only a sample of actual recording and verification, a definition of red light running had to be obtained. This was done by finding the distribution of the presence times of vehicles on the video detectors as well as the distribution of the times vehicle spent between detector actuations. From these plots the criteria for defining a red-light-running event were used. These were the same as that used in the initial deployment of AWEGS.

Development of Red-Light Running Criteria

Prior to the installation of the AWEGS system, red-light running data were collected and reduced to obtain the number of red light runners for each day. A plot of the actuations of passage times of vehicles was made to determine the nature of the distribution of these data in order to determine an appropriate range of passage times on detectors and to distinguish between a high-speed vehicles going across the intersection during a red signal from some other event. These other events included vehicles from the cross street that actuate the second video detector and any opposing left turn vehicles that may trigger an actuation from the first detector.

Based on these plots, the researcher realized that about 80 percent of detection presence times were between 200 and 600 milliseconds. Red-light running constitutes a traffic violation that occurs when a motorist enters an intersection (often deliberately) some time after the signal light has turned red. Motorists who inadvertently enter an intersection when the signal changes to red when waiting to turn, for example, aren't red-light-runners. A defined period of time of five seconds after the start of red clearance was used to measure red-light running.

Thus, together with the nature of the placement of video detectors and speeds of vehicles, the red-light running event was defined as follows:

- Any vehicle crossing the stop line (from the input side of the first through VIVDS detector) during red clearance; or
- Any vehicle crossing the stop line during real red following red clearance, timed from the start of real red until 5 seconds of red display had elapsed, where the initial time on this clock starts at start of red clearance; and
- A crossing was defined as the first (A) detector being briefly activated followed within 2 seconds by its trailing (B) detector briefly coming on. “Briefly” was defined by a detector presence time between 0.2 and 0.6 seconds, as noted above.

These conditions were used partly to separate true red-light runners from other (false) events like cross street and main street left-turning vehicles who inadvertently trigger one of the video detectors during red. However, in Brenham, there was only one video detector available for each approach, thus the third criterion was altered to account for the fact there was no trailing detector.

AWEGS Treatment – Before vs. After

The effect on red light running events observed during the installation and operation of AWEGS was measured using three main measures of effectiveness in this research. Brenham had a Before and After (Level 2) period only.

Table 3.1 Study Conditions for AWEGS Treatment

Site	Before	AWEGS	
		Level 1	Level 2
Waco	X	X	X
Brenham	X		X

Red Light Running Rates per Exposure

The three measures of effectiveness was used to obtain an idea of the exposure rate and provide a better reference for the red light running rates determined. Suggested exposure rates found in the literature include a per 100 cycle, per 1,000 vehicle and a per 10,000 veh-cycle rate (*5*). Thus, all three measures were computed and some comparison done to determine the most appropriate measure to use.

Daytime vs. Nighttime

This section of the research effort involved the determination and comparison of red-light-running rates during daytime and nighttime. To determine these rates, a decision had to be made as to what was considered "daytime" and what would pass for "nighttime". This was especially important depending on the goal of the project. What may pass for daytime may be important with regards to the human factors or performance of drivers, but it may not be relevant in terms of the effects of traffic volumes. However, it was impossible to go to each day and determine when the start of the peak period was and how much it varied from the start of sunset.

To simplify matters, the times for sunset and sunrise were obtained from the U.S. Naval Observatory website for each day of the red light running period recorded, and these times were used to determine the corresponding rates. A check was made, however, to verify the differences or otherwise in the typical morning / afternoon peak period hour and the corresponding sunrise / sunset times. It was observed that in most cases, sunrise occurred before the typical morning peak hour while the last two events coincided (i.e. sunset/afternoon peak hour). The daytime rates and night time rates were then determined using Microsoft Excel.

Nature of Red-Light Runners

Entry Time of Red-Light Runner

The time after the end of the yellow indication (start of all red), at which a red-light-runner enters the intersection, is logically related to the potential for a right-angle collision. It is likely that, with the increase in this "time into red", crash frequency will increase. For instance, drivers who enter the intersection, say 0.5 seconds after the end of yellow indication, are less likely to encounter conflicting vehicles because these vehicles would typically not have started to move into the intersection. This is especially true if there is an all-red interval (which was the case for the two study site intersections with a 1.5-second all-red interval). The threat of entry of conflicting vehicles thus increases, as the existing all-red time is used up.

Speeds of Vehicles

To determine the nature of red-light runners and provide a better understanding of the initial red-light-running rates obtained in the earlier study, the speeds of individual vehicles was determined. To determine the speeds of these vehicles it was necessary to find some measurement of distances covered between the detection zones.

This was especially difficult as attempts to mark out the detection zones were extremely difficult to do due to the spatial and angled nature of the video detection zones. The best way was to determine the moment at which the front of approaching vehicles trigger the first video detector (the ON) and the same for the trigger of the second video detector. Two measurements were taken of the detection zone distances for each approach and the average of these distances was determined. Thus, using the time gap between the ON – ON times of the two detections, the speeds of vehicles as they cross the stop line were determined.

In relation to speeds, there were three main measures that were determined to provide an insight into the effect of AWEGS on the speeds of vehicles. These were:

- Reduction in Mean Speeds of Red-Light Runners;
- Percent of Red-Light-Runners above Speed Limit; and
- The Variation of Speeds with Time into Red.

CHAPTER IV

STUDY RESULTS

DATA RESULTS AND ANALYSIS

The results of the data reduction are presented in this section. Two main areas will be presented including the effect of AWEGS as well as the nature of red-light-runners. The data will be presented in the following format:

- Selection of MOE

An appropriate MOE will be selected and used for RLR comparison purposes.

- AWEGS Treatment

The effect of AWEGS on total RLR rates are provided for with comparisons among the Before and Levels 1 and 2 periods in Waco as well as the Before and Level 2 comparison in Brenham.

- Day vs. Night Comparison

Comparison of day vs. night RLR rates are presented as well as the effect of AWEGS on the reduction or otherwise of these rates by time of day.

- Nature of Red-Light-Runners

Under this section, two main sections are presented. The first contains results of RLR and time into red that the light was run. The other section analyses the speeds of vehicles that run the red light with results on the difference in mean speeds, percentage of speeds above the speed limit as well as the variation of speeds with time into red.

Measures of Effectiveness (MOEs)

For the purposes of this research an effort was made to determine the most appropriate measure of effectiveness to use in the analysis of changes in red-light-running (RLR) rates due to the AWEGS treatment. These measures of effectiveness analyzed included RLR per 100 cycles, per 1,000 vehicles and per 10,000 veh-cycles. Plots of RLR rates for the three different measures of effectiveness were done to give an indication of how they compared in the analysis of various treatment levels. Figures 4.1 and 4.2 show plots of Total RLR rates of Before vs. Levels 1 and 2 in Waco for the three MOEs for the Eastbound (Phase 2) and Westbound (Phase 6) respectively. In the Figures, M1, M2 and M3 represent RLR per 100 cycles, 1,000 vehicles and 10,000 veh-cycles respectively. M3 rates have been multiplied by 100 for scaling purposes.

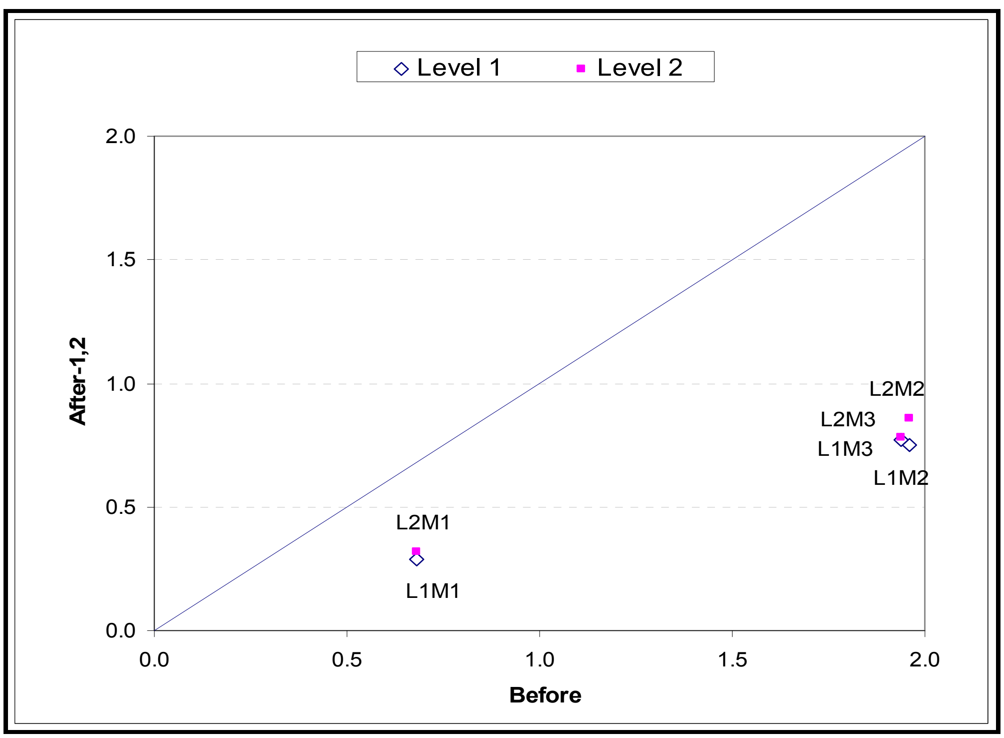

Figure 4.1 Comparing Different MOEs for Eastbound (Phase 2) in Waco

From Figure 4.1, MOE M2 (per 1,000 vehicles) provided the most difference between Level 1 and Level 2, while in Figure 4.2 M2 was the only measure to show higher RLR rates for Level 2 than Level 1. A per 100 cycles usage (M2) gives better RLR rate reduction for Level 2 compared to Level 1 (which might be due to the higher number of cycles per day recorded during Level 2 as compared to Level 1) indicating a likely bias for Level 2. The use of M3 (per 10,000 veh-cycles) seems to provide an average of M1 (per 100 cycles) and M2 (per 1,000 vehicles). It lessens the effect of any biases that might exist in using either a per 100 cycle or a per 1,000 vehicle measure. For the purposes this section on comparing RLR rates for the different periods of study, a per 10,000 veh-cycle MOE will be used. Values for the other three measures are given but not used to determine the reduction or otherwise in RLR rates.

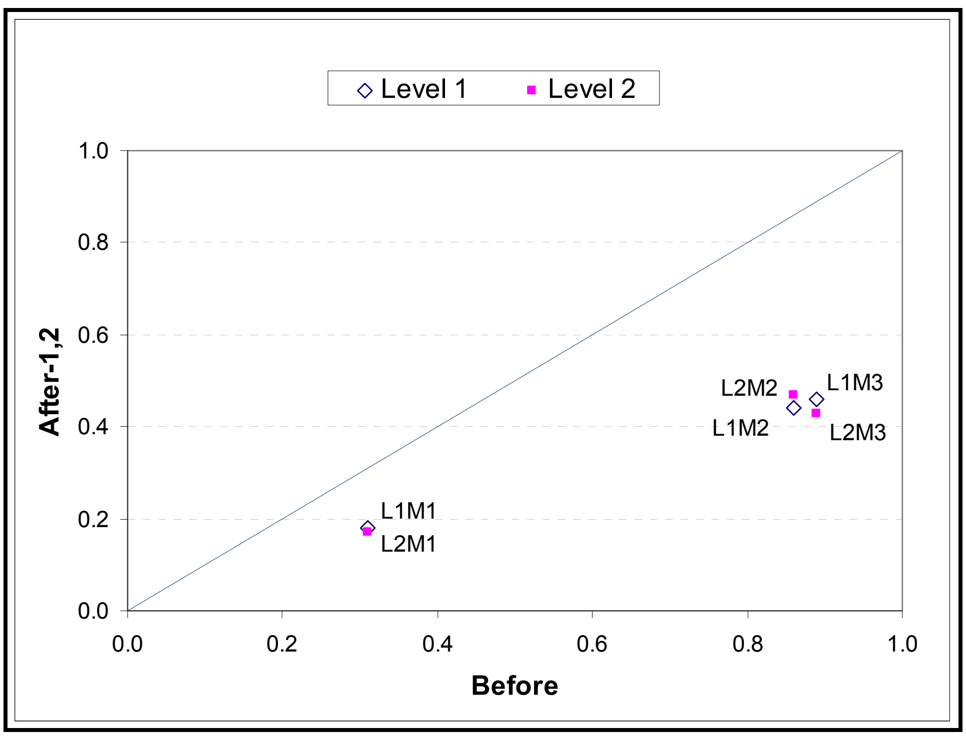

Figure 4.2 Comparing Different MOEs for Westbound (Phase 6) in Waco

AWEGS Treatment – Before vs. After

The red-light-running rates were computed for the two study sites near Brenham and Waco. These were expressed in three different rates of per 100 cycles, per 1,000 vehicles, and per 10,000 vehicle-cycles. The effect of AWEGS on the RLR rates was determined for Brenham and Waco.

Brenham

Table 4.1 below summarizes the red-light-running rates obtained for the two study periods conducted at the intersection of US 290 and FM 577 in southeast Brenham. This summary contains data depicting the total rates for the two approaches on US 290. To determine the rates per time of day, the sunset and sunrise times previously discussed were utilized and the results are displayed in Table 4.3. A total of 21 days in May was collected for the data before installation of AWEGS and another 21 days of data collected from July and August for the analysis of the post-AWEGS installation (Level 2 deployment). From the results in Table 4.1, it can be seen that red-light-running events per 10,000 veh-cycles was reduced for both approaches by about 50% in phase 8 and about 30% in phase 4. Table 4.1 show percent reductions for the different MOEs. The percent reductions are shown in parentheses.

Waco

Similar analysis of Before and After was done for Waco. Deployment of AWEGS in Waco was done at two levels of technology. Results for the Level 1 and Level 2 periods are both presented and compared with the Before period. Table 4.2 gives a summary of the total RLR rates for the three periods of study. From the table it can be seen that the highest reduction in RLR rates (60%) occurred during Eastbound (phase 2) AWEGS deployment (Levels 1 and 2). Using a per 10,000 veh-cycle comparison, Eastbound RLR remained the same after Level 2 deployment while Westbound RLR decreased by about 6%. The figures in parentheses are the percent reductions from Before.

The RLR per MOE results compared to the initial results in AWEGS (see Table 2.3) showed that when RLR was expressed as a per MOE rate, Level 2 performed much better. Initial results showed that total (for both approaches) RLR increased by about 12% (4.69 to 5.24 per day). Using a per 10,000 veh-cycle MOE, total RLR (for both approaches) actually decreased by about 2% (0.0123 to 0.0121 per 10,000 veh-cycles) showing an almost 14% change from the initial results. See Appendix A for summary of observations on number of vehicles and number of cycles at the intersection.

Table 4.1 Summary of Red-Light-Running Rates, Brenham

Study Period	Intersection Approach	Red-Light-Running Rate		
		Per 100 cycles	*Per 1,000 vehicles*	*Per 10,000 veh-cycles*
Before	Phase 4	*2.63*	*2.44*	*0.027*
	Phase 8	*10.36*	*7.46*	*0.117*
After (Level 2)	Phase 4	*1.76 (33)*	*1.85 (24)*	*0.019 (29)*
	Phase 8	*5.07 (51)*	*3.87 (33)*	*0.059 (50)*

() - Percent reduction from Before

Daytime vs. Nighttime

Brenham

In the daytime vs. nighttime analysis, there were large reductions in phase 8 for all measures of effectiveness and all daytime and nighttime rates. The largest reduction of 50% was during phase 8 nighttime while the lowest reduction of 12% was on phase 4 nighttime. Table 4.3 gives a summary of RLR rates for daytime and nighttime while Table 4.4 gives a summary of day vs. night comparison, and shows that phase 4 night rates were higher than day rates while phase 8 night rates were lower than day rates for both Before and After periods using an MOE of per 10,000 veh-cycles. All other MOEs had higher day RLR rates than night RLR rates. See Appendix for detailed results of observations of nighttime and daytime cycles and vehicles.

Table 4.2 Summary of Total Red-Light-Running Rates, Waco

Study Period	Intersection Approach	Red-Light-Running Rate		
		Per 100 Cycles	***Per 1,000 Vehicles***	***Per 10,000 Veh-Cycles***
Before	**Phase 2**	*0.68*	*1.96*	*0.0194*
	Phase 6	*0.31*	*0.86*	*0.0089*
Level 1	**Phase 2**	*0.29 (57)*	*0.75 (62)*	*0.0077 (60)*
	Phase 6	*0.18 (42)*	*0.44 (49)*	*0.0046 (48)*
Level 2	**Phase 2**	*0.32 (53)*	*0.86 (56)*	*0.0078 (60)*
	Phase 6	*0.17 (45)*	*0.47 (45)*	*0.0043 (52)*

() - Percent reduction from Before

Analysis of Variance (ANOVA) tests were performed on RLR rates per 10,000 veh-cycles for the differences observed after the installation of AWEGS, for both the total and the nighttime and daytime rates. In Brenham, all reductions from Before to After (Level 2) were found to be significant with the only exception being Westbound (Phase 4) nighttime RLR rates. Refer to Appendix for details of the ANOVA tests. Table 4.5 gives a summary of RLR reduction for the Total, Daytime and Nighttime for Brenham.

Table 4.3 Summary of Day vs. Night Red-Light-Running Rates, Brenham

Study Period	Time of Day	Intersection Approach	Red-Light-Running Rate		
			Per 100 Cycles	*Per 1,000 Vehicles*	*Per 10,000 Veh-Cycles*
Before	**Daytime**	**Phase 4**	*3.80*	*2.51*	*0.048*
		Phase 8	*12.99*	*8.69*	*0.189*
	Nighttime	**Phase 4**	*1.03*	*2.14*	*0.056*
		Phase 8	*3.54*	*3.18*	*0.179*
After (Level 2)	**Daytime**	**Phase 4**	*2.42 (36)*	*1.96 (22)*	*0.032 (33)*
		Phase 8	*6.95 (47)*	*4.36 (50)*	*0.103 (46)*
	Nighttime	**Phase 4**	*0.83 (19)*	*1.96 (8)*	*0.049 (12)*
		Phase 8	*1.72 (51)*	*2.13 (33)*	*0.090 (50)*

() - Percent reduction from Before

Table 4.4 Results of Day vs. Night RLR Comparison for Brenham

Approach	Period	RLR per 10,000 veh-cycles
Phase 4	**Before**	N>D
	After	N>D*
Phase 8	**Before**	D>N
	After	D>N

D – daytime; N – nighttime; * - significant at the 95% confidence level

Table 4.5 Results of RLR Comparison for Brenham

Comparison Periods	Type of Comparison	Per 100 cycles	Per 1,000 vehicles	Per 10,000 veh-cycles
Phase 4	Total	D	D	D*
	Daytime	D	D	D*
	Nighttime	D	D	D
Phase 8	Total	D	D	D*
	Daytime	D	D	D*
	Nighttime	D	D	D*

D – decrease; I – increase; S – no change; * - significant at the 95% confidence level

Waco

The red-light-running events at the intersection of Texas Highway 6 and FM 185 was separated into nighttime and daytime rates and compared as shown in this section. Table 4.6 shows RLR rates for Before and Level 1 for all MOEs. Comparing the nighttime versus daytime red-light running rates for these two study periods using RLR per 10,000 veh-cycles the following can be observed:

- In Before period, Eastbound day rates were greater than night RLR rates while Westbound night RLR rates were greater than the daytime rates,
- On both approaches, Level 1 period had higher daytime rates than nighttime rates; and
- All RLR rates for both day and night were reduced from Before to Level 1 with the largest reduction in nighttime Westbound (phase 6).

Table 4.6 Summary of Day vs. Night Red-Light-Running Rates (Before and Level 1)

Study Period	Time of Day	Intersection Approach	Red-Light-Running Rate		
			Per 100 Cycles	*Per 1,000 Vehicles*	*Per 10,000 Veh-Cycles*
Before	**Daytime**	**Phase 2**	*0.90*	*2.25*	*0.0348*
		Phase 6	*0.31*	*0.75*	*0.0121*
	Nighttime	**Phase 2**	*0.29*	*1.16*	*0.0318*
		Phase 6	*0.32*	*1.16*	*0.0325*
Level 1	**Daytime**	**Phase 2**	*0.42*	*0.92*	*0.0152*
		Phase 6	*0.25*	*0.53*	*0.0089*
	Nighttime	**Phase 2**	*0.09*	*0.31*	*0.0083*
		Phase 6	*0.06*	*0.20*	*0.0053*

Tables 4.7 shows the daytime and nighttime red-light-running rates for Before and Level 2 study periods. It can be observed that, all RLR rates were reduced from the Before to Level 2 periods. Using a per 10,000 veh-cycle MOE, the largest reduction was observed on the Eastbound (phase 2) day RLR rates which was reduced by almost 70%. The least reduction occurred in nighttime RLR rates on the Eastbound (phase 2) approach. In addition to this, it can be observed that nighttime rates were higher than daytime rates for both approaches during Level 2 deployment. Figure 4.4 depicts graphically the RLR rates for the Before and Level 2 periods. Figures 4.3 to 4.5 show a plot of Before and Level 1, Before and Level 2 and Level 1 and Level 2 daytime and nighttime rates per 10,000 veh-cycles. The rates have been scaled up by 10^2 for ease of plot. On these plots, D represents day and N night, while 2 and 6 represent the phases.

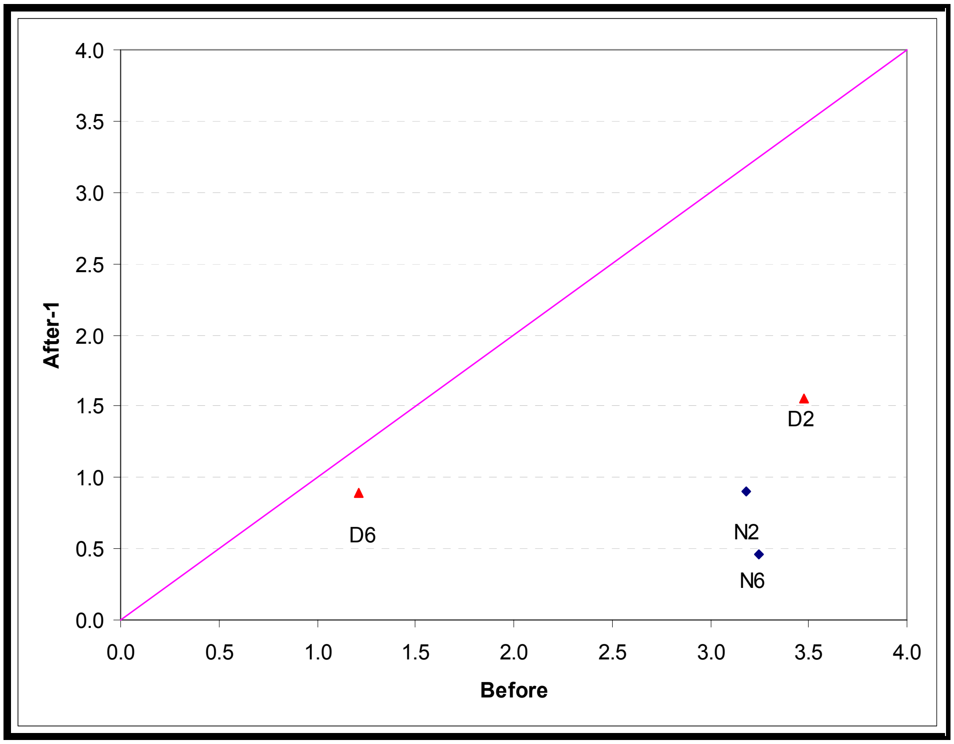

Figure 4.3 Day vs. Night RLR – Before vs. Level 1

Table 4.8 shows the daytime and nighttime red-light-running rates for Level 1 and Level 2 study periods. The following can be observed from the Table using an MOE of per 10,000 veh-cycles:

- Eastbound (phase 2) daytime RLR rates were reduced by about 30% from Level 1 to Level 2;
- Westbound (Phase 6) daytime rates were reduced by almost 35% from the Level 1 to Level 2; and
- Nighttime rates increased on both approaches from Level 1 to Level 2.

Figure 4.5 depicts graphically the RLR rates for the Level 1 and Level 2 periods.

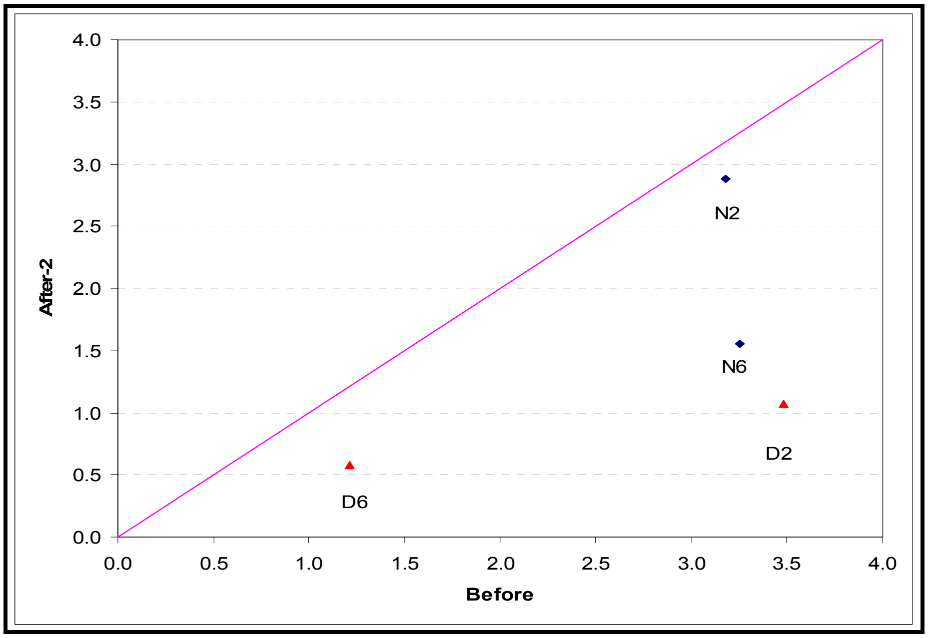

Figure 4.4 Day vs. Night RLR – Before vs. Level 2

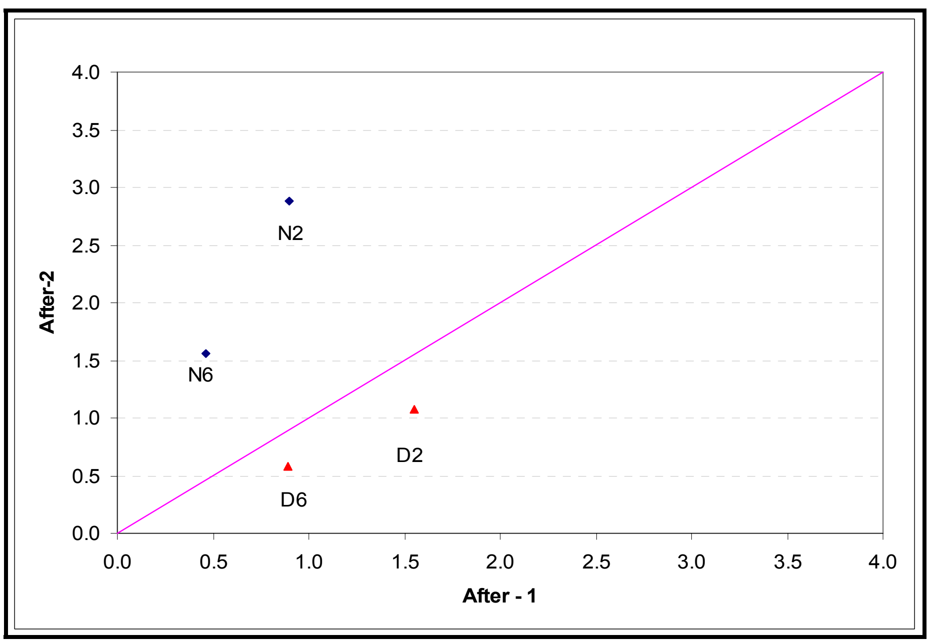

Figure 4.5 Day vs. Night RLR – Level 1 vs. Level 2

Table 4.9 and 4.10 gives a summary result of AWEGS treatment on RLR reduction for the Total, Daytime and Nighttime rates on the Eastbound and Westbound approaches respectively. From Tables 4.9 and 4.10, the following can be deduced:

- Reductions in RLR rates were recorded for both Levels 1 and Level 2 deployment of AWEGS for Total, Day and Night RLR rates; and
- Daytime rates for Level 1 were reduced in Level 2 deployment while nighttime rates increased.

These results are quite consistent, except in comparing Level 1 and Level 2 total RLR rates. The consistent reduction in RLR rates from Before to Levels 1 and 2 could be due to the significant reduction in actual RLR counts observed during the deployment of AWEGS. On the other hand, the seeming inconsistencies in Level 1 to Level 2 reduction could be due to the relative differences in volumes and number of cycles per day recorded as well as the slight differences in actual RLR counts.

Table 4.7 Summary of Nighttime vs. Daytime RLR Rates - Before and Level 2

Study Period	**Time of Day**	**Intersection Approach**	**Red-Light-Running Rate**		
			Per 100 Cycles	***Per 1,000 Vehicles***	***Per 10,000 Veh-Cycles***
Before	**Daytime**	**Phase 2**	*0.90*	*2.25*	*0.0348*
		Phase 6	*0.31*	*0.75*	*0.0121*
	Nighttime	**Phase 2**	*0.29*	*1.16*	*0.0318*
		Phase 6	*0.32*	*1.16*	*0.0325*
Level 2	**Daytime**	**Phase 2**	*0.36*	*0.87*	*0.0107*
		Phase 6	*0.20*	*0.48*	*0.0058*
	Nighttime	**Phase 2**	*0.20*	*0.85*	*0.0288*
		Phase 6	*0.09*	*0.44*	*0.0156*

Table 4.8 Summary of Nighttime vs. Daytime RLR Rates - Level 1 and Level 2

Study Period	Time of Day	Intersection Approach	Red-Light-Running Rate		
			Per 100 Cycles	*Per 1,000 Vehicles*	*Per 10,000 Veh-Cycles*
Level 1	Daytime	Phase 2	*0.42*	*0.92*	*0.0152*
		Phase 6	*0.25*	*0.53*	*0.0089*
	Nighttime	Phase 2	*0.09*	*0.31*	*0.0083*
		Phase 6	*0.06*	*0.20*	*0.0053*
Level 2	Daytime	Phase 2	*0.36*	*0.87*	*0.0107*
		Phase 6	*0.20*	*0.48*	*0.0058*
	Nighttime	Phase 2	*0.20*	*0.85*	*0.0288*
		Phase 6	*0.09*	*0.44*	*0.0156*

Table 4.9 Results of RLR Comparison for Eastbound (Phase 2) in Waco

Comparison Periods	Type of Comparison	Per 100 cycles	Per 1,000 vehicles	Per 10,000 veh-cycles
Before to L1	Total	D	D	D*
	Daytime	D	D	D*
	Nighttime	D	D	D*
Before to L2	Total	D	D	D*
	Daytime	D	D	D*
	Nighttime	D	D	D
Level 1 to Level 2	Total	I	S	S
	Daytime	D	D	D*
	Nighttime	I	I	I*

D – decrease; I – increase; S – no change; * - significant at the 95% confidence level

Table 4.11 sums up results of Daytime vs. Nighttime RLR rate comparison. ANOVA tests were conducted for per 10,000 veh-cycles MOE only. The results of comparison of daytime and nighttime RLR rates differ distinctly by approach and a summary is provided below:

- In the Eastbound approach (Phase 2) all daytime RLR was higher than the corresponding nighttime rates except for the Level 2 RLR per 10,000 veh-cycles which recorded higher nighttime rates;
- Westbound nighttime RLR rates were higher in the Before period (for all MOEs) while daytime rates were higher in the Level 1 period; and
- Five out of the 18 cases provided (for the three different MOEs) showed higher nighttime rates than daytime rates with four of those cases on the Westbound (Phase 6 approach).

Table 4.10 Results of RLR Comparison for Westbound Approach (Phase 6) in Waco

Comparison Period	Type of Comparison	Per 100 cycles	Per 1,000 vehicles	Per 10,000 veh-cycles
Before to L1	**Total**	D	D	D*
	Daytime	D	D	D
	Nighttime	D	D	D*
Before to L2	**Total**	D	D	D*
	Daytime	D	D	D*
	Nighttime	D	D	D*
Level 1 to Level 2	**Total**	S	I	S
	Daytime	D	D	D*
	Nighttime	I	I	I

D – decrease; I – increase; S – no change; * - significant at the 95% confidence level

Table 4.11 Results of RLR Comparison for Waco – Daytime and Nighttime

Approach	Period of Study	RLR per 10,000 veh-cycles
Phase 2	Before	D>N
	Level 1	D>N*
	Level 2	N>D*
Phase 6	Before	N>D*
	Level 1	D>N*
	Level 2	N>D

D – daytime; N – nighttime; * - significant at the 95% confidence level

SUMMARY OF LEVEL 1 VS. LEVEL 2 PERFORMANCES – SAFETY VS. EFFICIENCY

Safety vs. Efficiency

Often times, these two traffic operations goals present conflicting scenarios in any traffic engineering improvement project. This is because in achieving a safety standard, the efficiency of the system is tampered with and vice versa. This might have been observed in the upgrade of Level 1 to Level 2.

Safety

Generally, the performance of Level 1 and Level 2 were comparable over the periods of study. On the average, Level 1 produced slightly better rates than Level 2 results, especially during the nighttime. This could be due to the lower volumes meaning a more maximum allowable headway was being given to fewer vehicles that approached the intersection. Also the slightly overall higher rates during Level 2 could be due to the higher number of cycles observed during Level 2.

Significantly, despite the seeming increase in red-light-running from Level 1 to Level 2, a higher amount of red-light-running events (80%) in Level 2 occurred during the red clearance interval (refer to Figures 4.11 and 4.12).

Efficiency

The efficiency of Level 2 AWEGS deployment as compared to Level 1 deployment was determined in terms of the average cycle length over the periods of studies. Level 2 results showed the lowest average cycle length of 79 and 83 seconds on phase 2 and phase 6 respectively. This represented an almost 14% and 10% reduction for phases 2 and 6, respectively. Table 4.12 shows the average vehicular volumes, number of cycles and the average cycle lengths for the three different study periods.

The comparable volumes observed for both levels showed that Level 2 did perform more efficiently by reducing the average cycle lengths for similar and slightly heavier vehicular volumes (for phase 2 especially). This strengthens the case of a more efficient performance of the system during Level 2, but creating a slightly higher exposure level to frequency of phase terminations.

Table 4.12 Exposure Variables for Different Study Periods

	Direction	**Total**		
		Before	**Level 1**	**Level 2**
No. of Vehicles per day	**Phase 2**	3,267	3,700	4,019
	Phase 6	3,377	3,838	3,737
No. of Cycles per day	**Phase 2**	945	940	1,099
	Phase 6	939	932	1,042
Average Cycle Length (sec)	**Phase 2**	91	92	79
	Phase 6	92	93	83

NATURE OF RED LIGHT RUNNERS (TEXAS 6 @ FM 185, WACO)

Red Light Running and Time of Day

Variation of RLR with Time of Day for Different Periods of Study

This section of the results details the variation observed in the frequency of red-light-running with time of day. Figure 4.6 shows a plot of the frequency of RLR with time of day for the Eastbound (Phase 2) approach in Waco for the three different study periods. Generally, there was a peak RLR period between 8 a.m. to 10 a.m. during Level Two of the AWEGS deployment. However, a substantial percentage (8%) of RLR occurred between 8 p.m. and 10 p.m. in Level Two while the red-light-running rate percentage was less than 3% in the Level 1 and Before study periods. Generally, it can also be observed that RLR was observed throughout most of the day from 6 a.m. until about 8 p.m. A few isolated cases of RLR occurred at night after 10 p.m. with about 5% of Before RLR occurring between midnight and 2 a.m.

Figure 4.7 shows a similar plot of the Frequency of RLR with time of day but for the Westbound (Phase 6) approach on TX 6 near Waco. The frequency of RLR here was more distinct with a peak period between 4 p.m. and 6 p.m. Unlike the Eastbound (phase 2) approach; there is a gradual increase and decrease prior and after this peak RLR period. Level 1 RLR frequency was highest during the evening rush hours 4 – 6 p.m. (16 – 18 hrs) while that of Level 2 peaked at the 6 – 8 p.m. (18-20 hrs). Thus, generally the patterns in RLR for different study periods were not changed.

Variation of RLR with Time of Day for Different Approaches

It could be observed from the plots of percent frequency with time of day that the pattern of red-light-running events was different for the two approaches at Waco. This is illustrated in Figure 4.8 for Level 1 RLR distribution. It shows a more even RLR distribution for phase 2 (Eastbound approach) with a more distinct peaked shape in phase 6 (Westbound approach) shown in Figure 4.9. What these figures show again is that the RLR with time of day varied by approach.

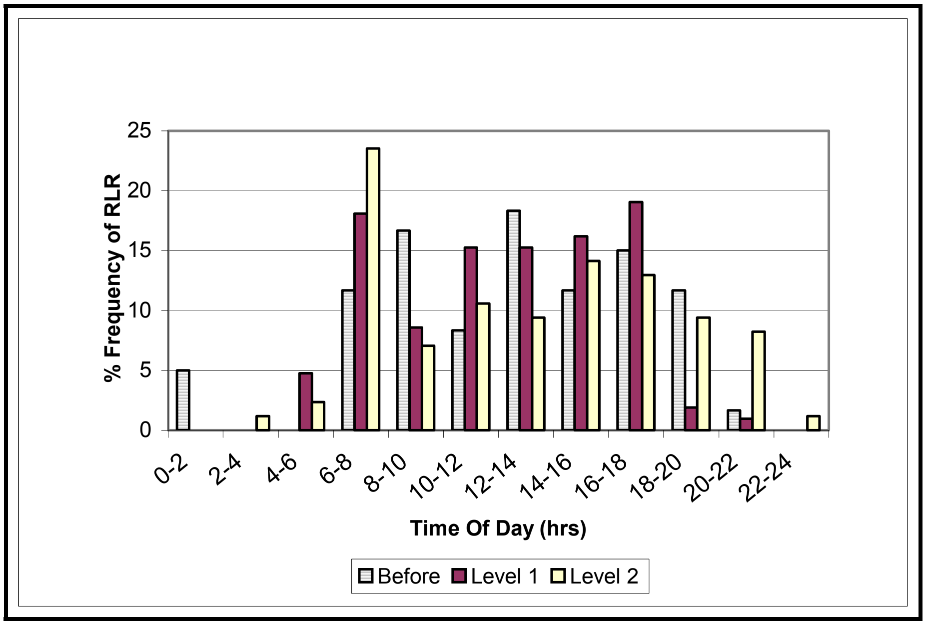

Figure 4.6 Variation of RLR with Time of Day for Phase 2

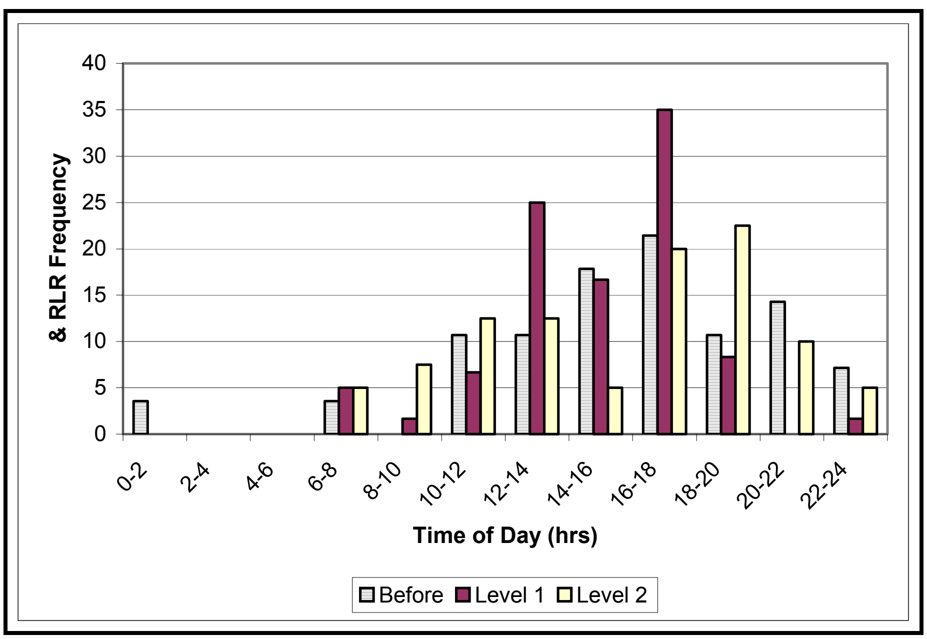

Figure 4.7 Variation of RLR with Time of Day for Phase 6

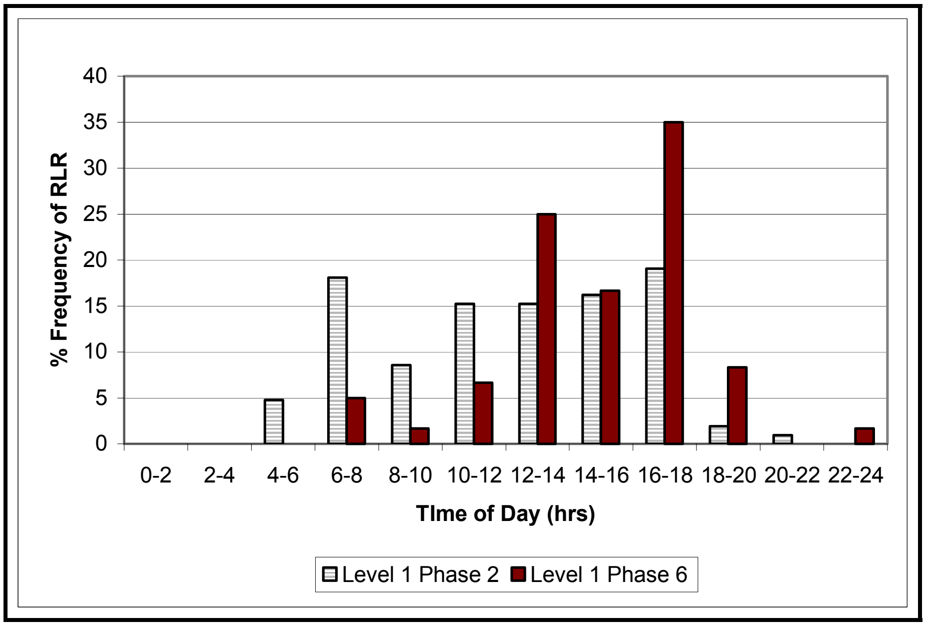

Figure 4.8 Variations in RLR with Time of Day for Different Approaches – Level 1

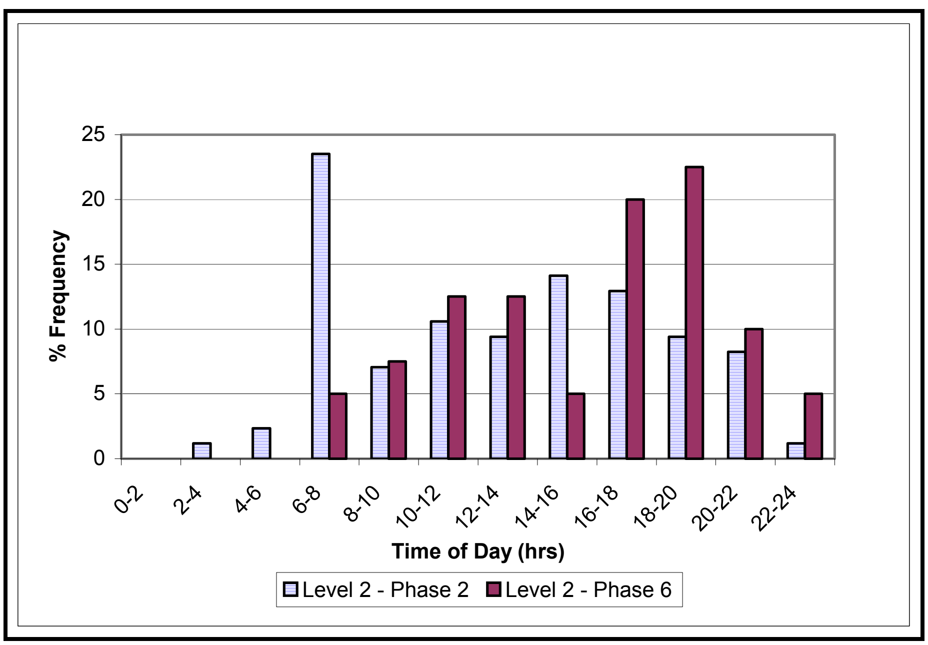

Figure 4.9 Variations in RLR with Time of Day for Different Approaches – Level 2

Entry Time into Red (TX 6 and FM 158, Waco)

A further analysis was done to determine the speeds of RLR vehicles and the time into the red period that they ran the light. This was done for the different study periods on the TX Highway 6 and FM 158 intersection. Approximately 63%, 71% and 65% of red-light-running occurred during the first second of red light indication during the Before, Level 1 and Level 2 studies, respectively. This is lower than values obtained from prior research (*5*, *34*) which reported 80% of drivers entered within 1.0 second after the end of yellow. About 86% of drivers who ran the red light did so during the all-red period (1.5 seconds after end of yellow indication) during the Before and Level 1 study while this percentage increased to almost 90% in the Level 2 study.

This trend is similar to the values found for the Westbound approach (Phase 6), in which approximately 64%, 62% and 55% of the red light running occurred during the first second of red light indication during the Before, Level 1 and Level 2 studies, respectively. Seventy-eight percent (78%) of drivers entered the RLR occurred during the all-red period (i.e. less than 1.5 seconds after end of yellow) during the Before and Level 1 study while this percentage increased to 80% in the Level 2 study. About 20% of RLR occurred more than 1.5 seconds into the red indication, slightly down from the 22% that occurred within the same time frame during the Before and Level 1 study periods. There were instances in which an occurrence of red-light-running was observed some 4 or so seconds after the start of all-red which has also been reported in an MnDOT study (*34*).

EFFECT OF AWEGS ON VEHICLE SPEEDS (WACO, TEXAS)

This section of the report summarizes results of analyses conducted with the speeds of red-light-running vehicles. The analyses conducted were intended to determine:

- The distribution of speeds for various levels;
- The significance in any differences in mean speeds;

- The distribution of higher speeds (Upper 50%) of speeds;
- The percentage of RLR speeds above the speed limit; and
- The variation of RLR speeds with time into red.

Nature of RLR Speed Distribution

Eastbound (Phase 2) Approach

Figures 4.10 to 4.12 show histogram plots of the speed distribution of RLR vehicles during all three study periods in Waco, on the Eastbound (phase 2) approach. The speed distribution during the period before AWEGS provides an interesting picture. There seems to be two distinct groups of red-light runners in Waco. One group comprises speeds below 50 mph with a peak of about 40 mph and the other a higher speed group with speeds generally between 60 mph and 70 mph with a 65 mph peak.

The mean and 85th percentile speeds of Before Eastbound RLR vehicles were 55.9 mph and 67.5 mph. See Appendix for details of statistics of the speed distribution for all Eastbound RLR speeds for Before, Level 1 and Level 2 periods.

From Figures 4.11 the mean and 85th percentile speeds for Level 1 RLR speeds were found to be 51.1 mph and 63.2 mph, respectively. Figure 4.12 shows the distribution for RLR speeds in Level 2 and this distribution had a mean speed of 54.0 mph and an 85th percentile speed of 67.3 mph. There was roughly the same variation in speeds from Level 1 to Level 2 while both were slightly lower than the Before period. Looking at the results, it is not clear that AWEGS had any impact on the distribution of RLR speed distribution on the Eastbound approach.

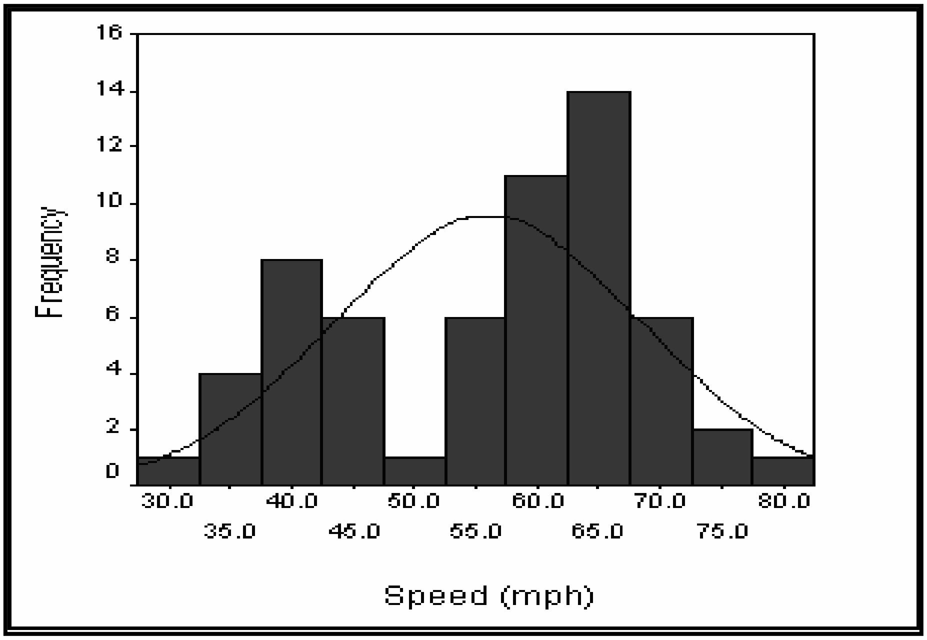

Figure 4.10 Speed Distribution on Phase 2 (Eastbound) Approach Before AWEGS

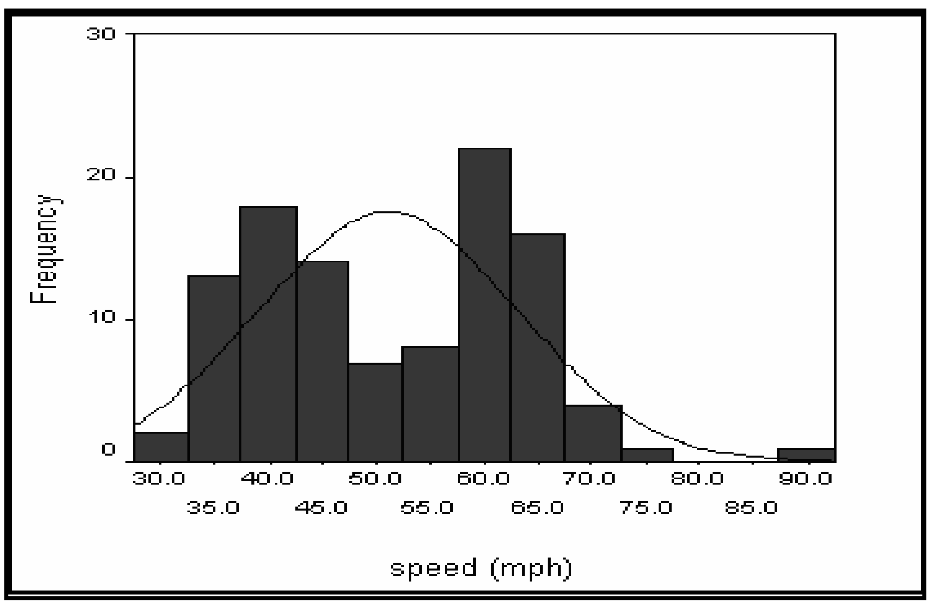

Figure 4.11 Speed Distribution on Phase 2 (Eastbound) Approach for Level 1

Westbound Approach

Similar plots were done for speeds of vehicles that run the red light on the Westbound (Phase 6) approach during all three study periods in Waco. The speed distribution of these speeds for Before, Level 1 and Level 2 are shown in Figures 4.13 through 4.15 respectively. The mean and 85th percentile speeds for the Before period were 57.6 mph and 65.7 mph, while Level 1 speeds had a mean of 57.1 mph and an 85th percentile speed of 66.4 mph. Level 2 speeds had a mean speed of 54.7 mph and an 85th percentile speed of 63.1 mph. See Table Appendix for summary statistics of speed distribution for Westbound RLR speeds distribution.

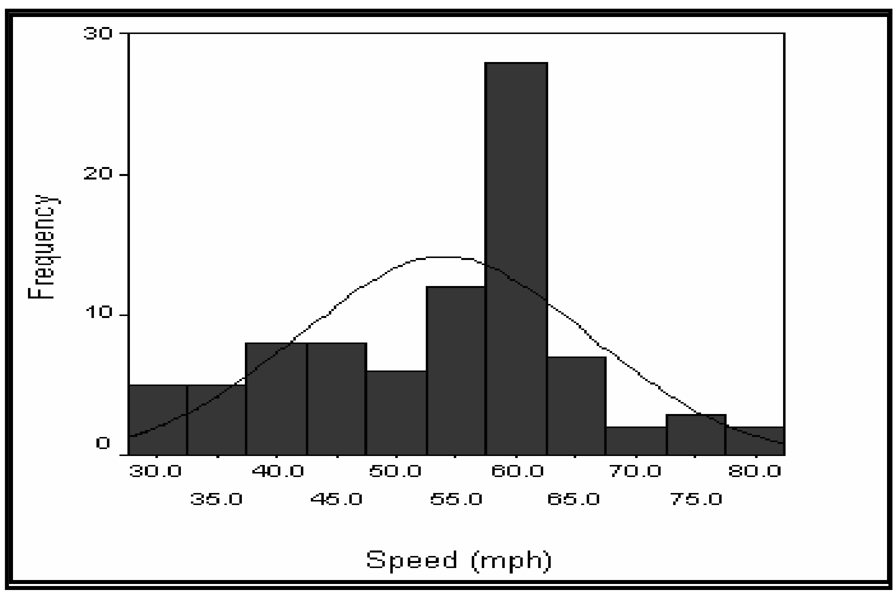

Figure 4.12 Speed Distribution on Phase 2 (Eastbound) Approach for Level 2

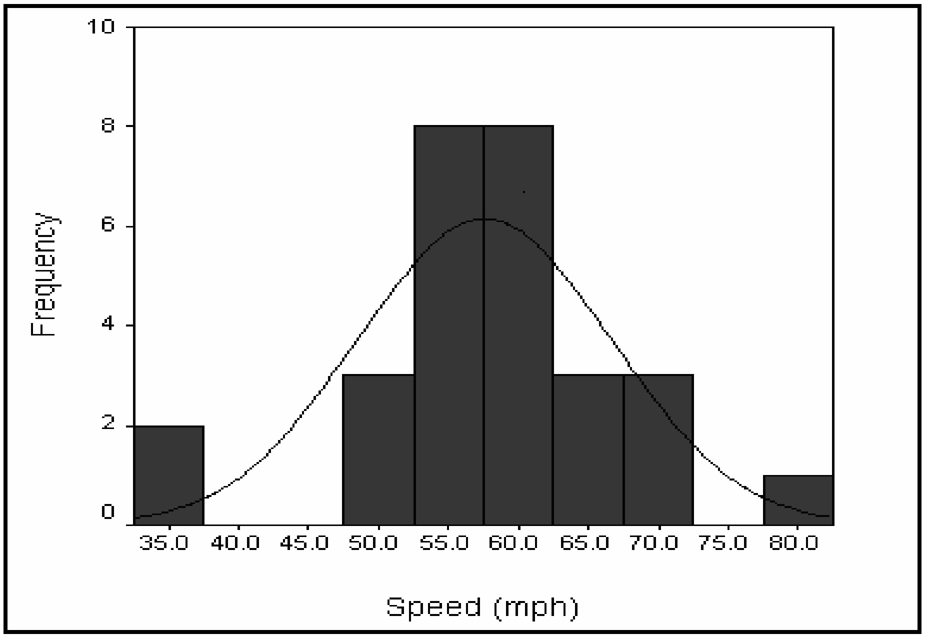

Figure 4.13 Speed Distribution on Phase 6 (Westbound) Approach Before AWEGS

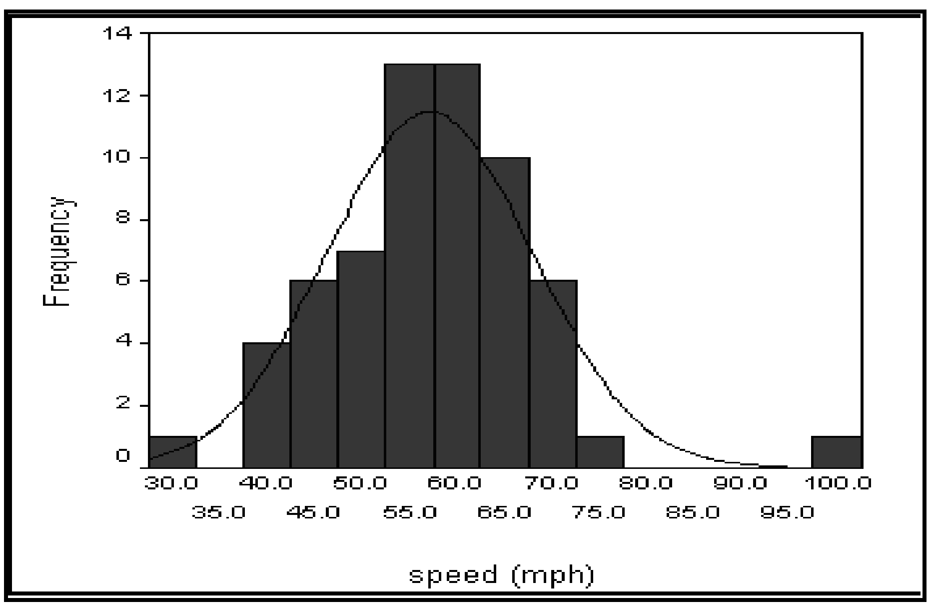

Figure 4.14 Speed Distribution on Phase 6 (Westbound) Approach for Level 1

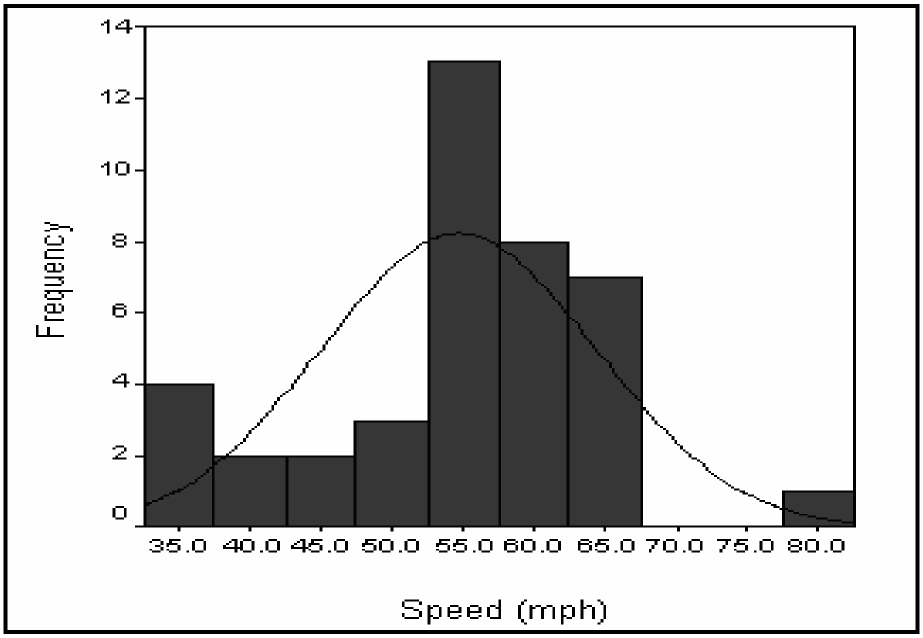

Figure 4.15 Speed Distribution on Phase 6 (Westbound) Approach for Level 2

Summary of Speed Distribution Observed

Below in Table 4.13 is a summary of the speed distribution observed over the three study periods. It summarizes the mean speeds, 85^{th} percentile speeds and the variance in the distribution. It shows that higher variation in speeds was observed on phase 2 (Eastbound approach) than on phase 6 (Westbound approach) RLR vehicles during all study periods. It can also be seen that the standard deviations recorded were quite high even though a test for normality failed to reject the Ho.

Test of Difference in Mean Speeds

Independent T-tests were done to test the significance or otherwise of the mean speeds of the various speeds among the three study periods per approach. Summary results are provided in this section. See Appendix for details of t-test results.

Table 4.13 Summary of Speed Characteristics for Various Study Periods per Approach

	Period	15th Percentile Speed (mph)	Mean Speed (mph)	85th Percentile Speed (mph)	Std. Deviation	CV
Eastbound (Phase 2)	**Before**	39.4	55.9	67.5	12.46	0.22
	Level 1	38.1	51.1	63.2	12.1	0.24
	Level 2	38.5	54.0	67.3	12.1	0.22
Westbound (Phase 6)	**Before**	50.7	57.6	65.7	9.07	0.16
	Level 1	45.8	57.1	66.4	10.8	0.19
	Level 2	39.6	54.7	63.1	9.69	0.18

Eastbound (Phase 2) Approach

Summary of results for the Eastbound are shown in Table 4.14. From the table in mean speeds from Before to both Level 1 and Level 2, with an increase in mean speed from Level 1 to Level 2. The 4.8 mph drop in mean speed after the deployment of Level 1 technology was the only significant reduction in speeds at the 95 % confidence level.

Table 4.14 Summary of Test for Difference in Mean RLR Speeds – Eastbound (Phase 2)

Period	Change in Mean speeds	*p* - value	Significance
Before to Level 1	- 4.8	0.02	X
Before to Level 2	- 1.9	0.35	O
Level 1 to Level 2	+ 2.9	0.10	O

X-significant; O– not significant

Table 4.15 Summary of Test for Difference in Mean RLR Speeds – Westbound (Phase 2)

Period	Change in Mean speeds	*p* - value	Significance
Before to Level 1	- 0.5	0.84	O
Before to Level 2	- 1.9	0.35	O
Level 1 to Level 2	+ 2.9	0.10	O

X-significant; O– not significant

Westbound (Phase 6) Approach

Similar tests were done to test the significance or otherwise of the mean speeds of the various speeds among the three study periods on the Westbound approach. Summary of this results are shown in Table 4.15 above. From the Table it can be seen that there was a drop in mean speeds from the period before AWEGS to both levels, as well as a drop in mean speed from Level 1 to Level 2. None of these reductions were significant at the 95% confidence level.

Considering Upper 50% of Speeds

AWEGS mainly targeted higher speeds (up to 99th percentile speeds), and an effort was made to determine if there was an impact on this category of red-light-running vehicles. The top 50% of speeds recorded for the Before, Level 1 and Level 2 study periods were analyzed separately to determine if there was a difference in the mean speeds as well as the variations in distribution. Results of this analysis of the upper 50% of speeds showed similar trends to that obtained from considering all speeds of red-light-running vehicles. Specifically the following were observed:

- For Eastbound approach, it was found that there was a significant reduction in speed from Before to Level 1 deployment;
- Eastbound (phase 2) red-light-running speeds for Level 2 showed no significant changes at the 95% confident interval, from before installing AWEGS to the deployment of Level 2 technology. Phase 6 (Westbound from Waco), speeds also did not show a significant drop in speeds for the same periods of study; and
- The differences in speeds observed in speeds from Level 1 to Level 2 deployments of AWEGS showed no statistically significant increase or decrease in speeds.

See Appendix E for detail statistics of speeds and results of tests of differences in mean speeds for upper 50% of speeds.

Variation of Speed with Time into Red

Figures 4.16 to 4.21 are plots showing the variation of speeds of red light running vehicles with the time into red that they entered the intersection. From the plots of the speed variation with time into red for Eastbound (Figures 4.16 through 4.18), RLR vehicles showed similar overall variation in speed with the time into red that they crossed the intersection. A linear regression analyses done, showed that only Level 2 slope showed significant difference from zero.

Figures 4.19 through 4.21 (Westbound approach) show a downward trend in speeds with time into red. Regression analysis showed that in the Before and Level 2 cases these slopes were significantly different from zero. See Table 4.16 for a summary of slope significance for these plots. It is difficult to tell if there was any impact of AWEGS on the change in RLR speeds with time into Red from these results. It only shows that there were some differences in RLR speeds and the time into red for different approaches.

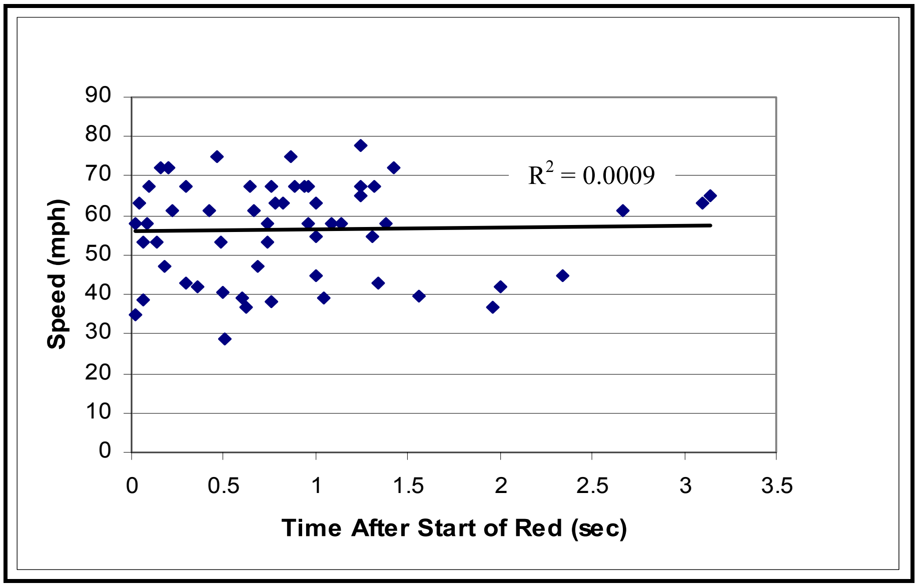

Figure 4.16 Variation of Speed with Time of Red for Eastbound Before

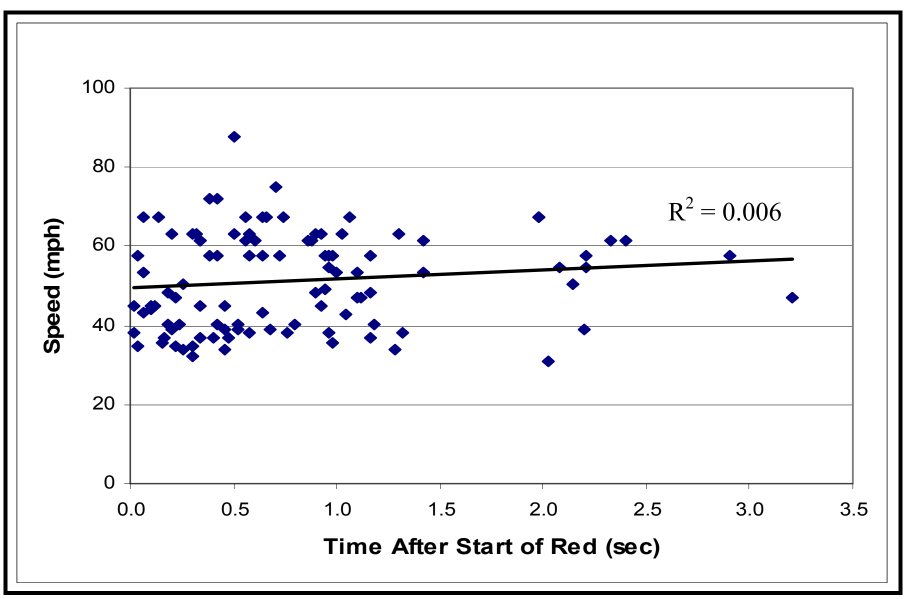

Figure 4.17 Variation of Speed with Time into Red for Eastbound Level 1

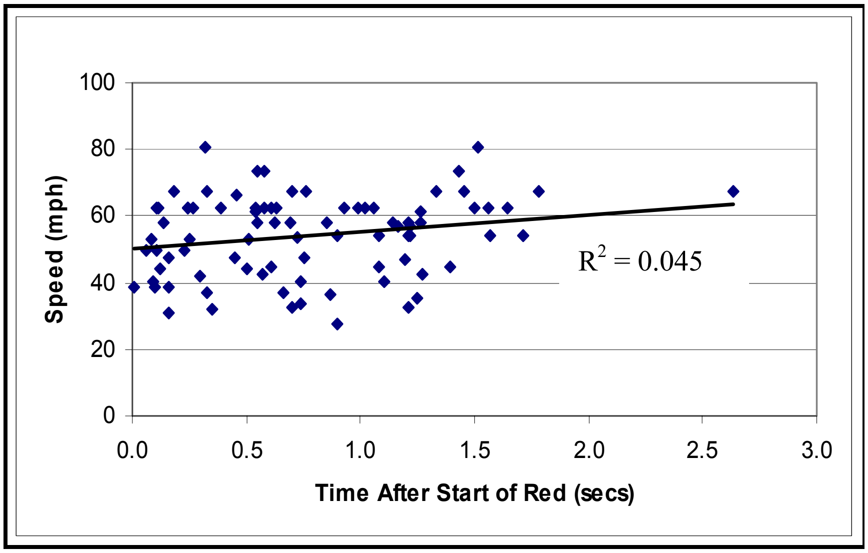

Figure 4.18 Variation of Speed with Time of Red for Eastbound Level 2

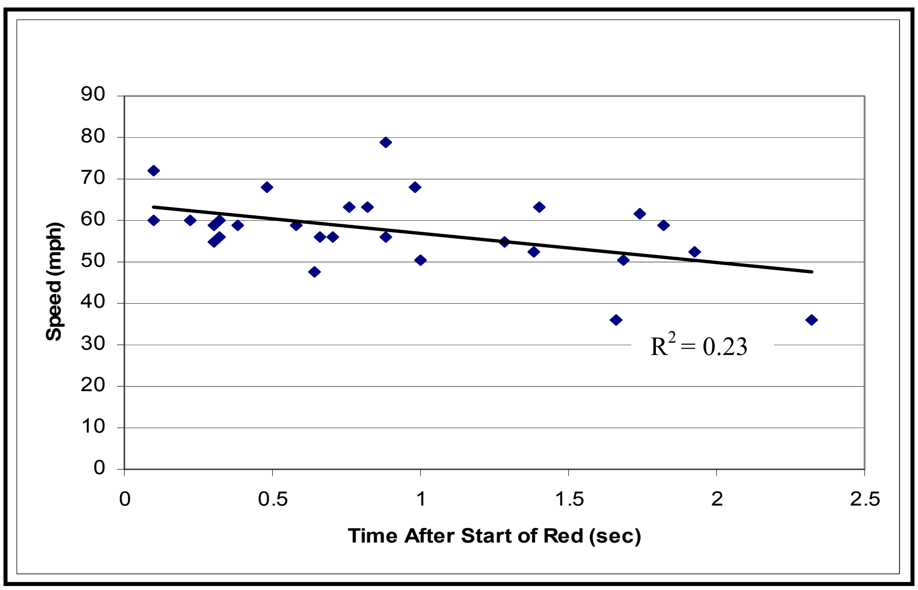

Figure 4.19 Variation of Speed with Time of Red for Westbound Before

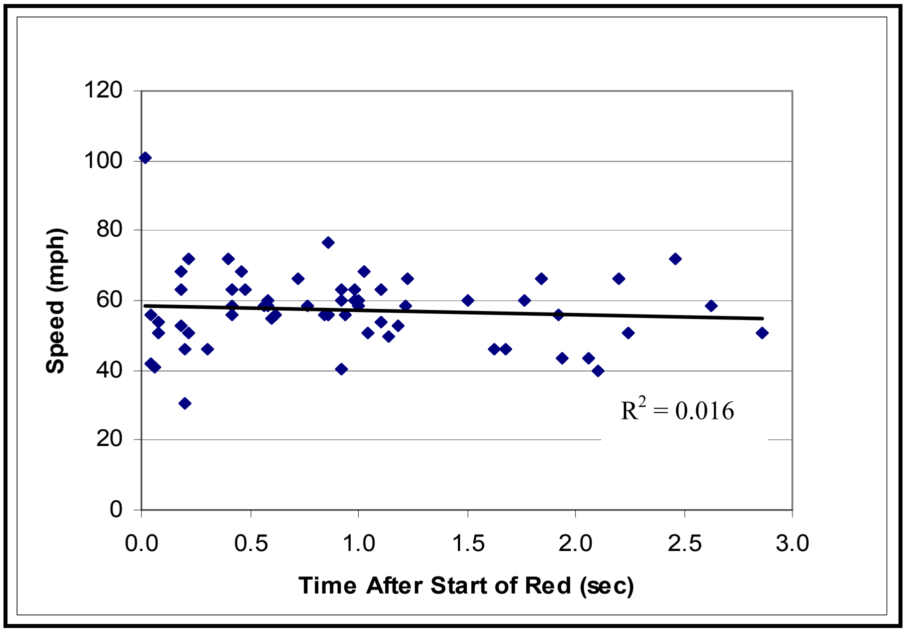

Figure 4.20 Variation of Speed with Time of Red for Westbound Level 1

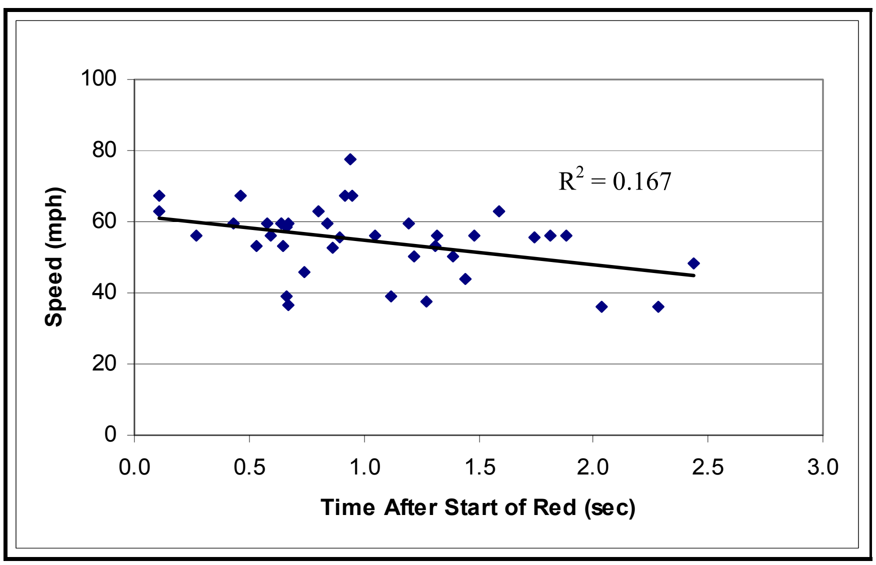

Figure 4.21 Variation of Speed with Time of Red for Westbound Level 2

Table 4.16 Nature of Speed Variation with Time into Red Slopes

Approach	Before	Level 1	Level 2
Eastbound (Phase 2)	Positive	Positive	Positive*
Westbound (Phase 6)	Negative*	Negative	Negative*

* – β_1 significant

Percentage of Red-Light-Runners above Speed Limit

To determine the effect of AWEGS on high speed vehicles that run the red light, an analysis of speeds of vehicles greater than the speed limit that run the red light was done. Table 4.17 shows the percentage of red-light running speeds above the speed limit. From the table, it can be deduced that, about 46% of Eastbound (phase 2) red-light-runners run the red indication at speeds greater than the speed limit. This figure is reduced to 30% and 40% in the Level 1 and Level 2 respectively. In the Westbound direction, 39% run the light at speeds greater than the speed limit in the Before period. This was reduced to 37% and 20% in the Levels 1 and 2 periods respectively. Thus from the results, AWEGS deployment saw a reduction in the percentage of RLR traveling above the speed limit, which was 60 mph in Waco.

Table 4.17 Percentage of Red-Light-Runners Above the Speed Limit

	Before	Level 1	Level 2
Phase 2	46 %	30%	40%
Phase 6	39%	37%	20%

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A summary of the analysis of data performed in this research are presented in this section. Conclusions drawn from results obtained in the research are also given, with recommendations for implementation and future research provided at the end of the section.

SUMMARY

Measures of Effectiveness (MOEs)

Due to differing volumes and cycles per day for the different levels of study in this research, it was found that the three MOEs used (per 100 cycles, per 1,000 vehicles and per 10,000 veh-cycles) produced different results. In most cases though, comparisons of the different levels using the different MOEs yielded similar results.

The per 100 cycle rate MOE provides some insight as to the red-light-running per exposure to yellow indications. However, no effect of volume of vehicles was noted. This might be a drawback to this rate, especially if there is a decrease or increase in vehicles due to some land development or some other traffic-generating event.

The red-light-running per 1,000 vehicles MOE does give some indication of the effect of volume on the red-light-running rate. However, the important effect of the frequency of exposure to the red indication is not captured by this MOE. If there is any temporary correlation between cross-street traffic volumes and the frequency of the main street signal changes, this effect may not be captured and these RLR rates may not be informative enough. It might be useful in comparing red-light running at intersections with fixed timing, as there will be a fixed phase timing and the number of cycles can be easily found.

Using the per 10,000 veh-cycles rate MOE seemed to capture some average effects of vehicular exposure to yellow onset. It does appear to provide the most useful insight into the effects of both volume and frequency of exposure to the red indication, and this may help ameliorate any biases that may crop up when the other two MOEs (per 100 cycles and per 1,000 vehicles) are used. This rate also allows for comparison of different intersections, and it can serve as input for prediction models for crashes and red-light-running.

Both intersections used in this study were actuated, thus it is likely that the use of a per 10,000 veh-cycle rate is more useful. It may be possible that for low-volume isolated intersections a *per 1x* 10^6 *veh-cycle* rate should be used. Also, it was found that when there was a significant reduction in red-light-running events for an approach, all the rates seemed to produce similar results in terms of significance of reduction or otherwise.

AWEGS Treatment- Before vs. After

From results found in this research, it can be said that AWEGS was very effective in reducing red-light-running at both study sites. The findings have been grouped by site.

Brenham

From the results in Brenham the following were found:

- AWEGS Level 2 reduced total red-light-running per 10,000 veh-cycles by 50% in the Eastbound direction and by 30% in the Westbound approach;
- Eastbound (Phase 8) rates were higher than Westbound (Phase 4) rates; and
- Larger RLR rate reductions were observed in the Eastbound (Phase 8) than the Westbound (Phase 4).

Waco

From the RLR rates observed at the intersection near Waco, the following were observed:

- Total RLR per 10,000 veh-cycles were reduced by up to 60% in both Level 1 and Level 2 from the Before period in the Eastbound direction;
- Westbound (Phase 6) RLR rates were reduced by about 5% from Level 1 to Level 2;
- Eastbound (Phase 2) RLR rates were slightly higher (about 2%) in Level 2 than in Level 1;
- Total Eastbound (Phase 2) RLR rates were higher than the Westbound (Phase 6) rates; and
- Larger total RLR rate reduction was observed on the Eastbound (Phase 2) than the Westbound (Phase 6).

Efficiency

The AWEGS system performed more efficiently in Level 2 than in Level 1 with a lower average cycle length observed. This is due to the variable holding feature in the Level 2 upgrade, which ensures that less time is wasted within a cycle for vehicles that don't require the full five-second hold applied in Level 1 deployment.

Daytime vs. Nighttime RLR

The nature of red-light-running per time of day had some interesting results. What was apparent was that it day and night RLR rates varied by intersection approach. The results are presented here by study site.

Brenham

Day vs. night RLR rates for intersection of US 290 and FM 577 in Brenham had the following results:

- Day RLR rates in Westbound (Phase 4) were lower than night RLR rates, but higher than night rates in the Eastbound (Phase 8) direction; and
- Largest reductions occurred in nighttime and daytime phase 8 with the least RLR reduction in phase 4 night RLR rates.

Waco

Results on day vs. night RLR rates for intersection of TX 6 and FM 185 in Brenham had the following results:

- In the Before study, Eastbound day RLR was higher than night RLR while the reverse was the case in the Westbound direction;
- Level 1 had higher daytime RLR rates than nighttime RLR rates, while Level 2 had higher nighttime rates than daytime rates;
- Both daytime and nighttime RLR rates were reduced from the Before to Level 1 and Level 2, with the largest reductions in the Eastbound direction;
- Daytime RLR was reduced by up to 70% in Level 2 in the Eastbound direction with the lowest Level 2 reduction occurring during nighttime EB RLR rates;
- Eastbound daytime RLR was reduced by up to 35% from Level 1 to Level 2; and
- Nighttime RLR rates increased considerably from Level 1 to Level 2.

Speed

From the analysis of speeds of RLR during the deployment of AWEGS in Waco at the intersection of TX Highway 6 and FM 185, the following were observed:

- Mean speeds of red-light-runners generally decreased from the period before AWEGS installation to the period after installation. The only statistically significant drop occurred in Level 1 on phase 2 approach;
- There was an observed downward trend in speeds with time into red for RLR events in phase 6, while a more upward trend in speeds with time into red for RLR was observed on phase 2;
- Percentage of RLR speeds on Eastbound approach above the speed limit was reduced from 46% in the Before case to 30% and 40% in Levels 1 and 2, respectively;
- Percentage of RLR speeds on the Westbound approach traveling above the speed limit was reduced from 39% in the Before case to 37% in Level 1 and 20% in Level 2; and
- An analysis of higher speeds (upper 50%) of observed red-light-runners showed slightly larger reductions in speeds but with similar statistical test results as those described for all speeds above.

CONCLUSIONS

From the research analysis provided in this research, the following can be concluded:

1. The per 10,000 veh-cycle MOE rate produces an average effect of the two other MOEs considered (per 100 cycles and per 1,000 vehicles).

2. AWEGS proved very effective in reducing red-light-running for both study sites. This was the case for all the MOEs used. Significant reductions were observed during the total RLR as well as day and night red-light-running.

3. Slight increase in initial RLR per day results in Level 2 RLR rates (as compared to Level 1) were found to occur mainly at night. One factor for this might include the increased number of cycles per day due to the variable

holds in Level 1 which reduces wasted green time existing during Level 1 operation. Another reason for this could be that those running the red indication in Levels 1 and 2 have similar characteristics. More likely than not; those drivers that would not intentionally run the light are now being safely carried across the intersection and do not form part of the current red-light-running population. This leaves those drivers who will typically run the light anyway, especially if it is a few seconds (say less than 2 secs) into the red indication.

4. Generally day RLR rates were higher than night RLR rates.

5. There was a reduction in the percentage of RLR speeds above the speed limit from Before to Levels 1 and 2. There was also a general reduction in mean speeds of RLR vehicles from Before to Levels 1 and 2.

6. The fail-safe mode of AWEGS, resulting in Level 1 operation in case of a detector-failure, was found to be very effective in reducing red-light-running for both day and night. It is an effective way of still providing reliable protection to high-speed vehicles and reducing red-light-running. This noticeable improvement on prior conditions at the Waco intersection could be attributed to the fixed hold time for high-speed approach vehicles, allowing most motorists to exit their dilemma zone before the onset of yellow clearance, thus reducing the red-light-running potential of such vehicles.

RECOMMENDATIONS

AWEGS is an example of a high-technology application to alleviate a potentially serious problem on high-speed highways of rural Texas. To facilitate the operations of AWEGS and to improve its operations, the following recommend actions are offered.

Measure of Effectiveness

It is recommended that for low volume rural intersections with relatively low red-light-running rates, RLR per $1x10^6$ vehicle-cycle should be used. This allows for reasonable values to be obtained and also serves to capture the vehicle and frequency of signal change parameters and their effects on red-light-running at such intersections.

Additional Implementation of AWEGS

Due to its innovativeness and relatively new system, further tests on AWEGS through additional implementations at varying intersection types and locations would be helpful. This would help improve AWEGS performance and the familiarity of TxDOT, city and county operation technicians with the system. Particularly, the following need to be researched in future implementations of AWEGS:

- The nature of speeds as they leave the AWEGS advanced detectors and approach the intersection to help filter local low-speed traffic from the targeted high-speed vehicles;
- Effects of cross street volumes on red-light-running on the main street and how this interacts with AWEGS performance in RLR reduction;
- The effect of intersection approach characteristics on the performance of AWEGS; and
- The effect of video detection zone layout and placement on effectively detecting red-light-runners.

Data Collection and Analysis Method

To facilitate data collection and data analysis, an effective and possibly automated method to collect and analyze the data obtained should be developed. Also, it is recommended that recording of video data be used as part of this data collection process for verification of computer-logged data (if this method is employed) and subsequent calibration.

Fail-Safe Mode Operation

The fail-safe mode of AWEGS operation which uses AWEGS Level 1 technology in case of detector failure in Level 2, should be implemented in areas where the technology of AWEGS Level 2 may be either too complex or too expensive to install.

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APPENDIX A

SUMMARY OBSERVATIONS OF CYCLES AND VOLUMES FOR DIFFERENT PERIODS OF STUDY - BRENHAM AND WACO

Tables A1-A2 Summary of Observations, Brenham

Table A1 Summary of Total Observations

Study Period	Intersection Approach	Total Observations			
		No. of Vehicles	*No. of Cycles*	*No. of Veh-Cycles*	*No. of RLR events*
Before	Phase 4	206,411	19,138	103,179,857	504
	Phase 8	184,347	13,277	117,484,733	1,375
After	Phase 4	193,392	20,305	187,440,288	358
	Phase 8	181,306	13,818	119,638,950	701

Table A2 Summary of Night and Day Observations

Study Period	Time of Day	Intersection Approach	Total Observations			
			No. of Vehicles	*No. of Cycles*	*No. of Veh-Cycles*	*No. of RLR Events*
Before	Daytime	Phase 4	167,618	11,082	88,311,877	421
		Phase 8	143,151	9,576	65,812,413	1,244
	Nighttime	Phase 4	38,793	8,056	14,867,980	83
		Phase 8	41,196	3,701	7,322,668	131
After	Daytime	Phase 4	146,592	11,884	89,978,630	288
		Phase 8	141,366	8,865	59,774,126	616
	Nighttime	Phase 4	35,805	8,421	14,307,743	70
		Phase 6	39,940	4,953	9,460,139	85

Tables A3-A6 Summary of Observations, Waco

Table A3 Summary of Total Observations

Study Period	Intersection Approach	Total Observations			
		No. of Vehicles	*No. of Cycles*	*No. of Veh-Cycles*	*No. of RLR Events*
Before	**Phase 2**	39,206	11,341	39,725,864	60
	Phase 6	40,519	11,266	39,545,006	28
Level 1	**Phase 2**	136,903	34,768	131,966,328	105
	Phase 6	142,002	34,487	134,802,585	61
Level 2	**Phase 2**	84,407	23,086	93,211,294	85
	Phase 6	78,481	21,885	86,413,263	40

Table A4 Summary of Day and Night Observations – Before and Level 1

Study Period	Time of Day	Intersection Approach	Total Observations			
			No. of Vehicles	*No. of Cycles*	*No. of Veh-Cycles*	*No. of RLR Events*
Before	**Daytime**	**Phase 2**	28,882	7,253	18,687,071	53
		Phase 6	29,292	7,142	18,188,080	17
	Nighttime	**Phase 2**	10,324	4,088	3,779,094	7
		Phase 6	11,227	4,124	4,000,888	11
Level 1	**Daytime**	**Phase 2**	98,303	21,628	59,296,527	92
		Phase 6	101,223	21,466	60,451,688	54
	Nighttime	**Phase 2**	38,600	13,140	14,456,618	13
		Phase 6	40,779	13,021	15,180,656	7

Table A5 Summary of Day and Night Observations – Before and Level 2

Study Period	Time of Day	Intersection Approach	Total Observations			
			No. of Vehicles	*No. of Cycles*	*No. of Veh-Cycles*	*No. of RLR Events*
Before	Daytime	Phase 2	28,882	7,253	18,687,071	65
		Phase 6	29,292	7,142	18,188,080	22
	Nighttime	Phase 2	10,324	4,088	3,779,094	12
		Phase 6	11,227	4,124	4,000,888	13
Level 2	Daytime	Phase 2	70,225	16,942	56,912,421	61
		Phase 6	67,160	16,256	54,882,889	32
	Nighttime	Phase 2	14,182	6,144	4,171,474	12
		Phase 6	11,321	5,629	3,209,050	5

Table A6 Summary of Day and Night Observations – Level 1 and Level 2

Study Period	Time of Day	Intersection Approach	Total Observations			
			No. of Vehicles	*No. of Cycles*	*No. of Veh-Cycles*	*No. of RLR Events*
Level 1	Daytime	Phase 2	98,303	21,628	59,296,527	92
		Phase 6	101,223	21,466	60,451,688	54
	Nighttime	Phase 2	38,600	13,140	14,456,618	13
		Phase 6	40,779	13,021	15,180,656	7
Level 2	Daytime	Phase 2	70,225	16,942	56,912,421	70
		Phase 6	67,160	16,256	54,882,889	35
	Nighttime	Phase 2	14,182	6,144	4,171,474	15
		Phase 6	11,321	5,629	3,209,050	5

APPENDIX B

ANOVA RESULTS FOR ANOVA TEST ON RLR per 10,000 VEHICLE-CYCLES RATES, BRENHAM

Tables B1 – B4 ANOVA Results for Red-Light Running in Brenham

Westbound (Phase 4) Results

Table B1 ANOVA Results for Phase 4 in Brenham

Test	Before			After			*p* value	Change[1]
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Total	21	0.030	0.021	21	0.019	0.007	0.033	-0.011
Daytime	21	0.054	0.039	21	0.032	0.013	0.021	-0.022
Nighttime	21	0.061	0.043	21	0.053	0.028	0.45	-0.008

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table B2 ANOVA Results for Daytime vs. Nighttime – (Phase 4)

Test	Day			Night			*p* value	Change[1]
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Before	21	0.054	0.039	21	0.061	0.043	0.576	0.007
After	21	0.032	0.013	21	0.053	0.028	0.004	0.02

1 – Change computed as "Ave. Night – Ave. Day". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Eastbound (Phase 8) Results

Table B3 ANOVA Results for Phase 8 in Brenham

Test	Before			After			*p* value	Change[1]
	Obs.	*Ave.*	*Std. Dev.*	*Obs.*	*Ave.*	*Std. Dev.*		
Total	21	0.121	0.030	21	0.059	0.020	2.2E-09	-0.06
Daytime	21	0.194	0.055	21	0.104	0.038	2.4E-07	-0.09
Nighttime	21	0.193	0.094	21	0.093	0.050	1.0E-04	-0.1

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table B4 ANOVA Results for Daytime vs. Nighttime – (Phase 8)

Test	Day			Night			*p* value	Change[1]
	Obs.	*Ave.*	*Std. Dev.*	*Obs.*	*Ave.*	*Std. Dev.*		
Before	21	0.194	0.055	21	0.193	0.094	0.973	8.0E-04
After	21	0.104	0.038	21	0.093	0.050	0.450	-0.01

1 – Change computed as "Ave. Night – Ave. Day". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

APPENDIX C

ANOVA RESULTS FOR ANOVA TEST ON RLR PER 10,000 VEHICLE-CYCLES RATES, WACO

Tables C1 – C8 ANOVA Results for Red-Light Running in Waco

Eastbound (Phase 2) Results

Table C1 ANOVA Results for Before and Level 1 – Eastbound (Phase 2)

Test	Before			Level 1			*p* value	Change[1]
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Total	13	0.024	0.020	35	0.008	0.004	2E-05	<u>-0.016</u>
Daytime	13	0.041	0.025	35	0.015	0.010	8E-06	<u>-0.025</u>
Nighttime	13	0.058	0.132	35	0.006	0.010	0.024	<u>-0.05</u>

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table C2 ANOVA Results for Before and Level 2 – Eastbound (Phase 2)

Test	Before			Level 2			*p* value	Change[1]
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Total	13	0.024	0.020	21	0.007	0.003	5E-04	<u>-0.016</u>
Daytime	13	0.041	0.025	21	0.010	0.004	8E-06	<u>-0.03</u>
Nighttime	13	0.058	0.132	21	0.028	0.036	0.33	-0.03

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table C3 ANOVA Results for Level 1 and Level 2 – Eastbound (Phase 2)

Test	Level 1			Level 2			*p* value	Change
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Total	35	0.008	0.004	21	0.007	0.003	0.975	3E-05
Daytime	35	0.015	0.010	21	0.010	0.004	0.04	<u>-0.004</u>
Nighttime	35	0.006	0.010	21	0.028	0.036	0.001	<u>0.021</u>

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table C4 ANOVA Results for EB (Phase 2) Daytime vs. Nighttime

Test	Day			Night			*p* value	Change
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Before	13	0.041	0.025	13	0.058	0.132	0.65	0.016
Level 1	35	0.015	0.010	35	0.006	0.010	3E-04	<u>-0.009</u>
Level 2	21	0.010	0.004	21	0.028	0.036	0.04	<u>0.017</u>

1 – Change computed as "Ave. Night – Ave. Day". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Westbound (Phase 6) Results

Table C5 ANOVA Results for Before and Level 1 – Westbound (Phase 6)

Test	Before			Level 1			*p* value	Change[1]
	Obs.	*Ave.*	*Std. Dev.*	*Obs.*	*Ave.*	*Std. Dev.*		
Total	13	0.01	0.007	35	0.004	0.003	5E-04	<u>-0.005</u>
Daytime	13	0.011	0.009	35	0.009	0.007	0.25	-0.003
Nighttime	13	0.047	0.058	35	0.005	0.013	2E-04	<u>-0.04</u>

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*

Table C6 ANOVA Results for Before and Level 2 – Westbound (Phase 6)

Test	Before			Level 2			*p* value	Change[1]
	Obs.	*Ave.*	*Std. Dev.*	*Obs.*	*Ave.*	*Std. Dev.*		
Total	13	0.01	0.007	21	0.004	0.002	0.002	<u>-0.006</u>
Daytime	13	0.011	0.009	21	0.005	0.003	0.008	<u>-0.006</u>
Nighttime	13	0.047	0.058	21	0.015	0.029	0.04	<u>-0.03</u>

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table C7 ANOVA Results for Level 1 and Level 2 – Westbound (Phase 6)

Test	Level 1			Level 2			*p* value	Change
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Total	35	0.004	0.003	21	0.004	0.002	0.75	2E-04
Daytime	35	0.009	0.007	21	0.005	0.003	0.049	<u>-0.003</u>
Nighttime	35	0.005	0.013	21	0.015	0.029	0.092	0.01

1 – Change computed as "Ave. After – Ave. Before". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

Table C8 ANOVA Results for WB (Phase 6) Daytime vs. Nighttime

Test	Day			Night			*p* value	Change
	Obs.	***Ave.***	***Std. Dev.***	***Obs.***	***Ave.***	***Std. Dev.***		
Before	13	0.011	0.009	13	0.047	0.058	0.040	<u>0.035</u>
Level 1	35	0.009	0.007	35	0.005	0.013	0.184	-0.003
Level 2	21	0.005	0.003	21	0.015	0.029	0.137	0.009

1 – Change computed as "Ave. Night – Ave. Day". An underlined value represents a statistically significant change at the 95% confidence (*i.e. p value < 0.05*)

APPENDIX D

DETAILS OF SPEED DISTRIBUTION AND RESULTS OF T-TESTS FOR DIFFERENCE IN MEAN SPEEDS OF ALL RLR SPEEDS

Tables D1-D2 Summary Statistics of Speeds, Waco

Table D1 Summary Statistics of Waco Speed Distribution on Eastbound Approach

Statistic		Before	Level 1	Level 2
Sample Size		60	106	86
Mean		55.9	51.1	54.0
Std. Error of Mean		1.61	1.17	1.31
Median		58.1	50.6	57.0
Mode		57.8	57.8	62.2
Std. Deviation		12.46	12.1	12.1
Range (mph)		48.85	56.8	53.0
Lowest Speed (mph)		28.89	31.1	27.9
Highest Speed (mph)		77.74	87.9	80.8
Percentiles	**5 th**	36.7	34.1	32.4
	15 th	39.4	38.1	38.5
	25 th	43.5	38.9	44.4
	75 th	66.2	61.3	62.2
	85 th	67.5	63.2	67.3
	90 th	70.6	67.4	67.4
	99 th	77.7	86.9	80.8

Table D2 Summary Statistics of Waco Speed Distribution in Westbound Approach

Statistic		Before	Level 1	Level 2
Sample Size		28	62	40
Mean Speed (mph)		57.6	57.1	54.7
Std. Error of Mean		1.71	1.37	1.53
Median Speed (mph)		58.6	57.3	56.04
Modal Speed (mph)		56.0	56.1	59.4
Std. Deviation		9.07	10.8	9.69
Range (mph)		42.78	70.5	41.7
Lowest Speed (mph)		36.04	30.4	36.0
Highest Speed (mph)		78.82	100.8	77.7
Percentiles	5th	36.0	40.5	36.0
	15th	50.4	45.8	39.6
	25th	53.1	50.5	50.4
	75th	62.7	63.1	59.4
	85th	66.4	66.4	63.1
	90th	68.6	68.2	67.3
	99th	78.8	100.8	77.7

Tables D3-D14 T-Test Results for Difference in Mean Speeds, Waco – All Speeds

Eastbound Approach (Phase 2)

Table D3 Group Statistics of Before and Level 1 – Eastbound Approach (Phase 2)

Period	Sample Size	Mean	Std. Deviation	Std. Error Mean
Before	60	55.9	12.5	1.61
Level 1	106	51.1	12.0	1.17

Table D4 T-test for Equality of Means (Phase 2)

	t	*p* (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	*Upper*
Equal variances assumed	2.430	0.016	4.79	1.97	0.90	8.68
Equal variances not assumed	2.407	0.018	4.79	1.99	0.85	8.73

Table D5 Group Statistics of Before and Level 2 – Eastbound Approach (Phase 2)

Period	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Before	60	55.9	12.47	1.61
Level 2	86	54.0	12.13	1.31

Table D6 T-test for Equality of Means - Eastbound Approach (Phase 2)

	t	*p* (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	*Upper*
Equal variances assumed	0.928	0.355	1.92	2.06	-2.19	6.00
Equal variances not assumed	0.924	0.357	1.92	2.07	-2.19	6.00

Table D7 Group Statistics of Level 1 and Level 2 - Eastbound Approach (Phase 2)

Period	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Level 1	106	51.1	12.05	1.17
Level 2	86	54.0	12.13	1.31

Table D8 T-test for Equality of Means- Eastbound Approach (Phase 2)

	t	df	*p*-value (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval	
						Lower	***Upper***
Equal variances assumed	-1.639	190	0.103	-2.87	1.75	-6.33	0.59
Equal variances not assumed	-1.637	181.4	0.103	-2.87	1.75	-6.34	0.59

Westbound Approach (Phase 6)

Table D9 Group Statistics of Before and Level 1 – Westbound Approach (Phase 6)

Period	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Before	28	57.6	9.07	1.71
Level 1	62	57.1	10.75	1.36

Table D10 T-test for Equality of Means – Westbound Approach (Phase 6)

	t	p (2-tailed)	Mean Difference (mph)	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	*Upper*
Equal variances assumed	0.193	0.847	0.45	2.34	-4.19	5.10
Equal variances not assumed	0.206	0.837	0.45	2.19	-3.93	4.83

Table D11 Group Statistics of Before and Level 2 – Westbound Approach (Phase 6)

Period	Sample Size	Mean Speed (mph)	Std. Dev.	Std. Error Mean
Before	28	57.6	9.07	1.71
Level 2	40	54.7	9.69	1.53

Table D12 T-test for Equality of Means – Westbound Approach (Phase 6)

	t	*p* (2-tailed)	Mean Difference (mph)	Std. Error Difference	95% Confidence Interval of the Difference	
					Lower	*Upper*
Equal variances assumed	1.238	0.220	2.89	2.33	-1.77	7.52
Equal variances not assumed	1.253	0.215	2.89	2.30	-1.72	7.48

Table D13 Group Statistics of Level 1 and Level 2 – Westbound Approach (Phase 6)

Period	Sample Size	Mean Speed (mph)	Std. Dev.	Std. Error Mean
Level 1	62	57.1	10.75	1.37
Level 2	40	54.7	9.69	1.53

Table D14 T-test for Equality of Means – Westbound Approach (Phase 6)

	t	*p* value (2-tailed)	Mean Difference (mph)	Std. Error Difference (mph)	95% Confidence Interval	
					Lower	***Upper***
Equal Variances Assumed	1.156	0.250	2.43	2.10	-1.74	6.59
Equal Variances not Assumed	1.183	0.240	2.43	2.05	-1.65	6.51

APPENDIX E

DETAILS OF SPEED DISTRIBUTION AND RESULTS OF T-TESTS FOR DIFFERENCE IN MEAN SPEEDS OF UPPER 50% SPEEDS

Tables E1 – E12 Results of T-Test for Upper 50% Speeds

Eastbound Approach (Phase 2)

T-Test - for Difference in Means of Before and Level 1

Table E1 Group Statistics – Westbound Before and Level 1

Study Period	Sample Size	Mean	Std. Deviation	Std. Error Mean
Before	28	66.9	4.88	0.92
Level 1	52	61.9	6.42	0.89

Table E2 T-Test for Equality of Means for Difference in Means – Eastbound Before and Level 1

	t	df	*p*-value (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval	
						Lower	*Upper*
Equal variances assumed	3.62	78	0.001	5.04	1.39	2.27	7.80
Equal variances not assumed	3.93	69.1	0.001	5.04	1.28	2.48	7.59

T-Test - for Difference in Means of Before and Level 2

Table E3 Group Statistics – EB Before and Level 2

Study Period	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Before	28	66.89	4.88	0.921
Level 2	42	64.12	5.66	0.874

Table E4 T-Test for Equality of Means for Difference in Means – EB Before and Level 2

	t	df	*p*-value (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval	
						Lower	*Upper*
Equal variances assumed	2.116	68	0.038	2.8	1.309	0.16	5.38
Equal variances not assumed	2.181	63.6	0.033	2.8	1.27	0.23	5.31

T-Test - for Difference in Means of Level 1 and Level 2

Table E5 Group Statistics – EB Level 1 and Level 2

Study Period	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Level 1	52	61.9	6.42	0.89
Level 2	42	64.1	5.66	0.87

Table E6 T-Test for Equality of Means for Difference in Means – EB Level 1 and Level 2

	t	df	*p* - value (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval	
						Lower	*Upper*
Equal variances assumed	-1.793	92	0.076	-2.27	1.26	-4.78	0.24
Equal variances not assumed	-1.817	91.3	0.073	-2.27	1.25	-4.74	0.21

Testing for Differences in Mean Speeds - Westbound Approach

T-Test - for Difference in Means of Before and Level 1

Table E7 Group Statistics – WB Before and Level 1

	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Before	14	63.886	5.9446	1.588
Level 1	30	63.743	4.9860	0.910

Table E8 T-Test for Equality of Means for Difference in Means - WB Before and Level 1

	t	df	*p* - value. (2-tailed)	Mean Difference (mph)	Std. Error Difference	95% Confidence Interval of the Difference	
						Lower	*Upper*
Equal variances assumed	0.083	42	0.934	0.142	1.7159	-3.3204	3.6051
Equal variances not assumed	0.078	21.8	0.939	0.142	1.8311	-3.6562	3.9410

<u>T-Test - for Difference in Means of Before and Level 2</u>

Table E9 Group Statistics – WB Before and Level 2

Study Periods	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Before	14	63.9	5.94	1.59
Level 2	20	61.8	5.42	1.21

Table E10 T-Test for Equality of Means for Difference in Means – WB Before and Level 2

	t	df	*p*-value (2-tailed)	Mean Difference	Std. Error Differenc e	95% Confidence Interval of the Difference	
						Lower	*Upper*
Equal variances assumed	1.087	32	0.285	2.136	1.9645	-1.8658	6.1373
Equal variances not assumed	1.069	26.4	0.295	2.136	1.9979	-1.9680	6.2394

T-Test - for Difference in Means of Level1 and Level 2

Table E11 Group Statistics – WB Level 1 and Level 2

Study Period	Sample Size	Mean Speed (mph)	Std. Deviation	Std. Error Mean
Level 1	30	63.7433	4.99	.91032
Level 2	20	61.7500	5.418	1.21138

Table E12 T-Test for Equality of Means for Difference in Means – WB Level 1 and Level 2

	t	df	*p*-value (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						Lower	*Upper*
Equal variances assumed	1.338	48	0.187	1.99	1.49	-1.02	4.99
Equal variances not assumed	1.315	38.5	0.196	1.99	1.52	-1.07	5.06

VITA

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